Effect of Plug-in Electric Vehicles Traffic Behavior on Multi-Energy Demand's Dependency

Nilufar Neyestani, Maziar Yazdani Damavandi,
Tiago D. P. Mendes, and João P. S. Catalão
FEUP, Porto, UBI, Covilha, and INESC-ID, IST,
Univ. Lisbon, Lisbon, Portugal
catalao@ubi.pt

Gianfranco Chicco
Politecnico di Torino, Energy Department
Torino, Italy
gianfranco.chicco@polito.it

Abstract—**In this paper, a multi energy system (MES) model incorporating the traffic behavior of plug-in electric vehicles (PEVs) is proposed. It is assumed that in a micro MES two charging options are available for the PEVs: the home charging (HC) stations and the PEV parking lot (PL). The operation of these elements within the micro MES concept is studied. The matrix model of the micro MES is adapted to enable the integration of PL and HC. Moreover, the traffic flow of the PEVs is added to the model as an input to the micro MES. The model is tested for various case studies and possible traffic behavior between the PL and HC. The results show that the presence of these two elements leads to effective integration of reduced system operation costs.**

Index Terms—**multi-energy demand, multi-energy system, parking lot, plug-in electric vehicle.**

NOMENCLATURE

Acronyms

AB	Auxiliary Boiler
CHP	Combined Heat and Power
HC	Home Charging Stations
HS	Heat Storage
MED	Multi Energy Demand
MES	Multi Energy System
PEV	Plug-in Electric Vehicle
PL	Parking Lot
SOC	State of Charge

Subscripts

e	Electricity
g	Gas
h	Heat
r	reserve
t	Time interval
ω	Uncertainty Scenario

Superscripts

ar/dep	Arrived/departed PEVs to/from PL or HC
cha/dcha	Charging or discharging mode
Con	Contingency
del	Delegated energy
EU	End User
G2V	Grid to Vehicle
in, out	Input/output energy
Mi	Micro MES
PL	Parking lot
V2G	Vehicle to Grid

Parameters and Variables

C, c	Capacity of PEVs or PL (kW)
Cd	Cost of battery degradation
FOR	Forced outage rate
G, g	Gas energy
n, N	Number of PEVs
Q, q	Heat energy
$\dot{q}$	Heat storage level difference in two consecutive time intervals
r	Reserve
SOC, soc	State of charge (kWh)
sòc	Difference in SOC level in two consecutive time intervals
v	Continuous decision variable determining the share of each energy element from input energy carriers
W, w	Electrical power
χ	SOC to capacity ratio for each PEV (kWh/kW)
π	Price
ϕ	PEVs participation ratio in V2G mode
γ	Charge/Discharge rate
ρ	Probability
η	Efficiency
$\dot{\mathbf{e}}$	(column vector) changes in stored carrier
$\mathbf{p}$	(column vector) input carrier
$\mathbf{l}$	(column vector) output carrier
$\mathbf{K}$	(column vector) surplus carrier
$\mathbf{c}$	Coupling matrix
$\mathbf{s}$	Storage coupling matrix

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

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

I. INTRODUCTION

A. Background and Aim

With the vast penetration of technology in everyday life, the interrelation of different energy resources has grown significantly. The multi-energy systems (MES) contain key resources, driving the evolution of the future systems. However, making MES consistent with all the possible components of the future systems is challenging and requires in-depth studies.

One of the inevitable elements in future energy systems, based on the recent trends, is the integration of plug-in electric vehicles (PEV). The PEVs not only can increase the amount of load in the system, due to their charging requirements, but also can bring the potential of vehicle to grid (V2G) and inject their battery's state of charge (SOC) into the system. In this regard, adapting various aspects of PEVs in a MES has been the issue of some recent studies. Firstly, the authors in [1] introduced the idea of modeling the plug-in hybrid electric vehicles (PHEV) with the energy hub approach. They considered the PHEV as a MES component that has the input of electricity, gasoline, and hydrogen and gives the services of mobility and electricity as the outcomes. This model is later developed in [2] for the integration of PHEVs in a larger energy hub system.

The main aspect of connecting PEVs in the system is their need of getting charged; therefore, the amount of demand that is added to the system due to the integration of these vehicles is considerable. The optimal charging schedule of the PHEVs in a multi-energy home is addressed in [3]. In a larger context, the authors in [4] and [5], studied the management of PHEV's demand in an energy hub. Moreover, in [6], an optimal demand management for PHEVs is proposed considering the probabilistic behavior of vehicles in the context of energy hub.

