This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

Modeling Operational Behavior of Plug-in Electric Vehicles' Parking Lot in Multienergy Systems

Maziar Yazdani-Damavandi, *Student Member, IEEE*, Mohsen Parsa Moghaddam, *Member, IEEE*, Mahmoud-Reza Haghifam, *Senior Member, IEEE*, Miadreza Shafie-khah, *Member, IEEE*, and João P. S. Catalão, *Senior Member, IEEE*

***Abstract*—Development of distributed energy resources introduces high level of interdependency and the need for integrated models in a multienergy system (MES). Moreover, highlighting environmental aspects facilitates electrification in the transportation sector and integration of plug-in electric vehicles (PEVs). In this paper, aggregation of PEVs' batteries in parking lots (PL) is considered as a bulk electric storage in MES. The energy hub approach is employed for modeling MES considering PL. Due to the profitable behavior of PL in the reserve market, the energy hub model is modified to consider the reserve sources as ancillary services in the output energy vector. Moreover, the uncertain traffic pattern of PEVs' owners in PL is modeled by a stochastic approach. The numerical results demonstrate the proficiency of the proposed model, determining the changes in the behavior of other MESs elements in the presence of PL.**

***Index Terms*—Energy hub modeling, multienergy system (MES), parking lot (PL), plug-in electric vehicles (PEVs).**

Nomenclature

Subscripts

e	Electricity.
g	Natural gas.
h	Heat.
r	Reserve.
t	Time interval.
ω	Scenario.

Superscripts

ar	Arrived plug-in electric vehicles (PEVs) in parking lot.
CHP	Combined heat and power.
con	Contingency.
dep	Departed PEVs from parking lot.
down	PEVs' departure SoC is less than scenario.
EC	Energy converter.
ES	Energy storage.
EV	Electric vehicle.
G2V	Grid to vehicle mode.
HS	Heat storage.
in	Input energy to micro-MES or parking lot.
inj	Injected energy to macro-MES.
MaMES	Macro-MES.
MED	Multienergy demand.
new	New matrix or vector.
old	Old matrix or vector.
out	Output energy from parking lot.
PL	Parking lot.
Sc	Scenario.
up	PEVs' departure state of charge is more than scenario.
V2G	Vehicle to grid mode.
WG	Wind generation.

Parameters and Variables

Ca	Total capacity of PEVs in PL.
Cd	Cost of battery degradation.
FOR	Forced outage rate.
g, G	Natural gas.
N	Number of PEVs in PL.
q, Q	Heat.
r, R	Reserve.
soc, SoC	State of charge.
v	Decision variable that determines the share of each MESs elements from input energy carriers.
w, W	Electricity.
x	Binary variable.
φ	PEVs participation ratio in V2G mode.
γ, Γ	Charge/Discharge rate.
λ	Heat to electricity ratio of CHP unit.
ρ	Scenario probability.
η	Efficiency.
π	Energy price.
$\mathbf{C}$	Coupling matrix of ECs.
$\mathbf{k}$	Vector of surplus energy services.
$\mathbf{l}$	Vector of output energy services.

Manuscript received August 7, 2014; revised December 8, 2014 and January 21, 2015; accepted February 15, 2015. The work of M. Yazdani-Damavandi, M. Shafie-khah, and J. P. S. Catalão was supported in part by FEDER funds (European Union) through COMPETE and by Portuguese funds through FCT under Project FCOMP-01-0124-FEDER-020282 (Reference PTDC/EEA-EEL/118519/2010) and Project UID/CEC/50021/2013, and in part by the EU Seventh Framework Programme FP7/2007-2013 under Grant 309048. Paper no. TSG-00789-2014.

M. Yazdani-Damavandi is with Tarbiat Modares University, Tehran 14155-143, Iran, and also with the University of Beira Interior, Covilha 6201-001, Portugal.

M. P. Moghaddam and M.-R. Haghifam are with Tarbiat Modares University, Tehran 14155-143, Iran (e-mail: parsa@modares.ac.ir).

M. Shafie-khah and J. P. S. Catalão are with University of Beira Interior, Covilha 6201-001, Portugal, and also with INESC-ID, Instituto Superior Técnico, University of Lisbon, Lisbon 1000-029, Portugal (e-mail: catalao@ubi.pt).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TSG.2015.2404892

M Matrix of converters' vacant capacity.
p Vector of input energy carriers.
S Coupling matrix of ESs.
U Matrix of converters participation in reserve.

Remark 1: An underlined (overlined) variable is used to represent the minimum (maximum) value of that variable.

Remark 2: Capital letters denote parameters and small ones denote variables.

I. Introduction

A. Motivation and Aim

ENVIRONMENTAL aspects have been highlighted in architecting future energy systems where sustainable development plays a key role. Sustainable development in the energy sector has been defined as a potential solution for enhancing the energy system to meet the future energy requirements without interfering with the environment and energy provision [1].

In this regard, studying the cross-impact of various energy vectors and electrification of energy demand are two main topics. In the first topic, the multienergy system (MES) concept has been developed to consider the cross-impacts among multienergy players (MEPs) from both decision making and energy provision points of view [2]. The MEPs are defined as the energy players who can trade more than one energy carrier to maximize their profits while satisfying the output energy services requirements. Moreover, electrification of energy demand in systems with high penetration of renewable energy resources can mitigate environmental aspects of carbon-based fuels. Transportation system as one of the main energy consuming sectors plays an important role in this vision. Commercializing PEVs technologies (e.g., battery and charge/discharge facilities) accelerates their integration in urban areas [3].

PEVs' PLs are located in populated districts and equipped with charge/discharge facilities. PEVs' PLs not only serve energy services to the PEVs, but also enable bi-directional interface among a group of PEVs as a new generation of bulk ES and energy system [4]. Therefore, in future energy systems they can play as independent MEPs, having an important role in a local MES as a bulk storage facility or flexible load.

This paper aims to model the operational behavior of PEVs' PL as an element of local MES. For this purpose, MES is described as a fractal structure and modeled by an energy hub approach. As a result of the PL operational characteristics, its behavior in both energy and reserve markets is considered. The energy hub model is modified to handle the participation of MES elements in the reserve market. Moreover, a stochastic approach is applied to model the uncertainty of WG and the behavior of PEVs' owners in PL.

B. Literature Review and Contributions

In the scientific literature, MES concept has been defined as an energy system that contains more than one energy carrier. "Energy hub system" [5] and "matrix modeling" [6] are two pioneer approaches that have been developed to model MES as the combination of operation centers (mostly co-generation or tri-generation units) and their interconnectors. Operation centers consist of ECs and ESs that transform input energy carriers into output energy services [7]. "Energy hub" and "distributed multigeneration" are models for operation centers in energy hub system and matrix modeling approaches, respectively. The model has been developed in [8] and [9] to consider the behavior of MESs operator in various time horizons (i.e., operation and planning). Furthermore, integration of different energy resources, ECs and ESs has been modeled on the energy hub framework in [10]–[12].

One of the main assumptions in the energy hub model is the unidirectional energy flow; therefore after integrating RER in [12] the model has been modified to inject the surplus energy to the upstream energy network. On the other hand, the capability of MES to serve ancillary services is discussed in [13] and the new concept of multienergy/power arbitrage has been developed for considering reserve in MES.

In this paper, the capability of MES to serve reserve ancillary service is modeled as an injected energy service to the upstream network, but contrary to [13], a virtual port is assumed in the output of the energy hub model and the whole system's coupling matrix is modified to consider the reserve provision of each energy element independently.

The proposed model for reserve provision is applied to PEVs integration in a PL that can maximize its profit by participating simultaneously in both reserve and energy markets.

For the integration of PEVs in the energy hub framework, the internal interaction of PEVs has been modeled in [14] as an independent energy hub. The model has been developed to consider integration of PEVs in G2V mode as a manageable load for optimal operation [15] and as an ancillary service provision (frequency control) [16] in the energy hub system.

Although these references are almost the sole references that survey the operational behavior of PEVs in MES, there are plenty of references that report the role of PEVs integration in power system studies.

Controlling the PEVs to maximize the income from frequency regulation has been described in [17]. In [18], a heuristic strategy for PEVs charging has been reported to provide the regulation service. In [19], a business model has been reported in which the PEV aggregator has been modeled as a load aggregator that purchases energy from the electricity market with no control over the PEV charging. A conceptual framework to operate the aggregated PEVs in the V2G mode has been proposed in [20]. In [21], a linear programming model has been presented to optimize the charging plan for PEVs by minimizing electricity costs and battery wears. In [22], a heuristic algorithm has been presented to control PEV charging in response to time-of-use prices in a traditional power system. In [23], an optimization algorithm has been proposed to manage the individual charging of PEVs to decrease the deviation costs and to ensure a reliable supply of manual reserve. A behavioral model for PEVs' aggregator in reserve and energy markets has been presented in [24]. In [25], an optimization method has been presented to support the participation of the PEV aggregator in the day-ahead spot and secondary reserve market. In [26], the behavior of PEV aggregator has been modeled as a linking agent between

PEV owners and the electricity market by using a stochastic multilayer agent-based model.

