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Distributed energy resources management using plug-in hybrid electric vehicles as a fuel-shifting demand response resource

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ABSTRACT

In the smart grids context, distributed energy resources management plays an important role in the power systems' operation. Battery electric vehicles and plug-in hybrid electric vehicles should be important resources in the future distribution networks operation. Therefore, it is important to develop adequate methodologies to schedule the electric vehicles' charge and discharge processes, avoiding network congestions and providing ancillary services.

This paper proposes the participation of plug-in hybrid electric vehicles in fuel shifting demand response programs. Two services are proposed, namely the fuel shifting and the fuel discharging. The fuel shifting program consists in replacing the electric energy by fossil fuels in plug-in hybrid electric vehicles daily trips, and the fuel discharge program consists in use of their internal combustion engine to generate electricity injecting into the network. These programs are included in an energy resources management algorithm which integrates the management of other resources. The paper presents a case study considering a 37-bus distribution network with 25 distributed generators, 1908 consumers, and 2430 plug-in vehicles. Two scenarios are tested, namely a scenario with high photovoltaic generation, and a scenario without photovoltaic generation. A sensitivity analyses is performed in order to evaluate when each energy resource is required.

1. Introduction

The intensive use of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) will become reality in the near future [1]. The high prices of fossil fuels and the environmental concerns lead to new opportunities to increase BEVs and PHEVs penetration [2]. However, the intensive use of these types of vehicles introduces several changes in the power systems operation, mainly in distribution networks [3]. Additionally, other distributed resources, such as distributed generation (DG) and demand response (DR) will increase their penetration. To ensure the security and reliability of future power systems it is necessary to develop new approaches and methodologies for the distribution network management and operation.

Concerning the demand response programs, several programs have been proposed and used mostly in the United States as described in [4] and in Australia as illustrated in [5]. The DR programs increase the network operation flexibility allowing preventing critical situations mainly in peak periods when the networks are operated nearby their boundaries [6]. The use of DR events is a powerful resource to the system operators, but it also provides additional incomes (or energy bill reduction) from the consumer's point of view [7].

Most of the proposed DR programs are developed taking into account the characteristics of a specific target of "traditional" consumers like the industries, the commercial consumers or the domestic consumers [6]. Regarding the participation of electric vehicles (EVs) in DR programs, some developments have been made considering the participation of EVs in the existing DR programs. In [8] is proposed the inclusion of EVs in the participation of domestic consumers in DR programs and [9] evaluates the impact of price signals DR, namely the *time of use* and the *real time pricing*, in the EVs charging process. More focus in the system operator point of view, [10] analyses the EVs participation in a load shaping demand response strategy to avoid the power transformers congestion. However, in a near future, will be necessary the development of new programs specifically designed to the EVs due to the high flexibility provided by these resources. In this sense, this paper has three main contributions:

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Nomenclature

Parameters

Δt	duration of period t, e.g. 30 min corresponds to $\Delta t = 0.5$
η_c	energy efficiency in charge mode
η_d	energy efficiency in discharge mode
η_{Fuel}	efficiency in discharge mode considering the use of internal combustion engine of plug-in hybrid electric vehicle
B	imaginary part in admittance matrix (S)
c_A	fixed component of cost function (m.u./h)
c_B	linear component of cost function (m.u./kW h)
c_C	quadratic component of cost function (m.u./kW h^2)
c	resource cost in period t (m.u./kW h)
E	stored energy in the battery of vehicle at the end of period t (kW h)
$E_{Initial}$	energy stored in the battery of vehicle at the beginning of period 1 (kW h)
E_{Trip_Elec}	energy consumption during a trip in period t (kW h)
G	real part in admittance matrix (S)
L^i	set of lines connected to bus i
N	total number of resources or buses
R	ramp rate limit for the start-up or shut-down services
S_{Lk}^{max}	maximum apparent power flow in line k (kV A)
T	total number of periods
$\overline{U}$	voltage in polar form (V)
$\overline{y}$	series admittance of line that connects two buses (S)
$\overline{y_{sh}}$	shunt admittance of line that connects two buses (S)
z	total operation cost (m.u.)

Variables

θ	voltage angle
P	active power (kW)
Q	reactive power (kVAr)
S	apparent power (kVA)
V	voltage magnitude (V)
X	binary variable

Subscript

B	bus
BatCap	battery energy capacity
minCharge	minimum stored energy to be guaranteed at the end of period t
BEV	battery electric vehicle
Ch	charge process
ChMax	maximum charge power for the storage device
D	power demand at bus i
Dch	discharge process
Dch_Fuel	discharge process of the use of the internal combustion engine of plug-in hybrid electric vehicle
DchMax	maximum discharge power for the storage device
Deg	battery degradation
DG	distributed generation unit
DGMax	maximum power generation of *DG* unit
DGMin	minimum power generation of *DG* unit
DR_A	demand response program for loads with continuous regulation
DR_B	demand response program for loads with discrete regulation (on/off)
Fuel_Stored	storage energy in the fuel tank of plug-in hybrid electric vehicle
Fuel_Shift	reduction of the energy consumption with the trip in the plug-in hybrid electric vehicle
FuelThank_min	minimum quantity of fuel litters in the thank of plug-in hybrid electric vehicle
G	power generation at bus i
GCP	generation curtailment power
i , j	bus i and bus j
K	line
L, Load	load
MaxDR_A	maximum power of *DR* program for loads with continuous regulation
MaxDR_B	maximum power of *DR* program for loads with discrete regulation (on/off)
NSD	non-supplied demand
PHEV	plug-in hybrid electric vehicle
SD	shut-down
SEF	storage device (storage system, battery electric vehicle and plug-in hybrid electric vehicle)
SP	external supplier
SPMax	maximum power generation of external supplier
St	storage system
SU	start-up
Stored	stored energy in the battery of the storage device

Superscript

i	bus i
Max	upper bound limit
Min	lower bound limit

- Development of fuel shifting demand response programs applied to the PHEV. Fuel shifting DR means a replacement of the use of electric energy by the use of other fuel (diesel fuel or gasoline in the case of vehicles). The existence of an electric motor and an internal combustion engine (ICE) in the PHEV allows using different fuel sources to move the vehicle. In this case, the owners can connect the PHEVs to the electric network in order to charge their batteries to reduce the fossil fuel consumption. However, it is possible to reduce or to cut the energy charged in the PHEV without affecting significantly the users' comfort level. In fact, the PHEVs can only use the ICE, which would have as main disadvantages high cost and high greenhouse gas emissions. This way, the PHEVs should be remunerated according to the fuel shifting DR contract established with the system operator or with an aggregator. Another service that the PHEV can provide is the electric energy discharge from the ICE. This process is usually called vehicle-to-grid (V2G) and it considers the capability of charging the electric vehicles' batteries from the network and then, if required by the operator, discharging that stored energy in the batteries in the network. In the proposed methodology, the V2G concept is extended and the PHEV can use the ICE as a mechanical resource to generate electric energy into the battery, and then the battery will inject this generated energy into the power system. The use of this program should be avoided in covered car parks but can be used in the open ones;
- Integration of the proposed fuel shifting demand response programs in the energy resources management (ERM) algorithm used by the aggregator. The algorithm considers the management of a large set of distributed energy resources, namely DG based on several technologies, with and without "take-or-pay" contracts to avoid wind and solar generation curtailment; direct load control DR events considering discrete and continuous regulation loads; electric storage systems (ESSs), BEVs and PHEVs. Contracts with external suppliers are considered to balance the distribution network operation. The alternating

current (AC) power flow is included in the problem constraints and the management of reactive power by the aggregator in all generators is addressed;
- Analysis of the fuel shifting DR contribution to support the growing penetration of load and EVs. A sensitivity analysis is performed to evaluate the contribution of the proposed fuel shifting demand response programs for different values of EVs penetration and load consumption increase. The evaluation is made for two scenarios of photovoltaic generation.