When the PEVs are included in a MES, various components of the MES have cross effects with the charging schedule and operation of PEVs. The modeling of PEVs in a renewable based network with multi-energy carriers supply is presented in [7]. The impacts of electric vehicles on strategic planning of the energy infrastructure are discussed in [8]. While integrating the electric vehicles in the multi-energy systems, the traffic pattern of the PEVs in the system and their choice on where to charge their vehicles is a matter of importance. The future energy systems should be provided with various facilities to encourage the electric vehicle manipulation. The adequate foreseeing of charging stations compatible to the number of PEVs in the system should be managed by system planners. As a result, the concept of PEV parking lots (PLs) as an aggregated form of PEVs can provide a proper solution for charging the PEVs as well as establishing an interface for interactions of the PEVs with the grid [9]. In this regard, the PEV PL can deliver grid to vehicle (G2V) and V2G opportunities brought by the PEVs' batteries. On the other hand, the PEVs' owners' preferences and charging requirements as well as their daily traffic pattern can significantly affect the system operation. The amount of input energy to the PEV batteries and their potential of V2G participation is influenced by their traffic pattern. The interactions of PEV owners with their home-charging aggregators or public charging stations can change the amount of electricity demand for the multi-energy demand (MED).

Moreover, considering the PEV PL as a resource in the MES, the status of PEVs entering the PL and their SOC can change the behavior of PL as a resource in the MES operation. As a result, the traffic behavior of the PEVs has to be added to the demand management of a MES.

The intention of this paper is to provide a comprehensive model for the integration of PEV facilities in the form of PL and aggregated charging stations in the MES. The results will investigate the charging behavior of PL and the strategy of MES operator in providing the demand. The hourly electricity provision of MES and the operation of various MES components (such as combined heat and power (CHP)) in response to changes in electricity demand (due to PEVs) are analyzed.

B. Problem Description and Contributions

It is assumed that in a MES serving a MED, the PEVs are owned by the end-users in the MED and can be charged in the charging stations provided on the demand side (presumably residential area) which are referred as Home charging (HC) stations.

For commercial purposes, a PEV PL is embedded in the MES. The PL can act as storage in the system deploying the potential of PEV batteries. However, it should be considered that the operation of charging stations on the demand side and the PL's charging strategy causes a dependency between these two elements of the MES. On the other hand, the travel statistics of the PEVs and their consumption pattern also affect PL operation.

The schematic of the MES and its components are depicted in Fig. 1.

As it is shown, the PL is added as a module to the micro MES while the HC is considered on the MED side. The difference between PL and HC is the traffic pattern of the PEVs that enter or leave them. The PEVs are staying in the PL during the working hours of the day, which makes the PL a potential resource consisting of the batteries SOC. On the other hand, the PEVs are in the HC during early hours in the morning or late at night, which makes it a proper place for charging the batteries in the hours when the energy price is lower. This difference between the patterns and their effect on the operation of the MES is studied in this paper.

In addition, adding the PL in the MES necessitates the introduction of new inputs to the model to represent the traffic flow of the PEVs in the MES. In this study, these inputs are the SOC and capacity of the arrived PEVs to the MES. The contributions of this study can be stated as:

- Proposing the matrix modeling for the micro MES with PL and HC elements;
- Modeling the inter-relation of PEVs PL and HC within the energy hub concept;
- Considering the PEVs traffic pattern as the inputs of the energy hub.

C. Paper organization

The rest of the paper is organized as follows. Section II presents the matrix modeling for a MES with PL and HC modules. Section III introduces the operation of the MES with these components and the mathematical model. Section IV shows the numerical results and Section V contains the conclusions.

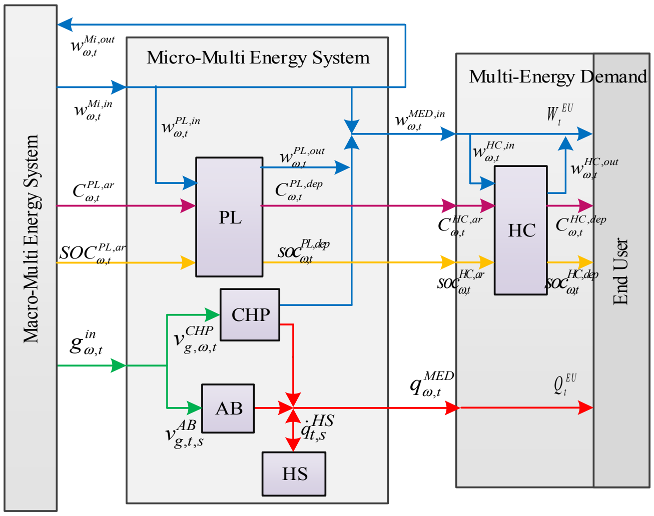

Figure 1. Schematic of micro MES with PL and HC.

II. MATRIX MODELING OF MES WITH PL AND HC

In this study, a micro multi-energy system is considered that serves multi-energy demand with the demand of electricity and heat. The micro MES consists of a CHP unit, an auxiliary boiler (AB), and heat storage (HS). It is assumed that the PEV PL is added as a module to the micro MES while the HC stations are on the MED side.