Although these models have precisely considered the behavior of aggregator and market characteristics, there are some differences between PEVs' aggregator and PL owner behavior. The PEVs' aggregator has wide knowledge about its contracted PEVs, e.g., the number and battery characteristics, but the knowledge of PL owner is mostly about the traffic pattern in its PL zone. On the other hand, the main aim of this paper is to investigate the role of PL in MES and the impact of its behavior on other elements' operational characteristics.

Therefore, in this paper, the PL behavior is modeled based on the aggregated PEVs' traffic pattern in PL and the main objective is to fit this model with an energy hub approach.

Regarding the role of PEVs in future MES, the main contributions of this paper are threefold:

1) modeling PEVs' PL in MES considering the uncertain behavior of PEV owners, which can be operated in both V2G and G2V modes;
2) modifying the mathematical model of energy hub to consider the reserve ancillary service in MES;
3) developing a new operational model of PL to consider its interface with MES and PEVs simultaneously.

C. Paper Organization

The rest of this paper is organized as follows. Problem overview is presented in Section II. Section III models the MES by energy hub approach and presents the modifications to consider PEVs' PL and the system reserve. In Section IV, the operational framework of MESs elements is described. The numerical results are represented in Section V and the conclusion is provided in Section VI.

II. Problem Overview

In this paper, the behavior of PEVs' PL in MES is modeled. In this regard, the energy hub model of MES is modified to consider PL as an uncertain storage and enable MES to trade reserve as PLs ancillary service. The proposed mathematical model is applied in an operation problem. As a matter of fact, the operational framework in this paper is an optimization problem that MES operator maximizes its profit by considering its operational constraints. The module of energy hub is added to the optimization problem as a set of constraints. Therefore, in this section, first the MES structure is discussed and the modeling domain is determined. After that, the proposed approach for modeling PL in MES is described, and finally the uncertainty characterization of uncertain resources is represented.

A. Fractal Structure of MES

From the architecting point of view, MES can be modeled as a self-similar multilayer structure. Each layer consists of a number of sub-modules of MES with almost the same characteristics and domains so that each of them is the interior layer of this fractal structure.

In this vision, the system can be divided into three main layers, namely MaMES, micro-MES, and MED, being modeled by an energy hub approach.

1) *MaMES:* MaMES is the main MEPs in MES. It can be assumed as large regional energy companies that can produce, transfer, and consume bulk energy amount. In this paper, a typical MaMES supplies energy carriers to the micro-MES.
2) *Micro-MES:* Micro-MES can be considered as an urban district that consists of medium level ECs and ESs. Micro-MES receives energy from MaMES and delivers energy to the MED. MaMES and micro-MES have the same structure but their main differences are the type of carriers and energy elements that are operated. As a matter of fact, MaMES is the integration of some micro-MESs and their related interconnectors.
3) *MED:* MED is an energy demand which can receive various types of energy carriers and serves the required energy services to its internal demands by implementing internal energy resources (e.g., micro-CHP, residential PEVs charging stations, and photovoltaic arrays). In reality, smart buildings and industrial plants can be considered as MED.

B. PEVs' Modeling Approach

PEVs' PL is located in micro-MES and it is operated by its own operator. Therefore, in this paper, only micro-MES is modeled by the energy hub approach and MaMES and MED are considered as a multienergy environment that can transact energy carriers with MES. PL serves energy reserve as an ancillary service that should be traded in MaMES level. The energy hub model is modified to consider PL as storage with an uncertain behavior. Moreover, a virtual port is added to the output of micro-MES to consider its reserve provision capability.

On this basis, the reserve is considered as an output energy service that can be served by the ESs and ECs. For ECs, the reserve is modeled as the ability of the converter to increase its output power, whereas for storages the reserve amount is additionally related to its SoC.

In order to investigate the interaction of PL with micro-MES and PEVs, a new method is proposed based on the changes in total amount of SoC and the capacity of PL. This method tracks SoC amount in each hour and determines the impact of PEVs arrival and departure traffic on total SoC of PL.

C. Uncertainty Characterization

The traffic pattern of PEVs in PL is related to the uncertain behavior of PEV owners. Therefore, a stochastic approach is applied to model the characteristics of PEVs in PL, i.e., the number, total capacity, and SoC in each hour. Furthermore, the stochastic approach covers the uncertainty of WG. On this basis, two groups of scenarios are generated for PL and WG, and the PL operation is accomplished by considering these scenarios.

Details of the stochastic approach are presented in the Appendix.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

III. Matrix Modeling of MES Considering PEVs' PL

A. Comprehensive Model of MES

The energy hub approach models MES as a coupling matrix that converts input energy carriers to output energy services [4]. Equation (1) shows the matrix model of an energy hub, where **p**, **l**, and $\dot{\mathbf{e}}$ are the vectors of input energy carriers, output energy services, and changes in ESs amount, respectively.

In this model, **C** and **S** are coupling matrices and rely on the ECs of energy hub and structure of ESs. One of the main assumptions in the energy hub modeling is unidirectional energy flow in the energy hub's elements. Therefore, vector **k** enables the model to inject energy hub's surplus energy into the upstream system [14]

$$\begin{bmatrix} \mathbf{C} & \mathbf{S} \end{bmatrix} \begin{bmatrix} \mathbf{p} \\ \dot{\mathbf{e}} \end{bmatrix} = [\mathbf{l}] + [\mathbf{k}]. \quad (1)$$

In the energy hub, PL behaves as a storage system with uncertainties in its total capacity and SoC in each hour. The uncertain behavior of PL has been modeled by the stochastic approach described in the Appendix. On the other hand, PL has an interaction with MES as well as PEVs. The PLs electric energy interaction with MES can be modeled by adding a new row in matrix $\dot{\mathbf{e}}$ that represents the share of PLs SoC changes in the output of energy services

$$\dot{\mathbf{e}}^{\mathbf{new}} = \begin{bmatrix} \dot{\mathbf{e}}^{\mathbf{old}} \\ \mathbf{s\dot{o}c}^{\mathbf{PL}} \end{bmatrix}. \quad (2)$$

In addition, electric reserve is considered as an output energy service of MES that can be served to the upstream system. Therefore, new rows ($\mathbf{r}^{\mathbf{inj}}$) are added to the matrices **l** and **k**, but due to sole usage of reserve in upstream network, the amount of reserve array in matrix **l** is equal to zero

$$\mathbf{l}^{\mathbf{new}} = \begin{bmatrix} \mathbf{l}^{\mathbf{old}} \\ \mathbf{0} \end{bmatrix}, \ \mathbf{k}^{\mathbf{new}} = \begin{bmatrix} \mathbf{k}^{\mathbf{old}} \\ \mathbf{r}^{\mathbf{inj}} \end{bmatrix}. \quad (3)$$

By adding new rows in the output, the matrices **C** and **S** will be modified to determine the share of each element on the new output energy service (electric reserve). In the modified model, the converter share can be modeled as the capability to maximize output electricity. However, for electric ES it depends on its rated output power and its stored energy in each hour. Determining the reserve service for electric ES needs new rows in **p** to show the share of electric ES for serving reserve to the MES as an input virtual energy carrier

$$\mathbf{p}^{\mathbf{new}} = \begin{bmatrix} \mathbf{p}^{\mathbf{old}} \\ \mathbf{r}^{\mathbf{ES}} \end{bmatrix} \quad (4)$$

$$\mathbf{C}^{\mathbf{new}} = \begin{bmatrix} \mathbf{C}^{\mathbf{old}} & \mathbf{0} \\ \mathbf{C}^{\mathbf{EC}} & \mathbf{C}^{\mathbf{ES}} \end{bmatrix}, \mathbf{S}^{\mathbf{new}} = \begin{bmatrix} \mathbf{S}^{\mathbf{old}} & \mathbf{S}^{\mathbf{PL}} \\ \mathbf{0} & \mathbf{0} \end{bmatrix}. \quad (5)$$

$\mathbf{C}^{\mathbf{old}}$ coupling matrix that states the conversion of inputs energy carriers into outputs energy services;

$\mathbf{C}^{\mathbf{EC}}$ coupling matrix to show the share of ECs in output reserve, which is based on the efficiency of ECs;

$\mathbf{C}^{\mathbf{ES}}$ coupling matrix to show the share of storage in output reserve, which is based on discharge efficiency of storage;

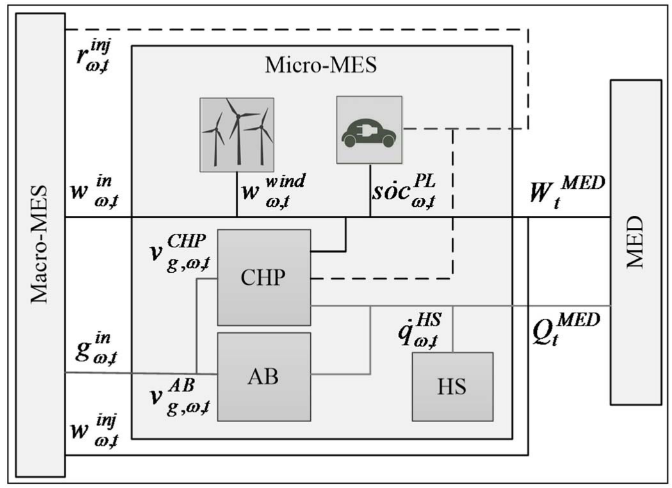

Fig. 1. Micro-MES schematic considering PEVs' PL.