This paper is organized as follows: after this introductory section, Section 2 presents an overview concerning demand response programs, plug-in hybrid electric vehicles, and energy resources management. Section 3 presents the proposed methodology regarding the inclusion plug-in hybrid electric vehicles in the fuel shifting demand response programs. Section 4 presents a case study considering the energy resources scheduling in two different scenarios. This section also includes a sensitivity analysis considering the increase of the consumers' demand and the increase of the electric vehicles and storage systems. The main conclusions of the paper are provided in Section 5.

2. Demand response, plug-in hybrid electric vehicles and energy resources management overview

The growing penetration of distributed energy resources connected to transmission and distribution power networks have been introducing new challenges in the power systems operation and management. The use of technologies based on natural sources turns the DG non-dispatchable and intermittent. Several solutions have been pointed as possible for the intermittent behavior of renewable sources. One of the most interesting solutions is to convert the passive consumers into active consumers through DR events in smart grids [7], in coordination with renewable resources to compensate their generation intermittencies [11] and in microgrids mainly when are operated in isolated mode [12]. Several types of DR programs have been proposed and some of them are used by different transmission system operators, such as the NYISO and PJM in the U.S.A. [4] or Transgrid in Australia [5]. One of the proposed DR programs is the fuel shifting demand response. This DR program consists in the capability of some loads to use other fuel sources instead of electricity. A simple example of this type of loads can be the combined heating systems composed of a cogeneration and an electric heat pump [13].

On the other hand, the increasing use of electric vehicles and mainly of PHEVs are changing the global demand behavior [14] imposing the rethinking of the "traditional" DR events in order to improve the integration of these new types of flexible demand (BEVs and the PHEVs). Due to their characteristics, PHEVs equipped with electric and internal combustion engines can participate in the fuel shifting demand response events.

In the following subsections an overview of three topics are presented, namely on the fuel shifting DR, BEVs and PHEVs technologies, and finally on the integration of BEVs and PHEVs into the energy resources management process.

2.1. Fuel shifting demand response

The use of demand response programs represents more flexibility in the power systems' planning and operation. Several DR programs have been proposed and implemented considering different objectives according to the system operators' requirements. The DR programs can be grouped into "price-based" demand response, like the time-of-use or the real-time pricing and in the "incentive-based" demand response, such as the direct load control, the interruptible/curtailable service or the emergency demand response programs, among others [6].

To participate in the demand response events, consumers can reduce the consumption by turning off non-priority equipments without affecting their comfort, for instance, turning off the lights in periods when the sun's light is enough to light up a room. The consumers can also participate in DR events by shifting the consumption of some equipments through an effective consumption scheduling method, or using onsite generation by turning on an onsite backup emergency generator [7]. However, the existence of the dual-fuel devices like the dual fuel chillers can introduce new types of demand response. In [15] this type of DR is called fuel shifting as is proposed in the present paper. In [16] the term fuel substitution is used to designate the substitution of the electricity by other type of source. Finally, in [13] is used the term energy shifting referring the use of different energy sources as primary resource. These types of programs can be classified as "incentive-based" programs.

Most of the previous studies focus on the dual fuel heating/cooling systems and the joint scheduling of gas and electricity devices. In [17] the combined use of cogeneration and electric heat pumps are studied, being the system tested under a real-time pricing demand response programs in [18]. In [19] the joint optimization of gas and electricity devices (loads and generators) is studied, and in [20] a more general overview concerning the importance of the natural gas in the smart grids is specified. In all these studies, the conclusion is that the flexible dual fuel loads, like the cogeneration based in natural gas combined with controllable electric heat pumps, can support the operation of the future smart grids based on renewable, non-dispatchable, and intermittent generation sources.

2.2. Battery electric vehicles and plug-in hybrid electric vehicles

Electric vehicles can be divided into three main categories depending on the type of on-board energy source [21]: battery electric vehicle, plug-in hybrid electric vehicle, and fuel cell vehicle. The battery electric vehicle and plug-in hybrid electric vehicles are currently in the commercial phase, whereas the fuel cell electric vehicles are in the prototype phase. In this sense, in the present study, the fuel cell electric vehicles are not considered.

The BEVs use batteries as their main power source. However, some BEVs use extra systems to support the batteries, such as the ultracapacitor [22]. The BEV power electronics system ensures the coordination between the motor and batteries controls [23], e.g. the energy flows (motor/batteries) in accelerating and breaking processes, and also the coordination of charge and discharge process of batteries when the BEV is connected to the power network.

Hybrid electric vehicles (HEVs) use two or more energy supplies/sources to propel the vehicle, being one of these sources an electrical energy engine [24]. The HEV has the goal of achieving consumptions and CO_2 emissions lower than conventional vehicles. The concept of PHEV emerges when a HEV model is developed with the capability of connecting it to the electric network. PHEV can also be designed by extended range electric vehicles (EREVs) depending on the power of electric motor and the capacity of the batteries. The EREVs are equipped with a full-sized electric motor allowing the use of this motor in a general use. The internal combustion engine is only used if the battery level is less than a specified limit [21].

2.3. Energy resources management considering electric vehicles and plug-in hybrid electric vehicles

The BEVs and PHEVs are a timely research topic and several PHEV functioning aspects are addressed in [25]. Several authors analyze the impact of BEVs and PHEVs in real power systems. As example, Hajian et al. [26] and Waddell et al. [27] present an analysis of the environmental benefits of PHEVs in the states of Alberta and Manitoba in Canada. In [28,29] are presented the studies concerning the PHEVs impact in two European countries, namely Germany and Sweden, respectively. In a broader perspective, Blumsack et al. [30] evaluate the impact of PHEV in coal-intensive regions and the impact of PHEV in peak hours.

The integration of EVs and PHEVs in the network is discussed in [31], and a real-time PHEV control methodology to manage the coordination between the batteries and ultracapacitor charge/discharge is proposed in [32].

Regarding the EVs and PHEVs charge and discharge scheduling several methodologies have been proposed recently. Wu et al. [33] show the need of using adequate BEVs charge management methods and proposes three management scenarios (Uncontrolled charging, Simple-delayed charging and Modified delayed charging). In the same way, in [34] it is proposed the use of the particle swarm optimization technique to optimize the BEVs charge/discharge management considering the costs and the greenhouse gas emissions reduction; in [35] it is presented an hourly coordination between wind power generation and the BEV charge/discharge control strategy; and in [36] the coordination of BEVs charge and discharge considering the operation costs and load diagram levelling is shown. Momber et al. [37] proposes the inclusion of PHEVs in building energy management systems and the advantages of this method is discussed; in [38] is proposed the management of PHEVs in parking lots; and in [39] the impact of the EVs and PHEVs charge control in active small consumers DR events participation is analyzed.