As previously described in [10-12], the matrix modeling of the micro MES with storage and the possibility of injecting power to the upstream network can be modeled as presented in (1). It consists of the coupling matrices **C** and **S** representing the conversion due to energy converters in the MES and energy storages, respectively.

$$\begin{bmatrix} \mathbf{c}_{\omega,t}^{\mathbf{Mi}} & \mathbf{s}_{\omega,t}^{\mathbf{Mi}} \end{bmatrix} \begin{bmatrix} \mathbf{p}_{\omega,t}^{\mathbf{Mi}} \\ \dot{\mathbf{e}}_{\omega,t}^{\mathbf{Mi}} \end{bmatrix} = \begin{bmatrix} \mathbf{l}_{\omega,t}^{\mathbf{Mi}} \end{bmatrix} + \begin{bmatrix} \mathbf{k}_{\omega,t}^{\mathbf{Mi}} \end{bmatrix} \qquad (1)$$

In this section, the modification of the matrix modeling for the micro MES with additional PEVs' PL and HC formulated

A. PL model in micro MES

When the PL is added as a module to the micro MES, the coupling matrix of the micro MES is going to be affected. The reason is that the ability of the PL to act as a resource in the system along with its capability to have the role of a storage will change the entries of the coupling matrix, the input vector, and the output vector.

As a result, the matrix modeling of the micro MES with the PL will change as (2).

$$\begin{bmatrix} \mathbf{c}_{\omega,t}^{\mathbf{Mi,new}} & \mathbf{s}_{\omega,t}^{\mathbf{Mi,new}} \end{bmatrix} \begin{bmatrix} \mathbf{p}_{\omega,t}^{\mathbf{Mi,new}} \\ \dot{\mathbf{e}}_{\omega,t}^{\mathbf{Mi,new}} \end{bmatrix} = \begin{bmatrix} \mathbf{l}_{\omega,t}^{\mathbf{MED,new}} \end{bmatrix} + \begin{bmatrix} \mathbf{k}_{\omega,t}^{\mathbf{Mi,new}} \end{bmatrix} \qquad (2)$$

Due to the twofold role of the PL as a resource and a storage in the system, the entries in (2) are shown in (3) to (8).

$$\mathbf{c}_{\omega,t}^{\mathbf{Mi,new}} = \begin{bmatrix} \mathbf{c}_{\omega,t}^{\mathbf{Mi}} & \mathbf{c}_{\omega,t}^{\mathbf{Mi,PL}} \\ \mathbf{0} & \mathbf{c}_{\omega,t}^{\mathbf{PL}} \end{bmatrix} \qquad (3)$$

$$\mathbf{s}_{\omega,t}^{\mathbf{Mi,new}} = \begin{bmatrix} \mathbf{s}_{\omega,t}^{\mathbf{Mi}} & \mathbf{0} \\ \mathbf{0} & \mathbf{s}_{\omega,t}^{\mathbf{PL}} \end{bmatrix} \qquad (4)$$

$$\mathbf{p}_{\omega,t}^{\mathbf{Mi,new}} = \begin{bmatrix} \mathbf{p}_{\omega,t}^{\mathbf{Mi}} \\ \mathbf{p}_{\omega,t}^{\mathbf{PL}} \end{bmatrix} \qquad (5)$$

$$\dot{\mathbf{e}}_{\omega,t}^{\mathbf{Mi,new}} = \begin{bmatrix} \dot{\mathbf{e}}_{\omega,t}^{\mathbf{Mi}} \\ \dot{\mathbf{e}}_{\omega,t}^{\mathbf{PL}} \end{bmatrix} \qquad (6)$$

$$\mathbf{l}_{\omega,t}^{\mathbf{MED,new}} = \begin{bmatrix} \mathbf{l}_{\mathbf{t}}^{\mathbf{MED}} \\ \mathbf{l}_{\omega,t}^{\mathbf{PL}} \end{bmatrix} \qquad (7)$$

$$\mathbf{k}_{\omega,t}^{\mathbf{Mi,new}} = \begin{bmatrix} \mathbf{k}_{\omega,t}^{\mathbf{Mi}} \\ \mathbf{k}_{\omega,t}^{\mathbf{PL}} \end{bmatrix} \qquad (8)$$

Based on the above equations, the total conversion matrix for the micro MES with the PL will be as (9).

$$\begin{bmatrix} \mathbf{c}_{\omega,t}^{\mathbf{Mi}} & \mathbf{c}_{w,t}^{\mathbf{Mi,PL}} & \mathbf{s}_{\omega,t}^{\mathbf{Mi}} & \mathbf{0} \\ \mathbf{0} & \mathbf{c}_{\omega,t}^{\mathbf{PL}} & \mathbf{0} & \mathbf{s}_{\omega,t}^{\mathbf{PL}} \end{bmatrix} \begin{bmatrix} \mathbf{p}_{\omega,t}^{\mathbf{Mi}} \\ \mathbf{p}_{\omega,t}^{\mathbf{PL}} \\ \dot{\mathbf{e}}_{\omega,t}^{\mathbf{Mi}} \\ \dot{\mathbf{e}}_{\omega,t}^{\mathbf{PL}} \end{bmatrix} = \begin{bmatrix} \mathbf{l}_{\mathbf{t}}^{\mathbf{MED}} \\ \mathbf{l}_{\omega,t}^{\mathbf{PL}} \end{bmatrix} + \begin{bmatrix} \mathbf{k}_{\omega,t}^{\mathbf{Mi}} \\ \mathbf{k}_{\omega,t}^{\mathbf{PL}} \end{bmatrix} \qquad (9)$$