$\mathbf{S}^{\mathbf{old}}$ storage coupling matrix that shows the changes of output energy service versus changes in stored energy;

$\mathbf{S}^{\mathbf{PL}}$ coupling matrix to show the share of PL in output reserve, which is based on discharge efficiency of PL;

M matrix of vacant capacity of ECs;

U Decision making matrix with binary arrays, determining the participation of each converter in output reserve.

In order to produce $\mathbf{C}^{\mathbf{EC}}$, each array of **M** is divided by the corresponding array of $\mathbf{P}^{\mathbf{old}}$ and then multiplied by the array of **U**

$$\mathbf{C}^{\mathbf{EC}} = \frac{\mathbf{M}}{\mathbf{p}^{\mathbf{old}}} \cdot \mathbf{U}. \quad (6)$$

By substituting the modified terms in (1), the system's new equation is

$$\begin{bmatrix} \mathbf{C}^{\mathbf{new}} & \mathbf{S}^{\mathbf{new}} \end{bmatrix} \begin{bmatrix} \mathbf{p}^{\mathbf{new}} \\ \dot{\mathbf{e}}^{\mathbf{new}} \end{bmatrix} = \begin{bmatrix} \mathbf{l}^{\mathbf{new}} \end{bmatrix} + \begin{bmatrix} \mathbf{k}^{\mathbf{new}} \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} \mathbf{C}^{\mathbf{old}} & \mathbf{0} & \mathbf{S}^{\mathbf{old}} & \mathbf{S}^{\mathbf{PL}} \\ \mathbf{C}^{\mathbf{EC}} & \mathbf{C}^{\mathbf{ES}} & \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{p}^{\mathbf{old}} \\ \mathbf{r}^{\mathbf{ES}} \\ \dot{\mathbf{e}}^{\mathbf{old}} \\ \mathbf{s\dot{o}c}^{\mathbf{PL}} \end{bmatrix} = \begin{bmatrix} \mathbf{l}^{\mathbf{old}} \\ \mathbf{0} \end{bmatrix} + \begin{bmatrix} \mathbf{k}^{\mathbf{old}} \\ \mathbf{r}^{\mathbf{inj}} \end{bmatrix}. \quad (8)$$

B. Micro-MES Detailed Model

Fig. 1 demonstrates a micro-MES equipped by a CHP unit, WG, auxiliary boiler (AB), HS, and PEVs' PL. Input energy carriers are electricity, natural gas, and electric reserve of PL ($\mathbf{p}^{\text{in}}_{\omega,t} = [w^{\text{in}}_{\omega,t} + w^{wind}_{\omega,t} \ g^{\text{in}}_{\omega,t} \ r^{\text{PL}}_{\omega,t}]$), while output energy services are electricity and heat ($\mathbf{l}^{\text{MED}}_t = [W^{\text{MED}}_t \ Q^{\text{MED}}_t \ 0]$), and surplus energy services are electric power and reserve ($\mathbf{k}^{\text{inj}}_{\omega,t} = [w^{\text{inj}}_{\omega,t} \ 0 \ r^{\text{inj}}_{\omega,t}]$).

Equation (9), as shown at the top of next page, shows the energy hub model of micro-MES considering its interaction with MaMES and MED.

$$\begin{bmatrix} 1 & v_{g,\omega,t}^{\text{CHP}}\eta_e^{\text{CHP}} & 0 & 0 & 1/\eta_e^{\text{PL}} \\ 0 & v_{g,\omega,t}^{\text{CHP}}\eta_h^{\text{CHP}} + v_{g,\omega,t}^{\text{AB}}\eta_h^{\text{AB}} & 0 & 1/\eta_h^{\text{HS}} & 0 \\ 0 & \left(\left(\overline{G}^{\text{in}} - v_{g,\omega,t}^{\text{CHP}} g_{\omega,t}^{\text{in}}\right)_e^{\text{CHP}} \Big/ g_{\omega,t}^{\text{in}}\right) & 1/\eta_e^{\text{PL,discha}} & 0 & 0 \end{bmatrix} \begin{bmatrix} w_{\omega,t}^{\text{in}} + w_{\omega,t}^{\text{WG}} \\ g_{\omega,t}^{\text{in}} \\ r_{\omega,t}^{\text{PL}} \\ \dot{q}_{\omega,t}^{\text{HS}} \\ s\dot{o}c_{\omega,t}^{\text{PL}} \end{bmatrix} = \begin{bmatrix} W_t^{\text{MED}} \\ Q_t^{\text{MED}} \\ 0 \end{bmatrix} + \begin{bmatrix} w_{\omega,t}^{\text{inj}} \\ 0 \\ r_{\omega,t}^{\text{inj}} \end{bmatrix} \tag{9}$$

Equations (10) and (11) show the efficiency of ES elements, i.e., PL and HS, to interact with micro-MES

$$\eta_e^{\text{PL}} = \begin{cases} \eta_e^{\text{PL,cha}}, & s\dot{o}c_{\omega,t}^{\text{PL}} \geq 0 \\ 1\big/\eta_e^{\text{PL,discha}}, & s\dot{o}c_{\omega,t}^{\text{PL}} < 0 \end{cases} \tag{10}$$

$$\eta_h^{\text{HS}} = \begin{cases} \eta_h^{\text{HS,cha}}, & \dot{q}_{\omega,t}^{\text{HS}} \geq 0 \\ 1\big/\eta_h^{\text{HS,discha}}, & \dot{q}_{\omega,t}^{\text{HS}} < 0. \end{cases} \tag{11}$$

IV. Operational Framework of PEVs' PL in MES

Micro-MES operator aims to maximize its profit by utilizing energy elements (i.e., ESs and ECs) while preserving operation constraints of MESs elements.

A. Objective Function

The objective function of micro-MES operator consists of revenue and cost terms. The operator has an income from injecting surplus energy to MaMES and selling energy to MED and PEVs. On the other hand, buying energy from MaMES and PEVs is costly and the operator should make a trade-off between its costs and revenues. Equation (12) shows the operator's objective function, which consists of electricity, gas, reserve, and heat profits from interaction with MaMES and MED, micro-MES profit from PL interaction and finally its profit from participating in reserve services

$$\begin{aligned} \text{Maximizing} \sum_{\omega} \rho_\omega \Bigg\{ \sum_t \Big[& \left(w_{\omega,t}^{\text{inj}} - w_{\omega,t}^{\text{in}}\right) \pi_{e,t}^{\text{MaMES}} \\ & - g_{\omega,t}^{\text{in}} \pi_{g,t}^{\text{MaMES}} + r_{\omega,t}^{\text{inj}} \pi_{r,t}^{\text{MaMES}} \\ & + \left(W_t^{\text{MED}}\right) \pi_{e,t}^{\text{MED}} + Q_t^{\text{MED}} \pi_{h,t}^{\text{MED}} \\ & + \text{soc}_{\omega,t}^{\text{PL,up}} \pi_{e,t}^{\text{G2V}} - \text{soc}_{\omega,t}^{\text{PL,down}} \pi_{e,t}^{\text{V2G}} \\ & - \left(p_{\omega,t}^{\text{PL,out}} + r_{\omega,t}^{\text{PL}} \rho_{r,t}\right) \text{Cd} \\ & + r_{\omega,t}^{\text{inj}} \rho_{r,t} \pi_{e,t}^{\text{MaMES}} \\ & - r_{\omega,t}^{\text{inj}} \rho_{r,t} \text{FOR}^{\text{MES}} \pi_{e,t}^{\text{con}} \\ & - r_{\omega,t}^{\text{PL}} \rho_{r,t} \pi_t^{\text{V2G,con}} \\ & - \left(r_{\omega,t}^{\text{CHP}} \rho_{r,t} \Big/ \eta_e^{\text{CHP}}\right) \pi_{g,t}^{\text{MaMES}} \Big] \Bigg\}. \end{aligned} \tag{12}$$

B. MES Operation Constraints

Micro-MES operation is constrained by energy elements' characteristics and the capability to interact with MaMES.

1) Input Energy Carriers: Input energy carriers to the system are restricted by system interconnectors' characteristics and should be lower than the maximum level

$$0 \leq \mathbf{p} \leq \overline{\mathbf{p}} \tag{13}$$

$$0 \leq w_{\omega,t}^{\text{in}} \leq \overline{W}^{\text{in}} \tag{14}$$

$$0 \leq g_{\omega,t}^{\text{in}} \leq \overline{G}^{\text{in}}. \tag{15}$$

2) CHP Unit: Heat and electricity output of CHP unit should be in a predetermined zone and its ratio is considered as a constant parameter (λ^{CHP})

$$0 \leq w_{\omega,t}^{\text{CHP}} \leq \overline{W}^{\text{CHP}} \tag{16}$$

$$0 \leq q_{\omega,t}^{\text{CHP}} \leq \overline{Q}^{\text{CHP}} \tag{17}$$

$$\lambda^{\text{CHP}} = q_{\omega,t}^{\text{CHP}} \Big/ w_{\omega,t}^{\text{CHP}}. \tag{18}$$

3) AB: Output heat of AB should be in its upper and lower operational bounds

$$\underline{Q}^{\text{AB}} \leq q_{\omega,t}^{\text{AB}} \leq \overline{Q}^{\text{AB}}. \tag{19}$$

4) HS: Rate of HS interaction with micro-MES should be within operational limit

$$\left|\dot{q}_{\omega,t}^{\text{HS}}\right| \leq \Gamma^{\text{HS}}. \tag{20}$$

5) WG: Maximum output of WG is lower than its scenario amount in each hour

$$0 \leq w_{\omega,t}^{\text{WG}} \leq W_{\omega,t}^{\text{WG,Sc}}. \tag{21}$$

6) Decision Variable Constraint: v is the dispatch factor and shows the share of each energy element from input energy, and its amount should be between 0 and 1

$$0 \leq v_{g,\omega,t}^{\text{CHP}}, v_{g,\omega,t}^{\text{AB}} \leq 1 \tag{22}$$

$$v_{g,\omega,t}^{\text{CHP}} + v_{g,\omega,t}^{\text{AB}} = 1. \tag{23}$$

C. PEVs' PL Operational Model

The SoC of PEVs in the PL is a tool for micro-MES operator to maximize its profit. PL has interactions with MES as well as PEVs. It buys electric energy from MES for charging the PEVs' batteries that, on the other hand, is solely to the MES in peak hours, while PEV owners will also be charged for that. Moreover, PL participates in the reserve market, which motivates the increase of its SoC for achieving more benefit.