3. Energy resources management considering the participation of the plug-in hybrid electric vehicles in the energy resources scheduling problem

To address the growing penetration of distributed energy resources several types of aggregators have been proposed in the literature. The virtual power plants are proposed in [40] considering the aggregation of several distributed generation units. In [41] is proposed the virtual power player (VPP) aggregating several types of resources but more focus in a commercial perspective. The curtailment service providers are proposed in [42] to aggregated active consumers allowing their participation in DR events. Finally, the fleet operators are proposed in [43] aggregating electric vehicles with main goal to coordinate the charge and discharge processes. Each aggregator has different characteristics and a lot of similarities at the same time. In the present study, the considered aggregator has the ability of managing all the distributed energy resources connected in a medium voltage distribution network. The network management is made by the distribution system operator. However, the aggregator has information concerning network characteristics and the operation limits of the distribution network in order to include the technical constraints in the resources optimization process. The proposed methodology allows the aggregator to manage different energy resources such as DGs, ESSs, BEVs, PHEVs, DR events including the interruptible/curtailable (I/C) service, and the fuel shifting in the PHEV. Fig. 1 presents the considered aggregator approach.

Regarding the PHEVs management, two new services are proposed – the fuel shifting in the daily trips and the discharge energy to the network using the battery through the generation of energy from the ICE.

In PHEVs, the fuel shifting DR program tries to stimulate the total or partial replacement of the battery by the ICE in the daily trips, which means replacing the electric energy by fuel energy (diesel fuel or gasoline) to support the vehicle trips. In PHEVs, the users should define the amount of energy required to support the trips during the scheduling period (typically one day). If the aggregator does not guarantee the energy required by the user, then it will always have the possibility to travel with the vehicle using the ICE. Under these circumstances, the use of ICE will involve a higher cost to the user than just using the battery. This way, the aggregator should compensate the PHEVs users to the fuel shifting from the battery to the ICE. On the other hand, the energy

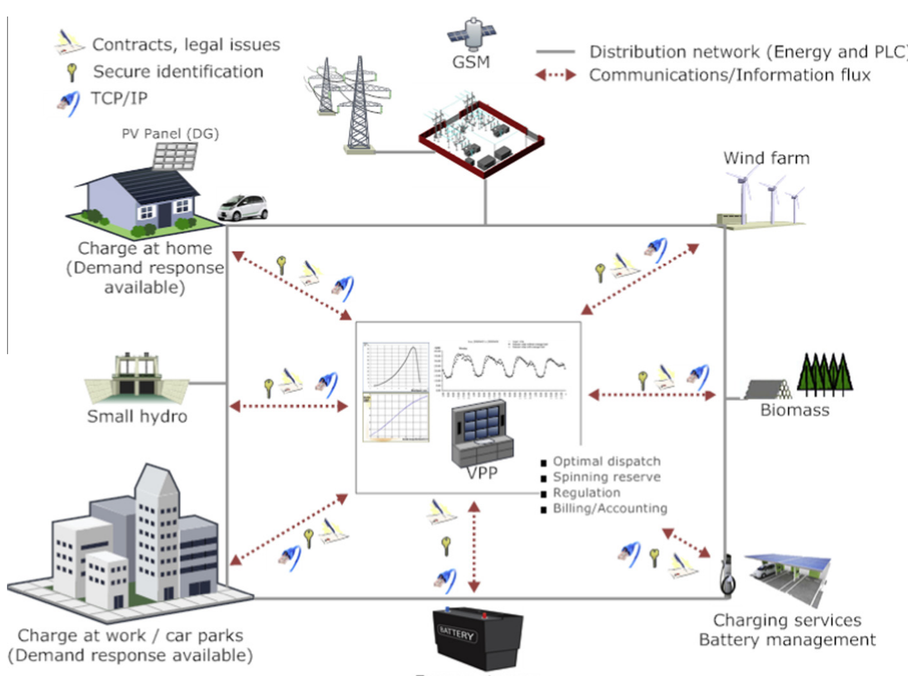

Fig. 1. VPP's interaction in a smart grid environment (adapted from [47]).

required in the BEV users is a hard constraint for the aggregator, because if the battery did not have the energy required, the user cannot travel with the vehicle.

PHEVs discharging energy service is usually designed by V2G [44]. The V2G consists in the energy discharging process from the batteries equipped in the PHEV models to the network. The discharged energy is stored in the batteries requiring a previous charge process. In the present methodology, this concept is extended considering the possibility of discharging energy through the use of the ICE to supply the mechanical energy to the electric motor, converting this motor in a generator. Then, the generator will supply the battery to inject the energy into the network. This means that the PHEVs can act as an emergency backup generator. The use of ICE as a generator is expensive and it has several constraints in its use due to the emissions, mainly in covered parking lots. However, the use of this service does not imply more technology and investments than the "traditional" V2G.

Fig. 2 is adapted from [24] and illustrates the different types of operation for HEV and PHEV. The "combined mode" joins the power from the ICE and from the electric motor providing energy for the transmission system and wheels of the vehicle (represented as the Power Train block in the Fig. 2). The "braking mode" uses the energy from braking to charge the battery. In the parking mode, the "recharge mode" charges the batteries through the electric network or through the ICE and the "V2G mode" injects energy into the power network, discharging the energy stored in the batteries. In the present case the system cannot discharge energy directly from the ICE to the electric network. However, in the present methodology it is considered that all the energy produced through the ICE is discharged in the network when the vehicle is parked.

The proposed methodology aims to minimize the operation cost of an aggregator player, considering its energy resources constraints and the contracts established with each player, including the participation of PHEVs in fuel shifting demand response programs. The proposed problem is formulated as a mixed integer non-linear programming (MINLP) problem and it is implemented on generic algebraic modeling system (GAMS) software [45]. GAMS include a large set of powerful solvers. In the proposed problem, the discrete and continuous optimizer (DICOPT) solver is used [46]. DICOPT split the MINLP in two sub-problems – non-linear programming (NLP) problem and mixed-integer programming (MIP) problems. DICOPT use three main principles to solve and coordinate the MIP and NLP solutions: 'Outer approximation', 'Equality relaxation' and 'augmented penalty'. Basically, the DICOPT create relaxed problems to be solved by MIP and NLP, trying to penalize the obtained solutions and decrease the relaxations until the stop criterion be achieved. To solve the sub-problems, DICOPT uses other solvers in GAMS. In the proposed method, the CONOPT is used to solve the NLP sub-problems and the CPLEX is used to solve the MIP problems. The main challenge to solve the MINLP is to avoid the local optima solutions. Although the DICOPT has provision to handle non-convexities, the algorithm does not necessarily obtain the global optimum solution. However, several scenarios were implemented by the authors in energy resources scheduling problems with good results namely in [36] to optimize the multi-objective function considering the operation cost and levelling the power demand curve, in [47] to optimize the electric vehicles charging considering the distribution network constraints, in [48] to evaluate the performance of a hybrid meta-heuristic technique, an in [49] to optimize the energy resources scheduling in an isolated network.