In order to derive the detailed format of the matrices, the interactions that occur within the micro MES should be considered. Referring to Fig. 1, it is shown that the inputs of the micro MES from the upstream network are electricity ($w_{\omega,t}^{Mi,in}$) and gas ($g_{\omega,t}^{Mi,in}$) energy carriers. However, the capacity ($c_{\omega,t}^{PL,ar}$) and the SOC of the PEVs that enter the PL ($SOC_{\omega,t}^{PL,ar}$) should be considered as the inputs of the micro MES as well. On the other hand, the level of SOC that is maintained in the PEV's batteries ($s\dot{o}c_{\omega,t}^{PL,ar}$) and the total capacity of the PEVs' batteries form the characteristics of the PL as storage which are shown by dot operator. Therefore, the complete format of the micro MES matrix model will be as (10).

$$\begin{bmatrix} 1 & v_{g,\omega,t}^{CHP}\eta_e^{CHP} & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & v_{g,\omega,t}^{CHP}\eta_h^{CHP} + v_{g,\omega,t}^{AB}\eta_h^{AB} & 1 & 0 & 0 & 0 & 1/\eta_{\omega,t}^{HS} & 0 & 0 \\ 0 & 0 & 0 & \eta_{\omega,t}^{PL} & 1 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} w_{\omega,t}^{Mi,in} \\ g_{\omega,t}^{Mi,in} \\ q_{\omega,t}^{Mi,in} \\ \kappa_{\omega,t}^{PL} \\ SOC_{\omega,t}^{PL,ar} \\ c_{\omega,t}^{PL,ar} \\ \dot{q}_{\omega,t}^{HS} \\ \dot{C}_{\omega,t}^{PL} \\ s\dot{o}c_{\omega,t}^{PL} \end{bmatrix} = \begin{bmatrix} w_{\omega,t}^{MED} \\ g_{\omega,t}^{MED} \\ q_{\omega,t}^{MED} \\ soc_{\omega,t}^{PL,dep} \\ c_{\omega,t}^{PL,dep} \end{bmatrix} + \begin{bmatrix} w_{\omega,t}^{Mi,out} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad (10)$$

In the complete format, the efficiency of the heat storage is included in the model based on the charging or discharging mode of the storage as shown in (11). The same approach is used for the PL in G2V/V2G mode (12).

$$\eta_{\omega,t}^{HS} = \begin{cases} \eta^{HS,cha}, & \text{if Charge / Standby} \\ 1/\eta^{HS,dcha}, & \text{if Discharge} \end{cases} \qquad (11)$$

$$\eta_{\omega,t}^{PL} = \begin{cases} \eta^{PL,cha}, & \text{if Charge / Standby} \\ 1/\eta^{PL,dcha}, & \text{if Discharge} \end{cases} \qquad (12)$$

The potential of the PL as an energy/reserve resource is obtained from the level of SOC that is maintained in the PEV batteries after the transactions of the PL (energy input to the PL and output from the PL). For this computation, the term $\kappa_{\omega,t}^{PL}$ is defined as in (13), where $w_{\omega,t}^{PL,in}$ and $w_{\omega,t}^{PL,out}$ are the input and output electric energy of the PL, respectively.

$$\kappa_{\omega,t}^{PL} = w_{\omega,t}^{PL,in} - w_{\omega,t}^{PL,out} \tag{13}$$

The amount of SOC that can be offered in the energy or reserve markets in each hour is shown by $s\dot{o}c_{\omega,t}^{PL}$ which is the difference in SOC level in two consecutive time intervals (14). In addition, the total available capacity in the PL that limits its maximum input power and consequently its stored energy is computed by (15).

$$s\dot{o}c_{\omega,t}^{PL} = soc_{\omega,t}^{PL} - soc_{\omega,t-1}^{PL} \tag{14}$$

$$\dot{C}_{\omega,t}^{PL} = C_{\omega,t}^{PL} - C_{\omega,t-1}^{PL} = C_{\omega,t}^{PL,ar} - C_{\omega,t}^{PL,dep} \tag{15}$$

There are other operational constraints that limit the interactions of the PL with the upstream network. The hourly input power to the PL cannot exceed the possible charging of the batteries which is calculated from the charging rate of the PL multiplied by the hourly number of PEVs in the PL (16). On the other hand, the output energy of the PL should not be lower than the possible discharging (based on the number of PEVs in the PL and the discharging rate) and the minimum PEV owners' requirement on their departure SOC (17).