Equation (24) demonstrates that PL interaction with micro-MES is equal to $s\dot{o}c$. Moreover, (25) represents the

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

amount of this variable based on the level of SoC in two consequent time intervals and the impact of arrived and departed PEVs

$$\dot{\text{soc}}^{\text{PL}}_{\omega,t} = w^{\text{PL,in}}_{\omega,t} - w^{\text{PL,out}}_{\omega,t} \quad (24)$$

$$\dot{\text{soc}}^{\text{PL}}_{\omega,t} = \text{soc}^{\text{PL}}_{\omega,t} - \text{soc}^{\text{PL}}_{\omega,t-1} + \text{soc}^{\text{PL},ar}_{\omega,t} - \text{soc}^{\text{PL,dep}}_{\omega,t}. \quad (25)$$

The following assumptions have been considered to formulate the impact of arrived and departed PEVs.

1) If the SoC amount increases in each scenario in two consecutive time intervals, the increase will be equal to arriving PEVs' SoC to the system [(26) and (27)].
2) If the SoC amount decreases in each scenario in two consecutive time intervals, the normalized reduction multiple PEVs' SoC in prior time will be equal to the departed PEVs' SoC from the system [(28) and (29)].
3) In each hour and scenario, one of the departure or arrival conditions will be considered

$$\text{if } \text{soc}^{\text{PL,Sc}}_{\omega,t} - \text{soc}^{\text{PL,Sc}}_{\omega,t-1} \geq 0 \Rightarrow \text{soc}^{\text{PL},ar}_{\omega,t} = \text{soc}^{\text{PL,Sc}}_{\omega,t} - \text{soc}^{\text{PL,Sc}}_{\omega,t-1} \quad (26)$$

$$\text{if } \text{soc}^{\text{PL,Sc}}_{\omega,t} - \text{soc}^{\text{PL,Sc}}_{\omega,t-1} < 0 \Rightarrow \text{soc}^{\text{PL},ar}_{\omega,t} = 0 \quad (27)$$

$$\text{if } \text{soc}^{\text{PL,Sc}}_{\omega,t} - \text{soc}^{\text{PL,Sc}}_{\omega,t-1} \geq 0 \Rightarrow \text{soc}^{\text{PL,dep}}_{\omega,t} = 0 \quad (28)$$

$$\text{if } \text{soc}^{\text{PL,Sc}}_{\omega,t} - \text{soc}^{\text{PL,Sc}}_{\omega,t-1} < 0 \Rightarrow$$
$$\text{soc}^{\text{PL,dep}}_{\omega,t} = \left(\left(\text{soc}^{\text{PL,Sc}}_{\omega,t-1} - \text{soc}^{\text{PL,Sc}}_{\omega,t}\right) \Big/ \text{soc}^{\text{PL,Sc}}_{\omega,t-1}\right).\text{soc}^{\text{PL}}_{\omega,t-1} \quad (29)$$

$$x^{\text{PL}Y,ar}_{\omega,t} + x^{\text{PL,dep}}_{\omega,t} = 1. \quad (30)$$

In addition, to determine the PL financial transaction with PEV owners, (31)–(35) calculated the SoC difference of PEVs' battery at departure time. Main assumptions are as follows.

1) If the SoC of departed PEVs is more than the SoC reduction in two consecutive time intervals in each scenario, PL is selling energy to the PEVs [(31) and (32)].
2) Otherwise, PL is buying energy from PEVs [(33) and (34)].
3) In each hour and scenario, PL is conditioned by one of the mentioned terms (35)

$$\text{if } \text{soc}^{\text{PL,dep}}_{\omega,t} \leq \left(\text{SoC}^{\text{PL,Sc}}_{\omega,t} - \text{SoC}^{\text{PL,Sc}}_{\omega,t-1}\right) \Rightarrow \text{soc}^{\text{PL,up}}_{\omega,t} = 0 \quad (31)$$

$$\text{if } \left(\text{SoC}^{\text{PL,Sc}}_{\omega,t} - \text{SoC}^{\text{PL,Sc}}_{\omega,t-1}\right) < \text{soc}^{\text{PL,dep}}_{\omega,t} \Rightarrow \text{soc}^{\text{PL,up}}_{\omega,t} = \text{soc}^{\text{PL,dep}}_{\omega,t} - \left(\text{SoC}^{\text{PL,Sc}}_{\omega,t} - \text{SoC}^{\text{PL,Sc}}_{\omega,t-1}\right) \quad (32)$$

$$\text{if } \text{soc}^{\text{PL,dep}}_{\omega,t} \leq \left(\text{SoC}^{\text{PL,Sc}}_{\omega,t} - \text{SoC}^{\text{PL,Sc}}_{\omega,t-1}\right) \Rightarrow \text{soc}^{\text{PL,down}}_{\omega,t} = \left(\text{SoC}^{\text{PL,Sc}}_{\omega,t} - \text{SoC}^{\text{PL,Sc}}_{\omega,t-1}\right) - \text{soc}^{\text{PL,dep}}_{\omega,t} \quad (33)$$

$$\text{if } \left(\text{SoC}^{\text{PL,Sc}}_{\omega,t} - \text{SoC}^{\text{PL,Sc}}_{\omega,t-1}\right) < \text{soc}^{\text{PL,dep}}_{\omega,t} \Rightarrow \text{soc}^{\text{PL,down}}_{\omega,t} = 0 \quad (34)$$

$$x^{\text{PL,up}}_{\omega,t} + x^{\text{PL,down}}_{\omega,t} = 1. \quad (35)$$

Equations (36)–(38) demonstrate the PLs capability to interact with micro-MES, which is related to the number of PEVs in each hour and PL facilities for charging/discharging of PEVs' battery. The amount of injected energy to the MES is restricted by the participation factor ($\varphi^{\text{PL}}_{e,t}$) of PEVs in V2G mode. Furthermore, the PLs capability of participating in the reserve service is limited by the free capacity of PL interconnector system with MES and the level of PEVs participation ($\varphi^{\text{PL}}_{r,t}$) in ancillary service. The participation factors in both reserve and energy cases can be determined based on the willingness of PEVs owners to share their PEVs' capability with the PL owner, instead of using parking facilities and receiving incentives

$$w^{\text{PL,in}}_{\omega,t} \leq \gamma^{\text{PL}}_{\omega,t} = \Gamma^{PEV}.N^{\text{PL,Sc}}_{\omega,t} \quad (36)$$

$$w^{\text{PL,out}}_{\omega,t} \leq \min\left(\gamma^{\text{PL}}_{\omega,t}, \varphi^{\text{PL}}_{e,t}.\text{soc}^{\text{PL}}_{\omega,t}\right) \quad (37)$$

$$r^{\text{PL}}_{\omega,t} = \min\left(\phi^{\text{PL}}_{r,t}\text{soc}^{\text{PL}}_{\omega,t} - l^{\text{PL,out}}_{\omega,t},\ \gamma^{\text{PL}}_{\omega,t} - l^{\text{PL,out}}_{\omega,t},\ 0\right). \quad (38)$$

SoC of PEVs should be kept at the minimum and maximum bounds of its operation condition. Therefore, (39) and (40) determine the minimum and maximum amount of PLs SoC based on the number of PEVs in the parking and safe criteria of PEVs' battery operation in each hour. Moreover, (41) restricts the amount of PLs SoC in its minimum and maximum value, being less than the total PL capacity

$$\underline{\text{SoC}}^{\text{PL}}_{\omega,t} = \underline{\text{SoC}}^{EV}.N^{\text{PL,Sc}}_{\omega,t} \quad (39)$$

$$\overline{\text{SoC}}^{\text{PL}}_{\omega,t} = \overline{\text{SoC}}^{EV}.N^{\text{PL,Sc}}_{\omega,t} \quad (40)$$

$$\underline{\text{SoC}}^{\text{PL}}_{\omega,t} \leq \text{soc}^{\text{PL}}_{\omega,t} \leq \overline{\text{SoC}}^{\text{PL}}_{\omega,t} \leq \text{Ca}^{\text{PL}}_{\omega,t}. \quad (41)$$

TABLE I
DATA OF MICRO-MES ELEMENTS

CHP	Output Electricity	250 kW
	Output Heat	300 kW
	FOR	0.02
	$\eta_e^{CHP}, \eta_h^{CHP}$	0.36, 0.45
AB	Output Heat	600 kW
	η_h^{AB}	0.85
HS	Capacity	200 kWh
	Γ_h^{HS}	100 kW
	$\eta_h^{HS,cha}, \eta_h^{HS,discha}$	0.9, 0.9
PL	Γ_h^{HS}	11 kW/EV
	$\eta_h^{PL,cha}, \eta_h^{PL,discha}$	0.9, 0.9
	FOR	0.02
	$\varphi_{e,t}^{PL}, \varphi_{r,t}^{PL}$	0.4, 0.7

V. NUMERICAL RESULTS

A. Input Data Characterization

In this paper, the micro-MES is equipped with CHP unit, AB, WG, HS, and PL. Data of the energy and reserve prices for input of micro-MES have been obtained from hourly data of the Spanish electricity market in July 2010 [27]. The output prices and MEDs consumption are obtained from [28] with some modifications.