3.1. Objective function

The total operation cost Zrepresents the objective function of the proposed methodology. The operation cost of the DG units is

$$
\min Z = \sum_{t=1}^{T}\left[\begin{array}{l}
\sum\limits_{DG=1}^{N_{DG}}\left(\begin{array}{l} c_{A(DG,t)} \times X_{DG(DG,t)} + c_{B(DG,t)} \times P_{DG(DG,t)} + c_{C(DG,t)} \times P^2_{DG(DG,t)} \\ + c_{SU(DG,t)} \times (1 - X_{DG(DG,t-1)}) \times X_{DG(DG,t)} + c_{SD(DG,t)} \times (1 - X_{DG(DG,t)}) \times X_{DG(DG,t-1)} \\ + c_{GCP(DG,t)} \times P_{GCP(DG,t)} \end{array}\right) + \\
\sum\limits_{SP=1}^{N_{SP}} c_{SP(SP,t)} \times P_{SP(SP,t)} + \sum\limits_{St=1}^{N_{St}}((c_{Dch(St,t)} + c_{Deg(St)}) \times P_{Dch(St,t)} - c_{Ch(St,t)} \times P_{Ch(St,t)}) + \\
\sum\limits_{BEV=1}^{N_{BEV}}((c_{Dch(BEV,t)} + c_{Deg(BEV)}) \times P_{Dch(BEV,t)} - c_{Ch(BEV,t)} \times P_{Ch(BEV,t)}) + \\
\sum\limits_{PHEV=1}^{N_{PHEV}}\left(\begin{array}{l} (c_{Dch(PHEV,t)} + c_{Deg(PHEV)}) \times P_{Dch(PHEV,t)} - c_{Ch(PHEV,t)} \times P_{Ch(PHEV,t)} + \\ c_{Dch\_Fuel(PHEV,t)} \times P_{Dch\_Fuel(PHEV,t)} + c_{Fuel\_Shift(PHEV,t)} \times E_{Fuel\_Shift(PHEV,t)} \end{array}\right) + \\
\sum\limits_{L=1}^{N_L}(c_{DR\_A(L,t)} \times P_{DR\_A(L,t)} + c_{DR\_B(L,t)} \times P_{DR\_B(L,t)} + c_{NSD(L,t)} \times P_{NSD(L,t)})
\end{array}\right] \quad (1)
$$

formulated in a quadratic function ($c_{A(DG,t)}$, $c_{B(DG,t)}$ and $c_{C(DG,t)}$), the start-up ($c_{SU(DG,t)}$) and shut-down ($c_{SD(DG,t)}$) are also considered. The generation curtailment power (GCP) of the DG units is also considered in the total operation cost with the purpose of enabling the proposed methodology to deal with emergency situations from high generation power of renewable sources. The total cost considers the VPP's cost with the acquisition of energy from external suppliers ($c_{SP(SP,t)}$) which can be retailers, bilateral contracts, electricity pools and other VPPs located outside the VPP's distribution network. Additionally, the operation cost with the electric storage systems is considered in the proposed methodology, which formulates the payments with discharge of energy ($c_{Dch(St,t)}$) and the incomes with charge of energy ($c_{Ch(St,t)}$). The costs concerning the batteries degradation during the charge and discharge cycles are included in the discharge prices ($c_{Deg(St,t)}$), considering the studies presented in [50] regarding the EVs batteries degradation and the economical analysis presented in [51]. The BEV users are formulated with the same kind of expression that is used for the electric storage systems. Regarding the costs with PHEV, there are the payments with discharge of energy from the battery, the incomes with charge of energy from the battery, and the fuel shifting DR programs. These DR programs consider the costs regarding the replacement of the use of the energy provided by the electric engine to the one provided by the ICE ($c_{Fuel\_Shift(PHEV,t)}$) and the use of the ICE to discharge power to the network ($c_{Dch\_Fuel(PHEV,t)}$). Finally, it is also included the costs with active consumers, namely with direct load

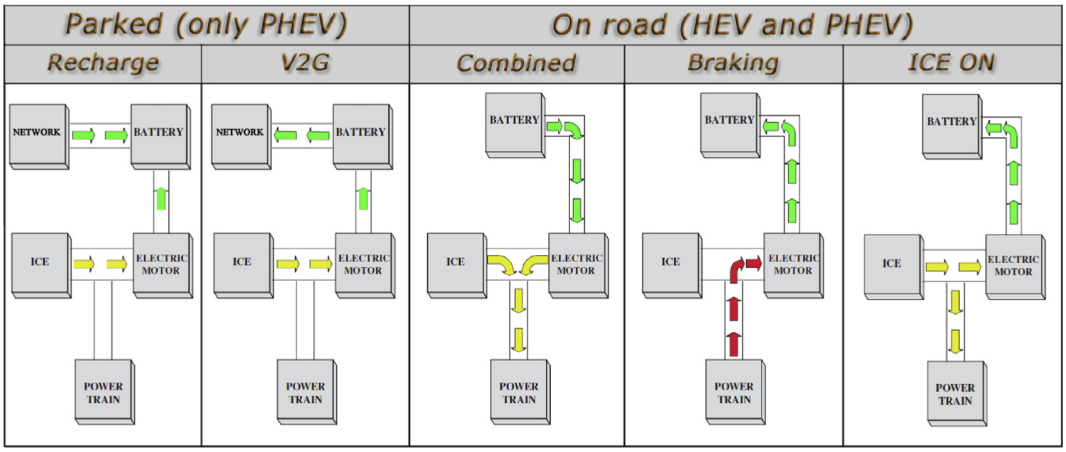

Fig. 2. The conceptual design modes of an HEV/PHEV (adapted from [24]).

control DR events in continuous ($c_{DR\_A(L,t)}$) and discrete loads ($c_{DR\_B(L,t)}$), and the cost with non-supplied demand in critical loads ($c_{NSD(L,t)}$).

3.2. Network constraints

The network constraints are introduced in the proposed approach with the goal of model the network and translating its influence into the optimal resource scheduling. The optimal resource scheduling should use an accurate AC power flow modeling the network in order to achieve a scheduling solution that is feasible in practice. The model must consider the active/reactive power losses in each network line, and verify if the power flow in the line is higher than their thermal limits. The network balance represents the hardest constraints in the problem due to the high mathematical complexity of the used expressions and the high number of variables involved.