$$w_{\omega,t}^{PL,in} \le \gamma^{PL} n_{\omega,t}^{PL} \tag{16}$$

$$w_{\omega,t}^{PL,out} + r_{\omega,t}^{PL} \le min\left\{\gamma^{PL} n_{\omega,t}^{PL}, soc_{\omega,t}^{PL}\phi^{PL}\right\} \tag{17}$$

The SOC in the PL is limited by the maximum and minimum possible SOC of each PEV in ratio to its capacity:

$$\underline{\chi}^{PEV} c_{\omega,t}^{PL} \le soc_{\omega,t}^{PL} \le \overline{\chi}^{PEV} c_{\omega,t}^{PL} \tag{18}$$

where X^{PEV} denotes the ratio of each PEV's SOC to its capacity indicating the maximum and minimum possible charging in each PEV.

B. HC model in MED

In this study, it is assumed that the individual charging stations are provided in the system; however, they are aggregated and operated by a single MED operator. In the system depicted in Fig. 1, the MED consists of the end-users with the energy need of electricity and heat. Thus, the matrix modeling for the input to the MED and the delivered service to the end-use for a MED without HC is defined as (19).

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} w_t^{MED,in} \\ q_t^{MED,in} \end{bmatrix} = \begin{bmatrix} W_t^{EU} \\ Q_t^{EU} \end{bmatrix} \tag{19}$$

When the HC is added to the MED, the arrival capacity and SOC to the HC will be added as the inputs of the MED to the input matrix. Following the basics on deriving the derivatives of the matrix from (10), the complete matrix format for MED including all the HC interactions is shown in (20).

$$\begin{bmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \eta_{\omega,t}^{HC} & 1 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 1 & -1 & 1 \end{bmatrix} \begin{bmatrix} w_{\omega,t}^{MED,in} \\ q_{\omega,t}^{MED,in} \\ \kappa_{\omega,t}^{HC,in} \\ soc_{\omega,t}^{HC,ar} \\ c_{\omega,t}^{HC,ar} \\ \dot{C}_{\omega,t}^{HC} \\ s\dot{o}c_{\omega,t}^{HC} \end{bmatrix} = \begin{bmatrix} W_{\omega,t}^{EU} \\ Q_t^{EU} \\ soc_{\omega,t}^{HC,dep} \\ c_{\omega,t}^{HC,dep} \end{bmatrix} \tag{20}$$

Following the same approach as the PL, the detailed description of each entries in (20) are shown in (21) to (27).

$$\eta_{\omega,t}^{HC} = \begin{cases} \eta^{HC,cha}, & \text{if Charge / Standby} \\ 1/\eta^{HC,dcha}, & \text{if Discharge} \end{cases} \tag{21}$$

$$\kappa_{\omega,t}^{HC,in} = w_{\omega,t}^{HC,in} - w_{\omega,t}^{HC,out} \tag{22}$$

$$s\dot{o}c_{\omega,t}^{HC} = soc_{\omega,t}^{HC} - soc_{\omega,t-1}^{HC} \tag{23}$$

$$\dot{C}_{\omega,t}^{HC} = C_{\omega,t}^{HC} - C_{\omega,t-1}^{HC} = C_{\omega,t}^{HC,ar} - C_{\omega,t}^{HC,dep} \tag{24}$$

$$w_{\omega,t}^{HC,in} \le \gamma^{HC} n_{\omega,t}^{HC} \tag{25}$$

$$w_{\omega,t}^{HC,out} + r_{\omega,t}^{HC} \le min\left\{\gamma^{HC} n_{\omega,t}^{HC}, soc_{\omega,t}^{HC}\phi^{HC}, W_{\omega,t}^{EU}\right\} \tag{26}$$

$$\underline{\chi}^{PEV} C_{\omega,t}^{HC} \le soc_{\omega,t}^{HC} \le \overline{\chi}^{PEV} C_{\omega,t}^{HC} \tag{27}$$

III. THE MES OPERATION MODEL

The PL and HC stations have different operators that when they are considered individually, they have different objectives. The PL and HC operators want to minimize the total cost of their interactions with the micro MES and the PEVs. However, as the PL is considered as a component in the micro MES, its objective is merged with the objective of micro MES operator and can be stated as (28).