The micro-MESs elements characterization, price signals, and MEDs consumption are represented in Table I and Figs. 2 and 3, respectively.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

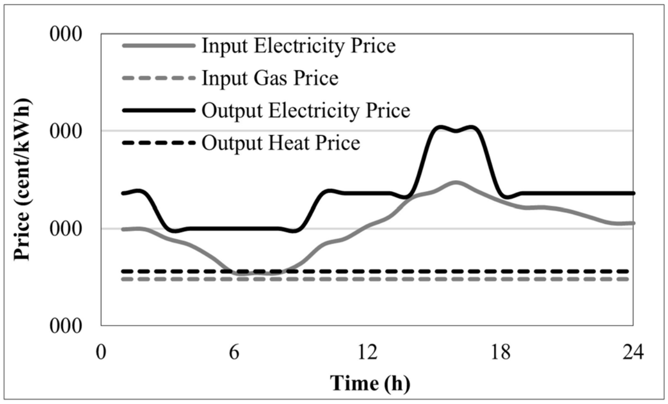

Fig. 2. Input and output energy price of micro-MES.

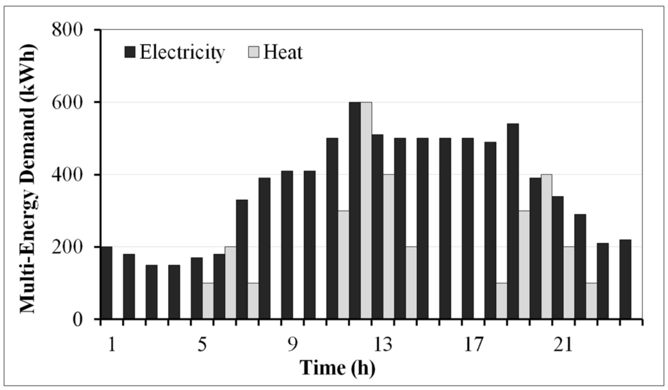

Fig. 3. MED energy consumption.

B. Case Studies

Three case studies are assumed for assessing the proficiency of the proposed model and the behavior of PL in micro-MES.

Case I is considered to demonstrate micro-MES operational behavior without PL interaction. In case II, the PL is added to the system to investigate the behavior of each micro-MESs elements in the presence of PL as a source of operational flexibility for the micro-MES operator. Moreover, case III compares the behavior of micro-MES operator with and without participating in the reserve market as another source of operational flexibility for micro-MES operator.

1) Case I: The operation of micro-MES is considered without interaction with PL.

Fig. 4 demonstrates the share of micro-MES, CHP, and WG in MEDs electricity demand. Moreover, Fig. 5 shows the share of AB, CHP, and HS in MEDs heat demand.

The CHP unit generates heat and electricity based on its economic considerations and between the hours 5, 11–14, and 18–22, while the MED consumes both electricity and heat and the electricity price is high. Although in hours 2, 10, 15–17, 23, and 24 there is no heat demand, due to high electricity price the CHP generates the electricity need of MED and surplus heat stored in HS. Moreover, AB and HS compensate the shortage of heat demand when more heat production of CHP is not beneficial. The surplus heat energy stored in HS is delivered to the micro-MES in heat demand hours.

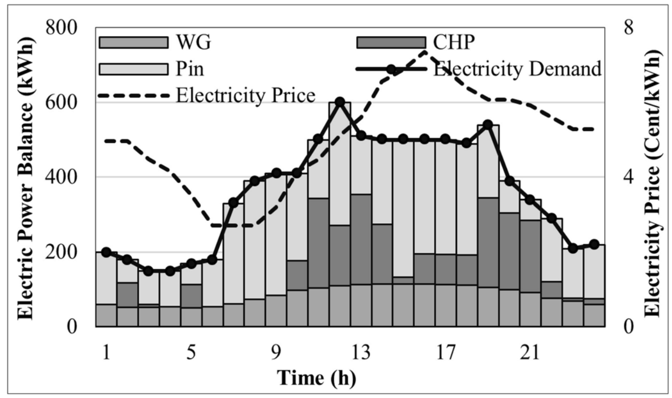

Fig. 4. Share of each micro-MESs energy elements in output electricity.

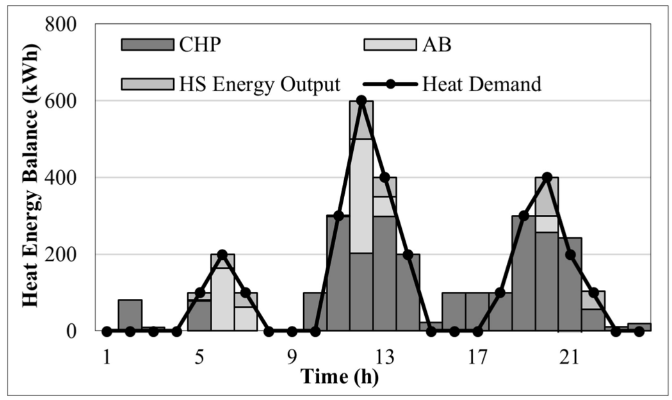

Fig. 5. Share of each micro-MESs energy elements in output heat.

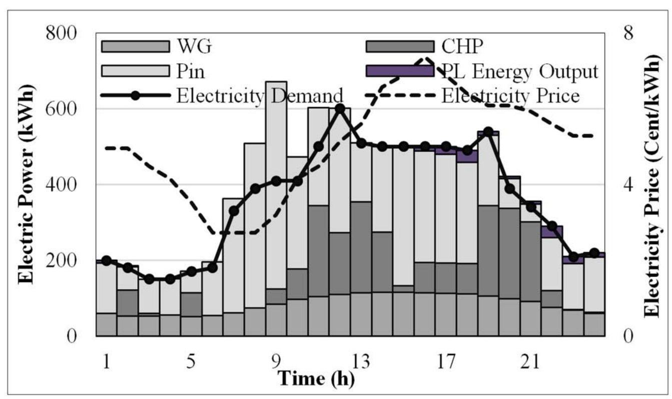

Fig. 6. Share of each micro-MESs energy elements in output electricity.

2) Case II: The PL is considered as one of the micro-MES elements and it interacts with both electric energy and reserve services.

Figs. 6 and 7 depict the share of each micro-MESs elements in electricity and heat energy balance of micro-MES, respectively. Between hours 7–12, the PL receives energy to charge its PEVs' batteries. Moreover, in hours 16–24, the PL injects about 154 kWh to the micro-MES while the electricity price is high.

Furthermore, Fig. 8 shows the share of CHP and PL in the output of reserve service. As it is shown, the CHP unit prefers to participate in the electric energy market rather than

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

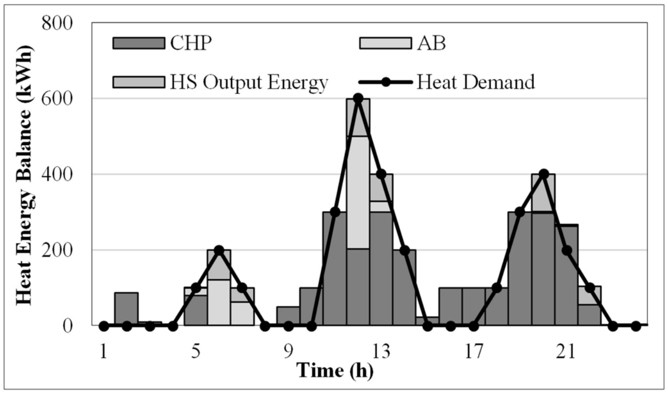

Fig. 7. Share of each micro-MESs energy elements in output heat.

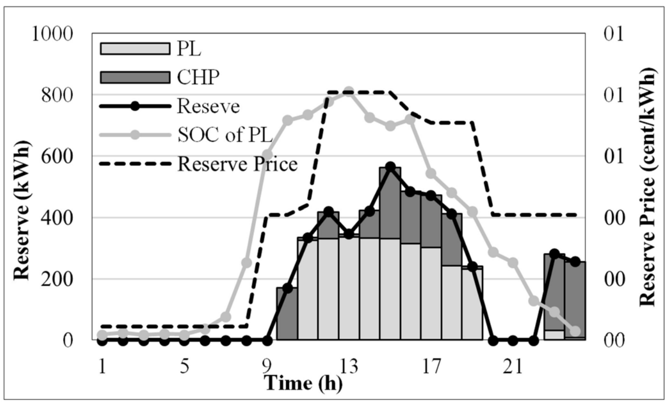

Fig. 8. CHP and PL share in reserve service.