For this purpose, during the optimization process, an AC power flow [52] is executed to determine the power flow and power loss in each line. The active power balance

$$P^i_{G(t)} - P^i_{D(t)} = V^2_{i(t)} \times G_{ii} + V_{i(t)} \times \sum_{j \in L^i} V_{j(t)} G_{ij} \cos(\theta_{i(t)} - \theta_{j(t)}) + B_{ij} \sin(\theta_{i(t)} - \theta_{j(t)}) \quad (2)$$

and reactive power balance

$$Q^i_{G(t)} - Q^i_{D(t)} = V_{i(t)} \times \sum_{j \in L^i} V_{j(t)} G_{ij} \sin(\theta_{i(t)} - \theta_{j(t)}) - B_{ij} \cos(\theta_{i(t)} - \theta_{j(t)}) - V^2_{i(t)} \times B_{ii} \quad (3)$$

translates the application of the Kirchhoff's current law (or node rule) [52] in each bus. The power injected in bus i is defined as the sum of the power flow through the lines that connect bus i to other buses, or to the ground. The injected power is equal to the power generation minus the power demand in each bus [52]. The active power generation

$$P^i_{G(t)} = \sum_{DG=1}^{N^i_{DG}} (P^i_{DG(DG,t)} - P^i_{GCP(DG,t)}) + \sum_{SP=1}^{N^i_{SP}} P^i_{SP(SP,t)} + \sum_{St=1}^{N^i_{St}} P^i_{Dch(St,t)} + \sum_{BEV=1}^{N^i_{BEV}} P^i_{Dch(BEV,t)} + \sum_{PHEV=1}^{N^i_{PHEV}} (P^i_{Dch(PHEV,t)} + P^i_{Dch\_Fuel(PHEV,t)}) \quad (4)$$

is equal to the sum of DG generation power, external supplier power, storage system discharge power, BEV discharge power, and PHEV discharge power from battery or from ICE in each bus. The active power demand

$$P^i_{D(t)} = \sum_{L=1}^{N^i_L} (P^i_{Load(L,t)} - P^i_{DR\_A(L,t)} - P^i_{DR\_B(L,t)} - P^i_{NSD(L,t)}) + \sum_{St=1}^{N^i_{St}} P^i_{Ch(St,t)} + \sum_{BEV=1}^{N^i_{BEV}} P^i_{Ch(BEV,t)} + \sum_{PHEV=1}^{N^i_{PHEV}} P^i_{Ch(PHEV,t)}$$
$$\forall t \in \{1, \ldots, T\};\ \forall i \in \{1, \ldots, N_B\} \quad (5)$$

is represented by the sum of consumer power, minus the demand response reduction, minus the non-supplied load power, storage system charge power, BEV charge power and PHEV charge power in each bus. The reactive generation power

$$Q^i_{G(t)} = \sum_{DG=1}^{N^i_{DG}} Q^i_{DG(DG,t)} + \sum_{SP=1}^{N^i_{SP}} Q^i_{SP(SP,t)} \quad (6)$$

is the sum of DG generation power and external supplier power in each bus. The reactive demand power

$$Q^i_{D(t)} = \sum_{L=1}^{N^i_L} Q^i_{Load(L,t)} - Q^i_{DR\_A(L,t)} - Q^i_{DR\_B(L,t)} - Q^i_{NSD(L,t)}$$
$$\forall t \in \{1, \ldots, T\};\ \forall i \in \{1, \ldots, N_B\} \quad (7)$$

can be obtained by the sum of reactive power consumption, minus the demand response reduction, and minus the non-supplied load power in each bus.

These equations influence the performance of the optimization problem and they are used to define the search space allowing imposing precise technical operation limits, namely for bus voltages magnitude and line thermal limits. Therefore, this will result in a solution for the optimal power flow according to the problem objective function.

In this AC power flow model, the voltage magnitude and angle are considered as influent variables to the calculation of the power flow in each line. The maximum and minimum limits for the voltage magnitude

$$V^{min}_i \leqslant V_{i(t)} \leqslant V^{max}_i; \quad \forall t \in \{1, \ldots, T\};\ \forall i \in \{1, \ldots, N_B\} \quad (8)$$

and voltage angle

$$\theta^{min}_i \leqslant \theta_{i(t)} \leqslant \theta^{max}_i; \quad \forall t \in \{1, \ldots, T\};\ \forall i \in \{1, \ldots, N_B\} \quad (9)$$

are verified for each bus of the network.

A slack bus is previously selected in the network, and fixed voltage magnitude and angle are specified for it. As mentioned before, the line power flows must be determined, so they can be compared to the thermal limit of each line.

$$\left| \overline{U_{i(t)}} \times \left[\overline{y_{ij}} \times \left(\overline{U_{i(t)}} - \overline{U_{j(t)}} \right) + \overline{y_{sh\_i}} \times \overline{U_{i(t)}} \right]^* \right| \leqslant S_{Lk}^{max}$$
$$\forall t \in \{1, \ldots, T\};\ \forall i,j \in \{1, \ldots, N_B\};\ i \neq j;\ \forall k \in \{1, \ldots, N_K\} \quad (10)$$

3.3. Distributed generation constraints

The constraints concerning the maximum capacity of distributed generation with “take-or-pay” contracts

$$P_{DG(DG,t)} = P_{DGMax(DG,t)} - P_{GCP(DG,t)}$$
$$\forall t \in \{1, \ldots, T\};\ \forall DG \in \{1, \ldots, N_{DG}\} \text{ With ''take or pay'' contract} \quad (11)$$

and without “take-or-pay” contracts

$$P_{DGMin(DG,t)} \times X_{DG(DG,t)} \leqslant P_{DG(DG,t)} \leqslant P_{DGMax(DG,t)} \times X_{DG(DG,t)}$$
$$\forall t \in \{1, \ldots, T\};\ \forall DG \in \{1, \ldots, N_{DG}\} \text{ Without ''take or pay'' contract} \quad (12)$$

represent the contractual constraints regarding the active power supplied by the DG. The reactive power constraint

$$Q_{DGMin(DG,t)} \times X_{DG(DG,t)} \leqslant Q_{DG(DG,t)} \leqslant Q_{DGMax(DG,t)} \times X_{DG(DG,t)}$$
$$\forall t \in \{1, \ldots, T\};\ \forall DG \in \{1, \ldots, N_{DG}\} \quad (13)$$

is similar for producers with and without “take or pay” contracts. Additionally, to take into account the technical behavior of some technologies, start-up limit

$$P_{DG(DG,t)} - P_{DG(DG,t-1)} \leqslant R_{SU(DG)} \quad \forall t \in \{1, \ldots, T\};\ \forall DG \in \{1, \ldots, N_{DG}\} \quad (14)$$

and the shut-down limit

$$P_{DG(DG,t-1)} - P_{DG(DG,t)} \leqslant R_{SD(DG)} \quad \forall t \in \{1, \ldots, T\};\ \forall DG \in \{1, \ldots, N_{DG}\} \quad (15)$$

constraints are introduced based in the equations proposed in [53].