$$Obj^{Mi} = $$

$$Min \quad \sum_{\omega} \rho_{\omega} \sum_{t} \begin{bmatrix} \left(w_{\omega,t}^{Mi,in} - w_{\omega,t}^{Mi,out}\right)\pi_{e,t} + g_{\omega,t}^{Mi,in}\pi_{g,t} + \\ \pi_t^{G2V}\left(soc_{\omega,t}^{PL,in} - soc_{\omega,t}^{PL,out}\right)\Big|_{soc_{\omega,t}^{PL,in} \le soc_{\omega,t}^{PL,out}} \\ +\pi_t^{V2G}\left(soc_{\omega,t}^{PL,in} - soc_{\omega,t}^{PL,out}\right)\Big|_{soc_{\omega,t}^{PL,in} > soc_{\omega,t}^{PL,out}} \\ -r_{\omega,t}^{PL}\pi_{r,t} - r_{\omega,t}^{PL}\rho_t^{del}\pi_{e,t} + \left(p_{\omega,t}^{PL,out} + r_{\omega,t}^{PL}\rho_t^{del}\right)Cd^{PL} \\ +r_{\omega,t}^{PL}\rho_t^{del}FOR^{PL}\pi_t^{Con} - r_{\omega,t}^{PL}\rho_t^{del}\pi_t^{PL,V2G} \end{bmatrix} \tag{28}$$

In (28), the costs imposed to the micro MES operator due to its interaction with the upstream energy and reserve electricity markets, purchase of gas from upstream network, the trade with PEVs for charging or discharging their batteries, and possible penalties for not being ready in the reserve call are considered.

The objective function for the MED operator with the HC is shown in (29). As can be seen, the objective of the MED operator is to minimize its costs from its interaction with the PEVs through HC, demand provision (electricity and heat), and the penalty for not committing the reserve call.

$$
Obj^{MED} = \\
Min \quad \sum_{\omega} \rho_{\omega} \sum_{t} \begin{bmatrix} \left(w_{\omega,t}^{MED,in} - w_{\omega,t}^{MED,out} \right) \pi_{e,t} + q_{\omega,t}^{MED} \pi_{h,t} \\ + \pi_t^{G2V} \left(soc_{\omega,t}^{HC,in} - soc_{\omega,t}^{HC,out} \right) \Big|_{soc_{\omega,t}^{HC,in} \le soc_{\omega,t}^{HC,out}} \\ + \pi_t^{V2G} \left(soc_{\omega,t}^{HC,in} - soc_{\omega,t}^{HC,out} \right) \Big|_{soc_{\omega,t}^{PL,in} > soc_{\omega,t}^{PL,out}} \\ - r_{\omega,t}^{HC} \pi_{r,t} - r_{\omega,t}^{HC} \rho_t^{del} \pi_{e,t} + \left(p_{\omega,t}^{HC,out} + r_{\omega,t}^{HC} \rho_t^{del} \right) Cd^{HC} \\ + r_{\omega,t}^{HC} \rho_t^{del} FOR^{PL} \pi_t^{Con} - r_{\omega,t}^{HC} \rho_t^{del} \pi_t^{HC,V2G} \end{bmatrix} \quad (29)
$$

The objective functions are limited by operational constraints of the system components including the CHP, AB, HS, and input energy carriers as well as the operational constraints of PL and HC previously mentioned in eq. (11) to (18) and eq. (21) to (27). The constraints of the CHP, AB, and HS are based on [13].

IV. NUMERICAL RESULTS

The model proposed in this study is tested on the micro MES schematically illustrated in Fig. 1. It is assumed that the CHP unit, AB, and HS are operated within the micro MES and has the characteristics as described in [13]. The PL which is added to the micro MES is considered to have 180 stations with fast charging rate of 11 kW/h. The charging stations installed in the HC have slow charging equipment with the rate of 7 kW/h. In order to implement the different PEV behaviors in the model, five different scenarios are considered for arrival to and departure pattern from PL and HC, which are shown in Figs. 2 and 3, respectively. It is assumed that the traffic pattern in the model is unidirectional, which means that the PEVs enter the micro MES directly to PL or HC and do not have travels within the micro MES. The problem is modeled as a mixed integer linear programming (MILP) problem and is implemented in GAMS utilizing the CPLEX12 solver.

In this paper, three case studies are designed for studying the proposed model and examining its efficiency:

- Case I, where only the PL is added to the model;
- Case II, where only HC stations are available in the model and no PL is provided;
- Case III, where both PL and HC are added to the model and a traffic flow between these two elements is considered.

1) *Case I: micro MES with PL and no HC*

In this case, the only charging possibility for the PEVs in the system is the PL. It is assumed that the PEVs enter the PL based on the pattern in Fig. 2 and based on [14]. The electricity balance for the micro MES in this case is illustrated in Fig. 4. As it is shown, the PL charges the PEVs mainly on their arrival (hours 8-10) and before their departure (hours 17-20). However, the PL does not participate in the energy interaction and its strategy is to make profit through reserve participation with its SOC. On the other hand, the CHP can sell the excess of its production to the upstream network.

2) *Case II: micro MES with HC on MED and no PL*

In this case, the impact of HC on the MED and electric demand is investigated. The result for the electricity balance of the MED is shown in Fig. 5.

The electric demand is increased significantly due to the PEVs' charging requirements and this increase in the demand follows the traffic pattern of the PEVs' arrival to or departure from the HC stations.