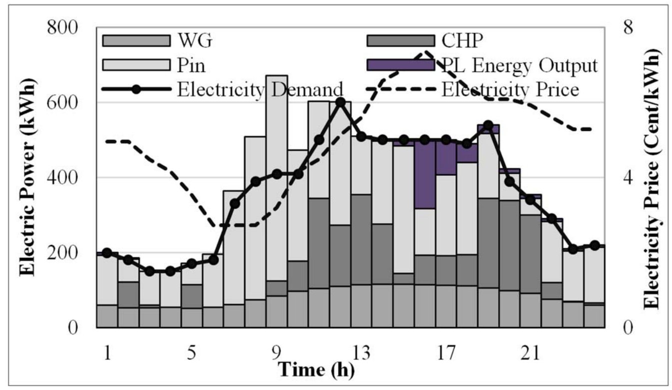

Fig. 9. Share of each micro-MESs energy elements in output electricity.

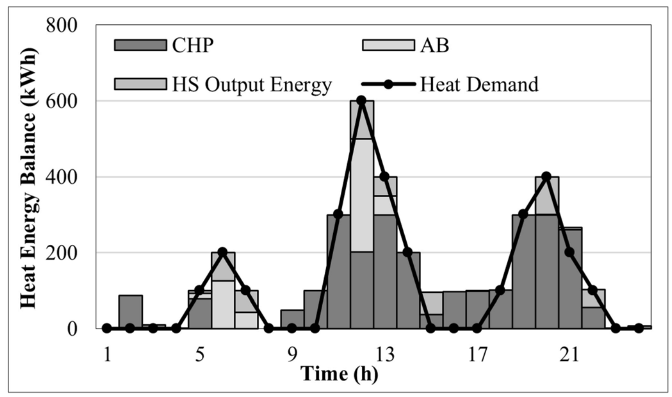

Fig. 10. Share of each micro-MESs energy elements in output heat.

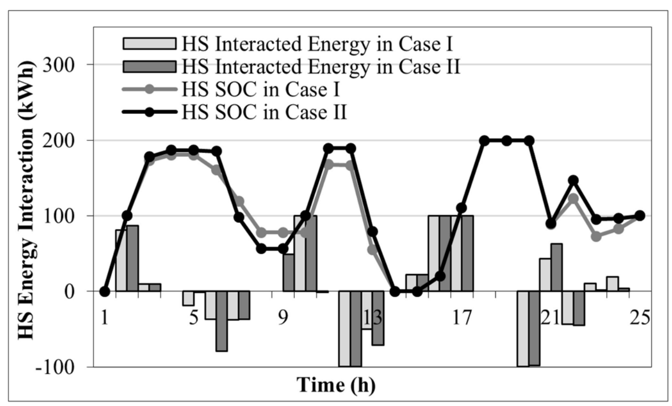

Fig. 11. Operation pattern of HS in cases I and II.

the reserve market and introduces only its vacant capacity in the reserve market. On the contrary, higher share of PLs profit is for its participation in the reserve market. Between hours 11–19 when reserve price is higher, PL delivers reserve service to the system. At other hours, because of lower reserve price and the risk of incurring penalty in reserve supplement, the PL does not deliver reserve service.

3) Case III: The interaction of PL with micro-MES is considered but the capability of micro-MES to deliver reserve service is denied.

Figs. 9 and 10 demonstrate electricity and heat balance in micro-MES, respectively. It is shown that through hours 7–12 the PL has the same behavior as in case II, but in this case the PL injects more electricity to the micro-MES (418 kWh) in hours 15–19 because the micro-MES operator is not capable to participate in the reserve market; hence, it prefers to enhance its energy trade to maximize profit.

C. Discussion

The MES concept introduces an operational flexibility to the system operators from both decision making and technical points of view. In this paper, participating in reserve market and adding PL as an ES element are considered as resources of operational flexibility. Participating in the reserve market, which is originated from a long-term policy making structure, gives a degree of freedom to the system operator for maximizing its profit. Furthermore, installing new energy elements (e.g., ESs and ECs) in the long-term facilitates the enhancement of system operator's flexibility to choose between carriers and time intervals in the operation time horizon. In this regard, the PL behaves like storage with uncertain behavior in micro-MES environment. Thus, it changes the operational pattern of micro-MES operator.

Fig. 11 compares the operation of HS in cases I and II as the indicator of change in micro-MES operational flexibility in the presence of PL. It shows that in case II, where the micro-MES has interaction with PL, the HS is utilized more and its charge and discharge are deeper. This means that by implementing new energy elements the operation of the other

TABLE II
FINANCIAL TRANSACTION OF MICRO-MES IN THREE CASES

	Case I	Case II	Case III
Electricity Cost (€)	238	255	248
Natural Gas Cost (€)	149	151	152
Reserve Profit (€)	6	19	0
PL Profit (€)	0	32	28
Selling to MED (€)	688	688	688
Total (€)	306	333	316

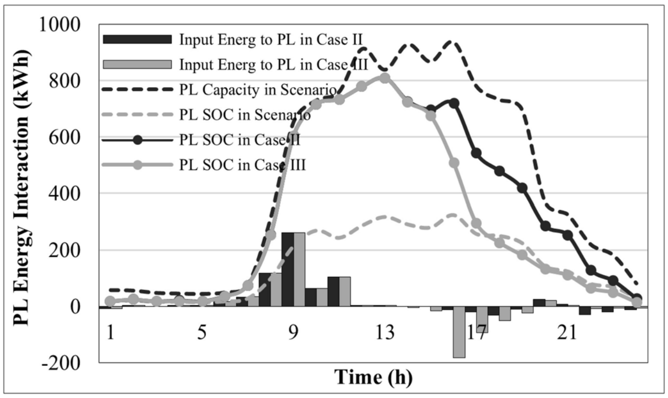

Fig. 12. Operation pattern of PL in cases II and III.

elements will be affected. Based on this, integrated models are needed to cover the mentioned internal interactions. Moreover, micro-MES profit has increased from 306 to 333 €, as shown in Table II, which also confirms the deduction that increasing the flexibility of the system will help in delivering energy services while assuring a higher system profit.

Moreover for determining the role of reserve market in the operational flexibility of micro-MES, Fig. 12 depicts the PL behavior in cases II and III.

As it can be seen, in case II when PL delivers reserve service its output electric energy is less than when it only participates in the electric energy interaction. The reason is that the PL prefers to charge the PEVs' battery and increase its SoC to deliver reserve service in the middle of a period and sell the charged energy to the PEVs' owners at the end of the period.

Table II demonstrates the total amount and each term in the objective function. It can be seen that in case II the operator has the maximum profit while it has both sources of flexibility in the system. Moreover, part of this maximum profit in case II is due to selling more SoC to the PEVs ($32 - 28 = 4$£). Case I shows that the profit of micro-MES participation in reserve market is 6 € and case III determines that the profit of micro-MES in the presence of PL and from participating in the energy market is 16 €. Moreover, utilizing both of these flexibilities added 33 € to micro-MES profit. The difference between these amounts are about 0.3%, which shows that the two flexibility resources have a cross-impact and utilizing both of them simultaneously increases each individual impact.

VI. CONCLUSION

This paper has modeled the PL as an energy element in MES. The proposed model considers PL as the aggregation of PEVs' batteries that reflects the uncertain behavior of PEVs' owners in arriving to and departing from PL. For assessing the realistic PL interaction with MES, the reserve service was considered as an output energy service. The energy hub model has been modified to cover all of these considerations. The numerical results have shown the role of PL in changing the operational behavior of other MESs elements and enhancing MES operational flexibility to deliver energy demand. Moreover, considering the reserve service in the modeling has highlighted the behavior of PL as a flexible load, rather than its storage nature, which increases profit from both charging the PEVs' batteries and participating in reserve supplement.

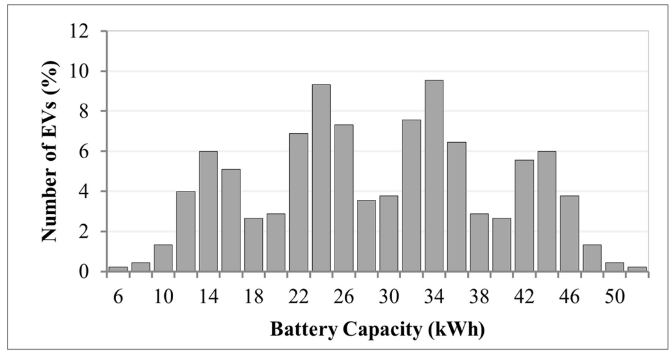

Fig. 13. Probability distribution of battery capacity.

APPENDIX

A. Uncertainty Characterization

1) PL: The uncertainties of total capacity and SoC of PEVs at PL are modeled by a stochastic model. The capacity of PL is dependent on both the number and type of PEVs parked at the PL. In this paper, the PL refers to a parking structure that is located at a specific point. However, the generated scenarios are based on an average traffic behavior of car owners. In other words, it is assumed that the PL is an aggregation of all PLs that are geographically scattered over the study region. The PEV owner's travel patterns are extracted from [29]. To this end, it is assumed that PEV drivers will have a travel behavior similar to internal combustion engine vehicle drivers, traveling an average daily distance of 39.5 miles. This is employed to calculate the SoC of PEVs arriving to the PL.