3.4. External supplier constraints

In order to model the energy supply contracts with the external entities it is necessary to limit the active power

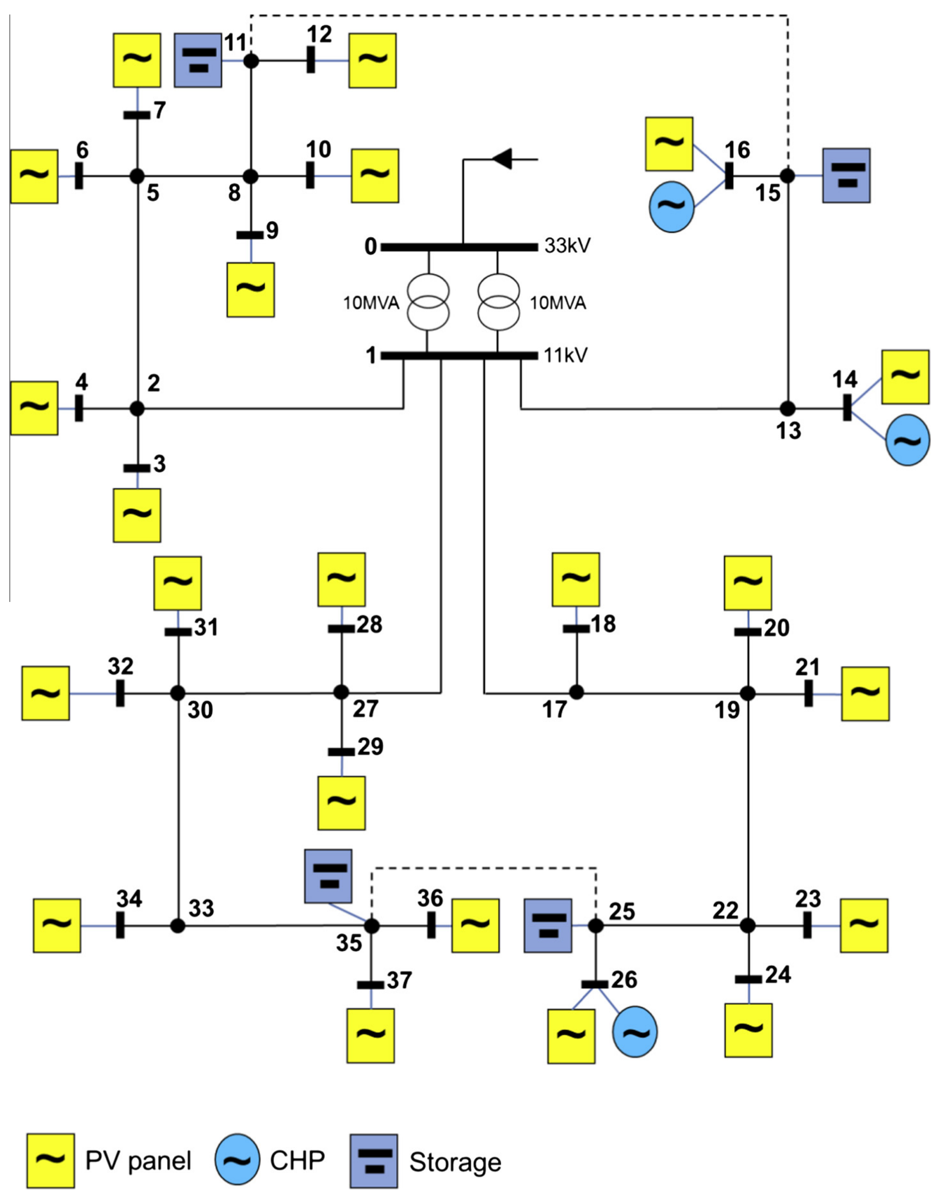

Fig. 3. 37-Bus distribution network (adapted from [54]).

Table 1
Energy resources characteristics and cost.

Technology		Number of units	Total installed power	Total installed capacity	Cost Scheme (m.u./kW h)		
					Max.	Mean	Min.
PV panel		22	7.74 (MWp)	–	–	0.0800	–
CHP		3	1.5 (MVA)	–	0.0300	0.0200	0.0100
External suppliers		2	10 (MVA)	–	0.0868	0.0666	0.0485
DR	Curtailment	22	0.45 (MW)	–	–	0.2000	–
	Reduction	22	0.65 (MW)	–	–	0.1500	–
ESS		4	–	1 (MW h)	0.0650	0.0613	0.0550
BEV + PHEV		2430	–	25 (MW h)	0.0650	0.0497	0.0400

Table 2
Consumers characteristics.

Load	Bus	P_{min} (kW)	P_{max} (kW)	P_{avg} (kW)	Q/P	Type of consumer	Profile of consumer
1	3	324.2	866.8	551.8	0.3	210 DM	1
2	4	324.2	866.8	551.8	0.3	210 DM	2
3	6	324.2	866.8	551.8	0.3	210 DM	3
4	7	342.9	916.7	583.5	0.3	1 SB	1
5	9	342.9	916.7	583.5	0.3	1 SB	4
6	10	280.6	750.0	477.4	0.3	10 Co	5
7	12	280.6	750.0	477.4	0.3	10 Co	1
8	14	609.0	1627.9	1036.3	0.3	1 In	2
9	16	700.3	1872.1	1191.7	0.3	1 In	5
10	18	324.2	866.8	551.8	0.3	210 DM	4
11	20	324.2	866.8	551.8	0.3	210 DM	3
12	21	272.7	729.1	464.1	0.3	200 DM	1
13	23	342.9	916.7	583.5	0.3	1 SB	5
14	24	342.9	916.7	583.5	0.3	1 SB	4
15	26	280.6	750.0	477.4	0.3	10 Co	1
16	28	280.6	750.0	477.4	0.3	10 Co	2
17	29	272.7	729.1	464.1	0.3	200 DM	3
18	31	272.7	729.1	464.1	0.3	200 DM	1
19	32	272.7	729.1	464.1	0.3	200 DM	5
20	34	342.9	916.7	583.5	0.3	1 SB	3
21	36	342.9	916.7	583.5	0.3	1 SB	2
22	37	280.6	750.0	477.4	0.3	10 Co	1

$$P_{SP(SP,t)} \leqslant P_{SPMax(SP,t)} \quad \forall t \in \{1,\ldots,T\};\ \forall SP \in \{1,\ldots,N_{SP}\} \tag{16}$$

and reactive power

$$Q_{SP(SP,t)} \leqslant Q_{SPMax(SP,t)} \quad \forall t \in \{1,\ldots,T\};\ \forall SP \in \{1,\ldots,N_{SP}\} \tag{17}$$

established in the contract between the VPP and the external suppliers.

3.5. Plug-in hybrid electric vehicles constraints

The constraints used to the PHEVs can also be used for BEVs and for ESSs with small changes. The amount of energy stored at the end of period t for the three types of energy storage devices (ESSs, BEVs and PHEVs)

$$\begin{aligned} E_{Stored(PHEV,t)} &= E_{Stored(PHEV,t-1)} - (E_{Trip\_Elec(PHEV,t)} - E_{Fuel\_Shift(PHEV,t)}) \\ &\quad + \Delta t \times \left(\eta_{c(PHEV)} \times P_{Ch(PHEV,t)} - \frac{1}{\eta_{d(PHEV)}} \times P_{Dch(PHEV,t)}\right) \\ &\forall t \in \{1,\ldots,T\};\ \Delta t = 1; \\ &\forall PHEV \in \{1,\ldots,N_{St}\} \cup \{1,\ldots,N_{BEV}\} \cup \{1,\ldots,N_{PHEV}\}; \end{aligned} \tag{18}$$

considers the trip profile for BEVs and PHEVs using the variable E_{Trip_Elec}. The aggregator needs to charge the batteries of BEVs and PHEVs to guarantee the energy required to complete all the trips during the time horizon of the optimization process. The aggregator will use forecast methods for the typical daily trip profile of drivers with the purpose of determining a more accurate optimal resource scheduling. PHEVs can reduce the electric energy required for the trips replacing it by the use of ICE. This possibility is represented in (18) by the variable E_{Fuel_shift}. Variables $\eta_{d(SEV)}$ and $\eta_{c(SEV)}$ correspond, respectively, to the discharge and charge efficiency of storage systems. These efficiency values depend on each battery technology and also on the type of connection with the network (e.g. inverter). The main differences between PHEVs and BEVs are the possibility of using ICE to fuel shifting DR programs and in the ESSs case when the energy consumed for trips (E_{Trip_Elec}) is zero. The storage balance is also a very hard constraint of the problem due to the consideration of all periods in this equation. In fact, all the other problem constraints can be treated independently for each hour excepting the stored energy balance constraints.