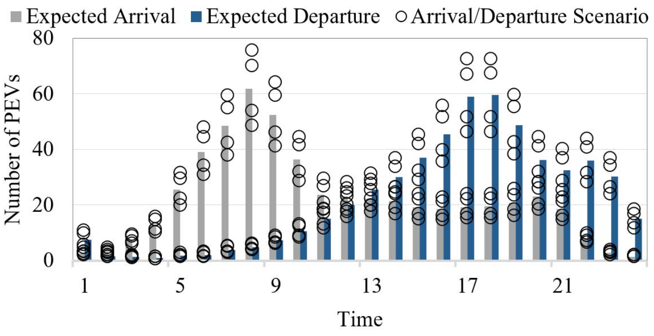

Figure 2. The PEVs' arrival/departure pattern to/from PL.

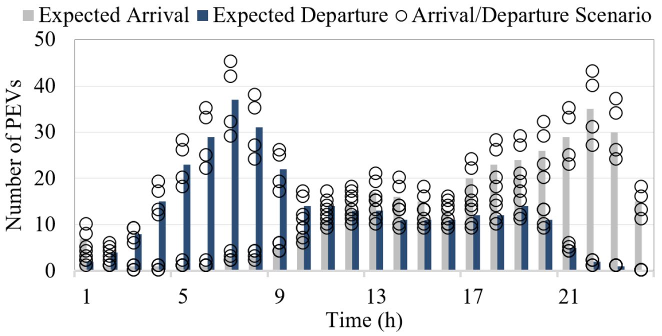

Figure 3. The PEVs' arrival/departure pattern to/from HC.

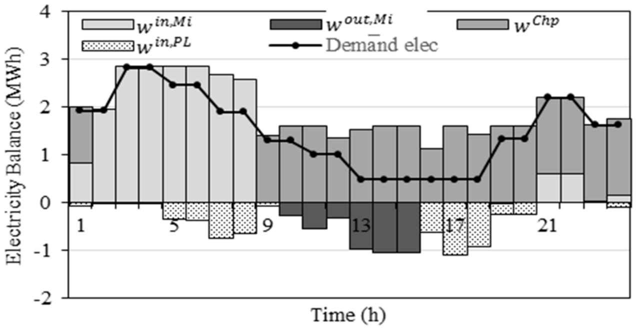

Figure 4. Electricity balance in micro MES components in case I.

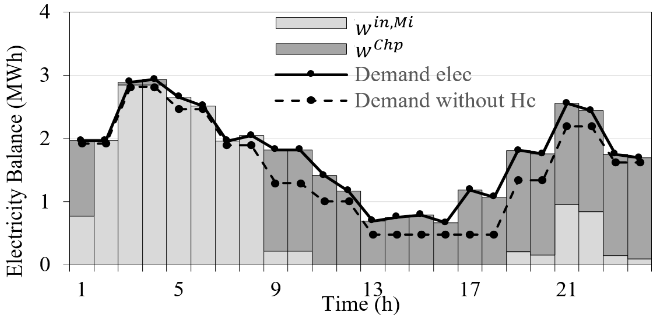

Figure 5. Electricity balance in micro MES components in case II.

3) *Case III: micro MES with PL and HC*

In this case, both PL and HC are added to the model and a traffic flow between these two elements is considered to occur. It is assumed that a certain percentage (α %) of the PEVs that depart from the PL enters the HC and the rest of the PEVs will not be plugged-in while they are not in the PL. The results for the electricity balance of the micro MES for α=80% is shown in Fig. 6. Here, the input of the HC is shown separately from the electric demand for better comparison of the PL and HC behavior. As it is shown, in this case both PL and HC benefit from participating in reserve market rather than the energy market. The reason is that in this situation they can make a profit from both selling the power to the PEVs as well as receiving the income from participating in the reserve market.

The comparison of costs in the three cases and the base case, where no PL or HC exist, is presented in Table I. The reserve profit is the profit gained by the MES operator through taking part in the reserve market with the SOC of the PEVs (whether in PL or HC). The PEV profit is the profit gained through selling energy to the PEV owners for charging their batteries. It can be deduced that the least cost operation of the system can be achieved in Case III where both HC and PL are available. In this situation, not only the preferences of the PEVs and their charging requirements can be fulfilled, but also a better scheme for operation of multi-energy resources can be obtained. It also proves that the profit from the available reserve in the PL and HC can be beneficial enough to reduce the costs imposed by the added load of the PEVs in the MES.

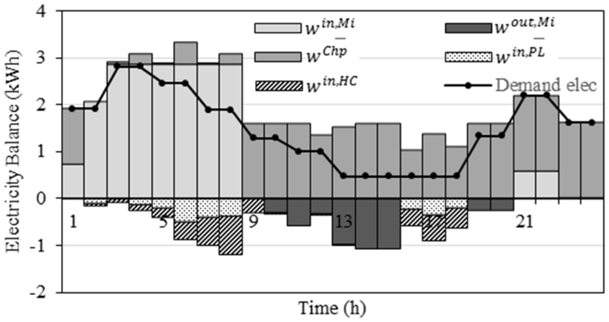

Figure 6. Electricity balance in micro MES components in case III.