On the other hand, the ES capacity of each PEV depends on the EV class. In [30], PEV batteries have been categorized to twenty four different classes. On this basis, the redundancy of the mentioned classes is considered as the probability distribution of the battery capacities in a market as in Fig 13.

According to the probability distribution of PEV classes and the probability of the number of PEVs at PL, the probable capacity of PEVs at PL is obtained as in Fig 14.

SoC of PL relies on the daily driven distance of each PEV and the mentioned capacity of PEVs at PL. The probabilistic traveled distance is applied to calculate the SoC of PL.

Based on [31], the lognormal distribution function is utilized to generate the probabilistic daily distance. The daily

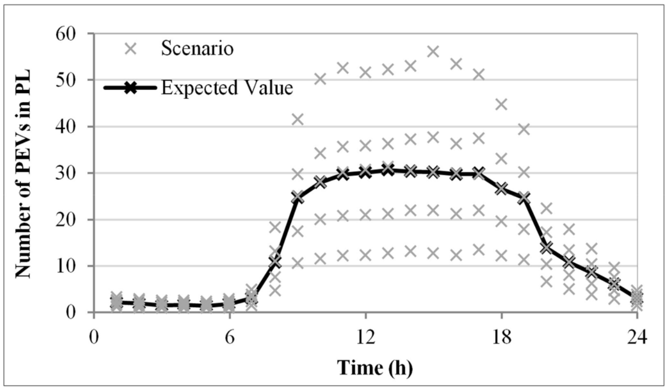

Fig. 14. Hourly nominal capacity of EVs at PL.

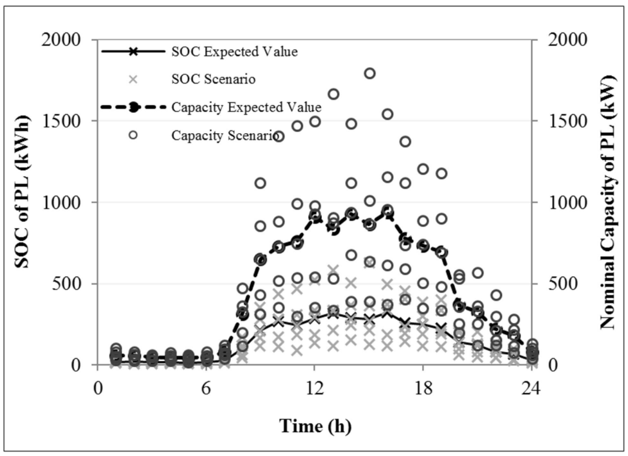

Fig. 15. Hourly SoC of PL.

traveled distance, M_d, can be formulated as (A.42) [32]

$$M_d = \exp\left(\ln\left(\mu_{md}^2 \Big/ \sqrt{\mu_{md}^2 + \sigma_{md}^2}\right) + N.\ln\left(\mu_{md}^2 \Big/ \sqrt{\mu_{md}^2 + \sigma_{md}^2}\right)\right) \tag{A.42}$$

where N is the standard normal random variable, and μ_{md} and σ_{md} are the mean and standard deviation of M_d, being both calculated based on historical data [29].

According to [29], vehicles travel an average daily distance of 39.5 miles. On the other hand, an EV takes approximately 0.35 kWh to recharge for each mile traveling [29]. On this basis and according to the above mentioned description, the hourly SoC of PL is obtained as in Fig 15.

2) Wind Power: Uncertainties of wind power are modeled to generate appropriate input scenarios for this paper. Although accurate probability distribution function (PDF) of wind speed is nonstationary and no discernible actual PDF can be adjusted to it, yet most of the previous researches (see [33]) have used Weibull distribution in order to model wind speed. On this basis, the probability of each wind speed scenario can be calculated as follows:

$$\text{prob}_\omega = \int_{\text{WS}_\omega}^{\text{WS}_{\omega+1}} (k/c)(v/c)^{k-1} \exp\left[-(v/c)^k\right] dv \tag{A.43}$$

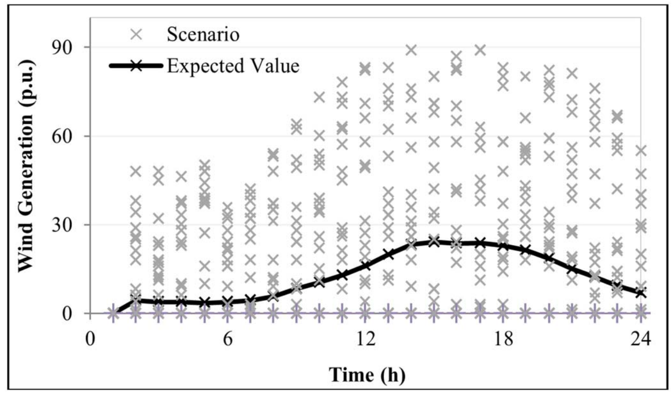

Fig. 16. Wind power generation scenarios.

where $c > 0$ and $k > 0$ are referred to as the scale and shape factors, respectively. WS_ω is the wind speed of the ωth scenario.

The wind power, P_{GW}, corresponding to a specific wind speed, WS_ω, can be obtained from (A.44). In (A.44), A, B, and C are constants that can be calculated according to [34]

$$P_{GW} = \begin{cases} 0 & 0 \le \text{WS}_\omega \le V_c \text{ or } \text{WS}_\omega \ge V_{c0} \\ P_r\left(A + B \times \text{WS}_\omega + C \times \text{WS}_\omega^2\right) & V_c \le \text{WS}_\omega \le V_r \\ P_r & V_r \le \text{WS}_\omega \le V_{co} \end{cases} \tag{A.44}$$

where V_c, V_{c0}, and V_{cr} represent cut-in speed, cut-out speed, and rated speed, respectively. According to the above mentioned descriptions, different scenarios are generated based on roulette wheel mechanism [35].

It should be noted that, although the higher number of scenarios produces a more accurate model to consider the uncertainties, it may yield an unmanageable optimization problem.

Therefore, a scenario reduction technique is considered, using k-means clustering technique, resulting in a scenario tree with independent scenarios that is applied to the case studies.

Moreover, in this paper, the swift current wind data are used to generate wind power scenarios [34]. On this basis, the generated scenarios are illustrated in Fig. 16.

REFERENCES

[1] K. Alanne and A. Saari, "Distributed energy generation and sustainable development," *Renew. Sustain. Energy Rev.*, vol. 10, pp. 539–558, Dec. 2006.

[2] P. Mancarella, "MES (multi-energy systems): An overview of concepts and evaluation models," *Energy*, vol. 65, pp. 1–17, Feb. 2014.

[3] M. D. Galus *et al.*, "Integrating power systems, transport systems and vehicle technology for electric mobility impact assessment and efficient control," *IEEE Trans. Smart Grid*, vol. 3, no. 2, pp. 934–949, Jun. 2012.

[4] S. Rezaee, E. Farjah, and B. Khorramdel, "Probabilistic analysis of plug-in electric vehicles impact on electrical grid through homes and parking lots," *IEEE Trans. Sustain. Energy*, vol. 4, no. 4, pp. 1024–1033, Oct. 2013.

[5] M. Geidl *et al.*, "Energy hubs for the future," *IEEE Power Energy Mag.*, vol. 5, no. 1, pp. 24–30, Jan./Feb. 2007.

[6] G. Chicco and P. Mancarella, "Matrix modelling of small-scale trigeneration systems and application to operational optimization," *Energy*, vol. 34, pp. 261–273, Mar. 2009.

[7] T. Krause, G. Andersson, K. Fröhlich, and A. Vaccaro, "Multiple-energy carriers: Modeling of production, delivery, and consumption," *Proc. IEEE*, vol. 99, no. 1, pp. 15–27, Jan. 2011.

[8] M. C. Bozchalui, S. A. Hashmi, H. Hassen, C. A. Canizares, and K. Bhattacharya, "Optimal operation of residential energy hubs in smart grids," *IEEE Trans. Smart Grid,* vol. 3, no. 4, pp. 1755–1766, Dec. 2012.

[9] P. Mancarella and G. Chicco, "Real-time demand response from energy shifting in distributed multi-generation," *IEEE Trans. Smart Grid*, vol. 4, no. 4, pp. 1928–1938, Dec. 2013.

[10] F. Kienzle, P. Ahčin, and G. Andersson, "Valuing investments in multi-energy conversion, storage, and demand-side management systems under uncertainty," *IEEE Trans. Sustain. Energy,* vol. 2, no. 2, pp. 194–202, Apr. 2011.

[11] F. Adamek, M. Arnold, and G. Andersson, "On decisive storage parameters for minimizing energy supply costs in multicarrier energy systems," *IEEE Trans. Sustain. Energy,* vol. 5, no. 1, pp. 102–109, Jan. 2014.

[12] M. Schulze, L. Friedrich, and M. Gautschi, "Modeling and optimization of renewables: Applying the energy hub approach," in *Proc. IEEE Int. Conf. Sustain. Energy Technol.*, Singapore, 2008, pp. 83–88.