The energy stored

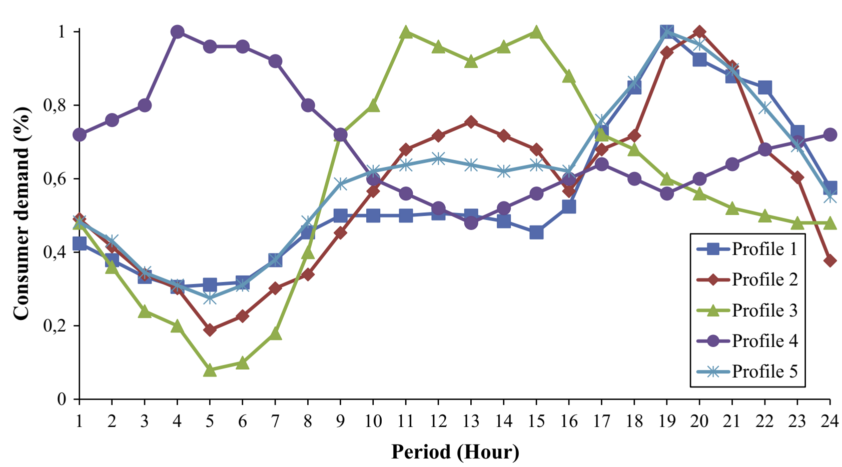

Fig. 4. Consumers' profiles.

$$E_{MinCharge(PHEV,t)} \leqslant E_{Stored(PHEV,t)} \leqslant E_{BatCap(PHEV)}$$
$$\forall t \in \{1,\ldots,T\};\ \forall PHEV \in \{1,\ldots,N_{St}\} \cup \{1,\ldots,N_{BEV}\} \cup \{1,\ldots,N_{PHEV}\} \quad (19)$$

should be less than or equal to the battery capacity, yet higher than a minimum amount of energy imposed by security reasons in order to extend the batteries lifetime, and to ensure the necessary energy for the BEVs and PHEVs trips.

$$E_{Fuel\_Shift(PHEV,t)} \leqslant E_{Trip\_Elec(PHEV,t)}$$
$$\forall t \in \{1,\ldots,T\};\ \Delta t = 1;\ \forall PHEV \in \{1,\ldots,N_{PHEV}\}; \quad (20)$$

BEV and PHEV users will request a minimum reserve energy that can be used for an unexpected travel in each period. In the ESSs case, the minimum energy required in the battery is usually zero.

In the present methodology, it is assumed that all the PHEVs trips can be assured by the internal combustion engine. This way, all the energy defined to the trips supported by the electric engine $(E_{Trip\_Elec(PHEV,t)})$ can be shifted to the internal combustion engine. However, other value can be considered according the users behavior.

The maximum charge rate

$$P_{Ch(PHEV,t)} \leqslant P_{ChMax(PHEV,t)} \times X_{Ch(PHEV,t)}$$
$$\forall t \in \{1,\ldots,T\};\ X_{Ch(PHEV,t)} \in \{0,1\};$$
$$\forall PHEV \in \{1,\ldots,N_{St}\} \cup \{1,\ldots,N_{BEV}\} \cup \{1,\ldots,N_{PHEV}\} \quad (21)$$

and discharge rate

$$P_{Dch(PHEV,t)} \leqslant P_{DchMax(PHEV,t)} \times X_{Dch(PHEV,t)}$$
$$\forall t \in \{1,\ldots,T\};\ X_{Dch(SEV,t)} \in \{0,1\};$$
$$\forall PHEV \in \{1,\ldots,N_{St}\} \cup \{1,\ldots,N_{BEV}\} \cup \{1,\ldots,N_{PHEV}\} \quad (22)$$

are imposed by technical characteristics of the charge/discharge stations/points for the three types of energy storage devices (ESSs, BEVs and PHEVs).

Eqs. (23)–(26) are specific to PHEV devices due to the use of an internal combustion engine in this type of vehicles.

The amount of fuel at the end of each period t

$$E_{Fuel\_Stored(PHEV,t)} = E_{Fuel\_Stored(PHEV,t-1)} - \frac{1}{\eta_{Fuel(PHEV)}} \times P_{Dch\_Fuel(PHEV,t)} \times \Delta t$$
$$\forall t \in \{1,\ldots,T\};\ \Delta t = 1;\ \forall PHEV \in \{1,\ldots,N_{PHEV}\} \quad (23)$$

depends the fuel spent to generate electric energy to inject in the network. This equation is only valid during the periods when the PHEV is connected to the network. The fuel spent in the trips is not considered due to the high probability of the users do the

Table 3
Electric vehicles by consumer.

	Consumers	Vehicle by consumer	Total vehicles	Electric vehicles
Domestic	1850	1.5	2775	1805
Industrial	2	80	160	105
Governmental	6	10	500	325
Commercial	50	50	300	125
Total	1908	–	3735	2430