TABLE I. COST-PROFIT ANALYSIS IN THREE CASES

	Base Case	Case I	Case II	Case III
Reserve Profit		454.51	285.75	744.46
PEV Profit		324.55	298.07	341.53
Utility Cost	-3479.3	-3768.06	-3765.02	-3787.93
Total	-3479.3	-2988.96	-3181.19	-2701.93

V. CONCLUSION

This paper has proposed a model for the integration of the PEVs traffic pattern in the matrix modeling of the MES. In this regard, two charging options within the MES environment have been considered for the PEVs: the PL and HC. The results demonstrated the effect of the charge needs of the PEVs on the electric demand as well as the effects that it can have on the operation of the micro MES components. It can be concluded that with the availability of the PL and HC, the inevitable added load of PEVs in the future system can be best managed using the internal resources of the MES, such as CHP unit. This will not only lead to the satisfaction of PEV owners, but also will provide the MES operator with higher levels of profit due to better manipulation of MES resources.

ACKNOWLEDGMENT

This work was supported by FEDER funds (EU) through COMPETE, by Portuguese funds through FCT, under Projects FCOMP-01-0124-FEDER-020282 (Ref. PTDC/EEA-EEL/118519/2010) and UID/CEC/50021/2013, and by funds from the EU 7th Framework Programme FP7/2007-2013 under grant agreement no. 309048.

REFERENCES

[1] M. D. Galus and G. Andersson, "Power System Considerations of Plug-In Hybrid Electric Vehicles based on a Multi Energy Carrier Model," in *Proc. IEEE Power & Energy Society General Meeting*, 2009.

[2] M. D. Galus and G. Andersson, "Integration of Plug-In Hybrid Electric Vehicles into Energy Networks," in *Proc. IEEE PowerTech*, Bucharest, 2009.

[3] M. Rastegar and M. Fotuhi-Firuzabad, "Optimal charge scheduling of PHEV in a multi-carrier energy home," in *Proc. 14th International Conference on Environment and Electrical Engineering (EEEIC)*, pp. 199-203, 2014.

[4] M. D. Galus and G. Anderson, "Demand Management of Grid Connected Plug-In Hybrid Electric Vehicles (PHEV)," in *Proc. 2008 IEEE Atlanta Energy 2030 Conf.,* pp. 1-8.

[5] D. Papadaskalopoulos, G. Strbac, P. Mancarella, M. Aunedi, and V. Stanojevic, "Decentralized Participation of Flexible Demand in Electricity Markets—Part II: Application With Electric Vehicles and Heat Pump Systems", *IEEE Trans. Power Syst.*, vol. 28, pp. 3667–3674, 2013.

[6] M. Moeini-Aghtaei, A. Abbaspour, M. Fotuhi-Firuzabad, and P. Dehghanian, "Optimized Probabilistic PHEVs Demand Management in the Context of Energy Hubs," *IEEE Trans. Power Del.* Vol. 30, No. 2, pp. 996-1006, Apr. 2015.

[7] M. R. Haghifam, S. Pazouki, and S. Pazouki, "Renewables and Plug in Electric Vehicles Modeling on Electricity and Gas Infrastructures Scheduling in Presence of Responsive Demand," in *Proc. 3rd International Conference on electric Power and Energy Conversion Systems (EPECS)*, 2013.

[8] M. Shulze and J. Zapata Riveros, "Impact of Electrical Vehicles on Strategic Planning of Energy Infrastructure", in Proc. International conf. Power System Technology, *POWERCON 2010*, pp.1-6.

[9] W. Kempton and S. E. Letendre, "Electric vehicles as a new power source for electric utilities," *Transportation Research Part D. Transport and Environment*, vol. 2, pp. 157-175, Sep. 1997.

[10] M. Arnold and G. Andersson, "Decomposed electricity and natural gas optimal power flow," in *Proc. 16th Power Systems Computation Conference (PSCC 08),* Glasgow, Scotland, 2008.

[11] F. Kienzle and G. Andersson, "A greenfield approach to the future supply of multiple energy carriers," in *Proc. IEEE Power & Energy Society General Meeting (PES'09),* Calgary, Jul. 2009, pp. 1-8.

[12] 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.

[13] N. Neyestani, M. Yazdani damavandi, M.R. Shafie-khah, G. Chicco, and J.P.S. Catalao, "Stochastic Modeling of Multienergy Carriers Dependencies in Smart Local Networks With Distributed Energy Resources," *IEEE Trans. Smart Grid*, vol. 6, no. 4, pp. 1748-1762, July 2015.

[14] N. Neyestani, M. Yazdani damavandi, and J.P.S. Catalao, "Modeling the PEV Traffic Pattern in an Urban Environment with Parking Lots and Charging Stations," in Proc. of the IEEE PowerTech 2015 Conference, Eindhoven, Netherlands, 29 June - 2 July, 2015.