[13] P. Mancarella and G. Chicco, "Integrated energy and ancillary services provision in multi-energy systems," in *Proc. IX IREP Symp. Bulk Power Syst. Dyn. Control Optim. Secur. Control Emerg. Power Grid*, Rethymno, Greece, 2013, pp. 1–19.

[14] M. D. Galus, "Agent-based modeling and simulation of large scale electric mobility in power systems," Ph.D. Dissertation, Dept. Inf. Technol. Elect. Eng., ETH Zürich, Zürich, Switzerland, 2012.

[15] M. D. Galus and G. Andersson, "Demand management of grid connected plug-in hybrid electric vehicles (PHEV)," in *Proc. IEEE Energy Conf (ENERGY)*, Atlanta, GA, USA, 2008, pp. 1–8.

[16] M. D. Galus, S. Koch, and G. Andersson, "Provision of load frequency control by PHEVs, controllable loads, and a cogeneration unit," *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4568–4582, Oct. 2011.

[17] S. Han, S. Han, and K. Sezaki, "Development of an optimal vehicle-to-grid aggregator for frequency regulation," *IEEE Trans. Smart Grid,* vol. 1, no. 1, pp. 65–72, Jun. 2010.

[18] E. Sortomme and M. A. El-Sharkawi, "Optimal charging strategies for unidirectional vehicle-to-grid," *IEEE Trans. Smart Grid,* vol. 2, no. 1, pp. 131–138, Mar. 2011.

[19] P. H. Andersen, J. A. Mathews, and M. Raska, "Integrating private transport into renewable energy policy: The strategy of creating intelligent recharging grids for electric vehicles," *Energy Pol.*, vol. 37, pp. 2481–2486, Jul. 2009.

[20] C. Guille and G. Gross, "A conceptual framework for the vehicle-to-grid (V2G) implementation," *Energy Pol.*, vol. 37, pp. 4379–4390, Nov. 2009.

[21] T. K. Kristoffersen, K. Capion, and P. Meibom, "Optimal charging of electric drive vehicles in a market environment," *Appl. Energy*, vol. 88, pp. 1940–1948, May 2011.

[22] Y. Cao *et al.*, "An optimized EV charging model considering TOU price and SOC curve," *IEEE Trans. Smart Grid,* vol. 3, no. 1, pp. 388–393, Mar. 2012.

[23] R. J. Bessa and M. A. Matos, "Optimization models for EV aggregator participation in a manual reserve market," *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 3085–3095, Aug. 2013.

[24] M. A. Ortega-Vazquez, F. Bouffard, and V. Silva, "Electric vehicle aggregator/system operator coordination for charging scheduling and services procurement," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1806–1815, May 2013.

[25] R. J. Bessa, M. A. Matos, F. J. Soares, and J. A. P. Lopes, "Optimized bidding of a EV aggregation agent in the electricity market," *IEEE Trans. Smart Grid,* vol. 3, no. 1, pp. 443–452, Mar. 2012.

[26] M. Shafie-khah and J. P. S. Catalao, "A stochastic multi-layer agent-based model to study electricity market participants behavior," *IEEE Trans. Power Syst.*, vol. 30, no. 2, pp. 867–881, Mar. 2015.

[27] RED Electrica de Espana. (Dec. 2014). *Energy Price and Capacity Payment.* [Online]. Available: http://www.esios.ree.es/web-publica/

[28] M. Geidl, "Integrated modeling and optimization of multi-carrier energy systems," Ph.D. Dissertation, Dept. Inf. Technol. Elect. Eng., ETH Zürich, Zürich, Switzerland, 2007.

[29] R. van Haaren, "Assessment of electric cars' range requirements and usage patterns based on driving behavior recorded in the national household travel survey of 2009," Dept. Earth Environ. Eng., Fu Found. School Eng. Appl. Sci., Columbia Univ., New York, NY, USA, 2011.

[30] F. Nemry, G. Leduc, and A. Muñoz, "Plug-in hybrid and battery-electric vehicles: State of the research and development and comparative analysis of energy and cost efficiency," Inst. Prospect. Technol. Studies, Joint Research Centre, Seville, Spain, Tech. Rep. JRC 54699, 2009.

[31] S. Meliopoulos, J. Meisel, G. Cokkinides, and T. Overbye, "Power system level impacts of plug-in hybrid vehicles," Power Syst. Eng. Res. Center, Tempe, AZ, USA, 2009, pp. 9–12.

[32] G. Alejandro, D. Domínguez-García, and S. Suryanarayanan, "Implications of the smart grid initiative on distribution engineering," Power Syst. Eng. Res. Center, Tempe, AZ, USA, vol. 4, 2011.

[33] R. Karki, H. Po, and R. Billinton, "A simplified wind power generation model for reliability evaluation," *IEEE Trans. Energy Convers.*, vol. 21, no. 2, pp. 533–540, Jun. 2006.

[34] (2006). *Canada's National Climate Archive*. [Online]. Available: http://www.climate.weatheroffice.ec.gc.ca

[35] N. Amjady, J. Aghaei, and H. A. Shayanfar, "Stochastic multiobjective market clearing of joint energy and reserves auctions ensuring power system security," *IEEE Trans. Power Syst.*, vol. 24, no. 4, pp. 1841–1854, Nov. 2009.

Maziar Yazdani-Damavandi (S'08) received the M.Sc. degree in electrical engineering from Tarbiat Modares University, Tehran, Iran, in 2010, where he is currently pursuing the Ph.D. degree from the Energy Management Laboratory.

He is a Researcher in the Smart and Sustainable Insular Electricity Grids Under Large-Scale Renewable Integration Project with the University of Beira Interior, Covilha, Portugal. His current research interests include optimization models in power system studies and multienergy system modeling.

Mohsen Parsa Moghaddam (M'05) received the B.Sc. degree in electrical engineering from the Sharif University of Technology, Tehran, Iran; the M.Sc. degree from the Toyohashi University of Technology, Toyohashi, Japan; and the Ph.D. degree from Tohoku University, Sendai, Japan, in 1980, 1985, and 1988, respectively.

He is currently a Professor with the Faculty of Electrical and Computer Engineering, Tarbiat Modares University, Tehran, Iran. His current research interests include power system planning, energy management, and smart grids.

Mahmoud-Reza Haghifam (M'95–SM'06) received the B.S., M.S., and Ph.D. degrees in electrical engineering from Tarbiat Modares University, Tehran, Iran, in 1989, 1992, and 1995, respectively.

He is currently a Professor of Power Systems with the Faculty of Electrical and Computer Engineering, Tarbiat Modares University, Tehran, Iran. His current research interests include electric distribution systems, power system operation, power system reliability, reactive power control, and soft computing applications in power system analysis and operation.

Miadreza Shafie-khah (S'08–M'13) received the M.Sc. and Ph.D. degrees in electrical engineering from Tarbiat Modares University, Tehran, Iran, in 2008 and 2012, respectively.

He is a Post-Doctoral Fellow with the Laboratory of Sustainable Energy Systems, University of Beira Interior, Covilha, Portugal, with Prof. J. P. S. Catalão, where he is researching the EU-funded FP7 Project Smart and Sustainable Insular Electricity Grids Under Large-Scale Renewable Integration. His current research interests include power market simulation, market power monitoring, power system optimization, operation of electricity markets, price forecasting, and smart grids.

João P. S. Catalão (M'04–SM'12) received the M.Sc. degree from the Instituto Superior Técnico, Lisbon, Portugal, in 2003, and the Ph.D. degree and Habilitation for Full Professor ("Agregação") from the University of Beira Interior (UBI), Covilha, Portugal, in 2007 and 2013, respectively.

He is a currently a Professor and the Director with the Sustainable Energy Systems Laboratory, UBI, and a Researcher with INESC-ID, Lisbon. He is the Primary Coordinator of the EU-funded FP7 Project Smart and Sustainable Insular Electricity Grids Under Large-Scale Renewable Integration. His current research interests include power system operations and planning, hydro and thermal scheduling, wind and price forecasting, distributed renewable generation, demand response, and smart grids. He has authored/co-authored over 320 publications, including 100 journal papers, 200 conference proceedings papers, and 20 book chapters, and has an H-index 22 (Google scholar). He has supervised over 25 Post-Doctorates, Ph.D., and M.Sc. students. He has edited the book *Electric Power Systems: Advanced Forecasting Techniques and Optimal Generation Scheduling* (CRC Press, 2012). He is currently editing another book entitled *Smart and Sustainable Power Systems: Operations, Planning and Economics of Insular Electricity Grids* (CRC Press, 2015).

Prof. Catalão was the recipient of the 2011 Scientific Merit Award UBI-FE/Santander Universities and the 2012 Scientific Award UTL/Santander Totta. He is an Editor of the IEEE TRANSACTIONS ON SMART GRID and the IEEE TRANSACTIONS ON SUSTAINABLE ENERGY, and an Associate Editor of *IET Renewable Power Generation*. He was the Guest Editor-in-Chief for the Special Section on Real-Time Demand Response of the IEEE TRANSACTIONS ON SMART GRID in 2012. He is currently the Guest Editor-in-Chief for the Special Section on Reserve and Flexibility for Handling Variability and Uncertainty of Renewable Generation of the IEEE TRANSACTIONS ON SUSTAINABLE ENERGY.