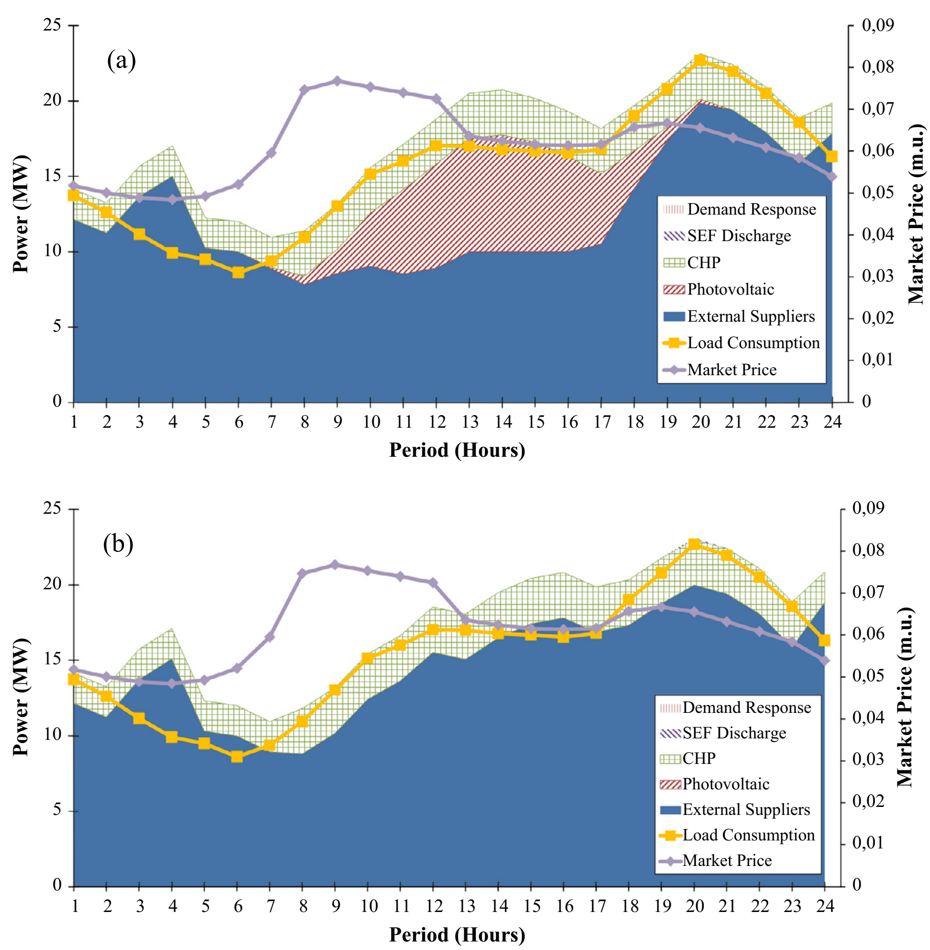

Fig. 5. Energy resources scheduling: (a) in scenario A (with PV generation); (b) in scenario B (without PV generation).

refuelling, if necessary. The minimum limit of fuel in the vehicle tank

$$E_{Fuel\_Stored(PHEV,t)} \geqslant E_{FuelThank\_min(PHEV,t)} \quad \forall t \in \{1,\ldots,T\};\ \forall PHEV \in \{1,\ldots,N_{PHEV}\} \tag{24}$$

allows to guarantee a minimum quantity of fuel in the tank. The maximum discharge rate using the ICE

$$P_{Dch\_Fuel(PHEV,t)} \leqslant P_{DchMax(PHEV,t)} \times X_{Dch\_Fuel(PHEV,t)} \quad \forall t \in \{1,\ldots,T\};\ \forall PHEV \in \{1,\ldots,N_{PHEV}\};\ X_{Dch\_Fuel(PHEV,t)} \in \{0,1\} \tag{25}$$

depends of the charging station characteristics and also from the EVs characteristics.

In this mathematical formulation, three binary variables for each energy storage device

$$X_{Ch(PHEV,t)} + X_{Dch(PHEV,t)} + X_{Dch\_Fuel(PHEV,t)} \leqslant 1 \quad \forall t \in \{1,\ldots,T\}; X_{Ch(PHEV,t)}, X_{Dch(PHEV,t)}, X_{Dch\_Fuel(PHEV,t)} \in \{0,1\}; \forall PHEV \in \{1,\ldots,N_{St}\} \cup \{1,\ldots,N_{BEV}\} \cup \{1,\ldots,N_{PHEV}\} \tag{26}$$

are used to avoid the operation of both processes at the same period. Variable X_{Dch_Fuel} is only used for the PHEVs. For the BEVs and ESSs this variable is equal to zero.

3.6. Demand response constraints

Direct load control DR events should be limited to the established contracts with active consumers as modeled by (27) and (28). Two different types of load control are considered in this paper.

In Type A – Continuous load

$$P_{DR\_A(L,t)} \leqslant P_{MaxDR\_A(L,t)} \quad \forall t \in \{1,\ldots,T\};\ \forall L \in \{1,\ldots,N_L\} \tag{27}$$

the VPP can adjust the load consumption to the minimum contracted value (maximum demand response). In Type B – Discrete loads

$$P_{DR\_B(L,t)} = P_{MaxDR\_B(L,t)} \times X_{DR\_B(L,t)} \quad \forall t \in \{1,\ldots,T\};\ \forall L \in \{1,\ldots,N_L\}; X_{DR\_B(L,t)} \in \{0,1\} \tag{28}$$

the VPP can only manage the ON/OFF load status. In this case, it is necessary to use a binary variable to control the load status.

4. Case studies and results

This paper presents a case study considering the use of the proposed ERM methodology in two operation scenarios of an 11 kV distribution network with 37 buses and a high penetration of distributed energy resources. Additionally, two sensitivity analyses are presented considering: (1) the increase of the loads in each bus; (2) the proportional increase of the loads the electrical vehicles, and storage systems (Loads/EVs/Storage).

The proposed methodology computational implementation uses Matrix Laboratory (MATLAB) software as the programming environment with GAMS being used to solve the MINLP problem. The case study has been tested on a computer with four processors Intel® Xeon® W3565 3.2 GHz, 6GB of random-access-memory (RAM) and Windows 7 Professional 64 bits operating system.

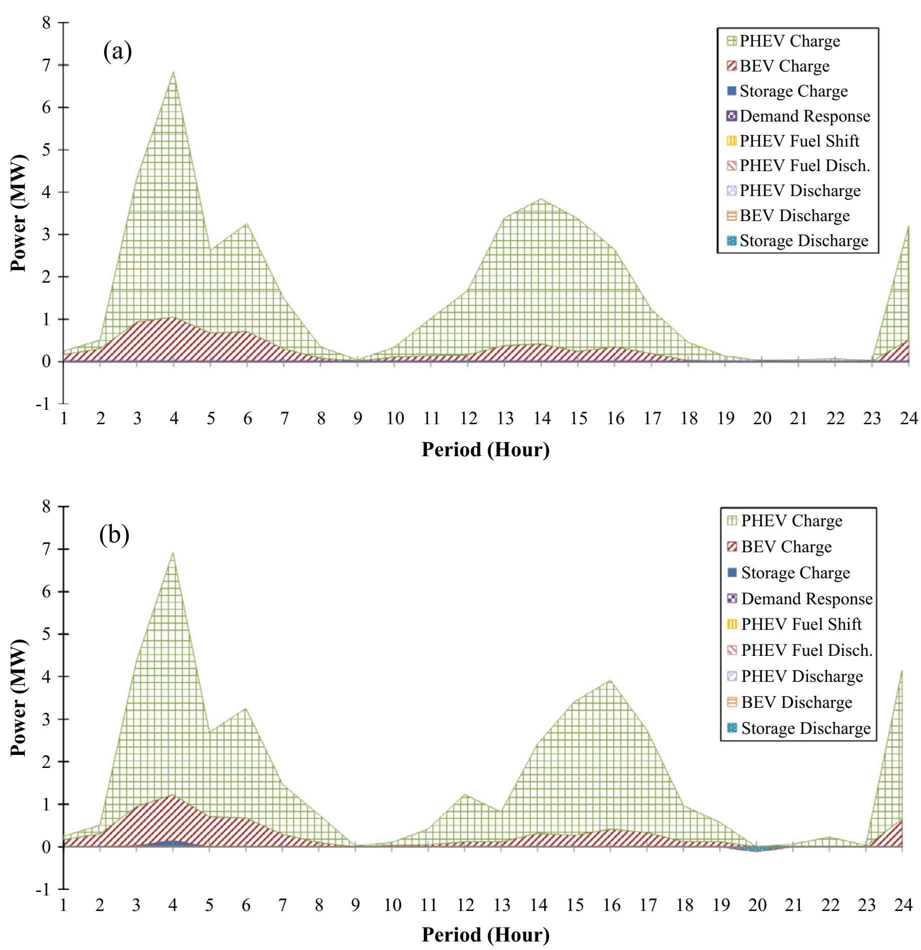

Fig. 6. EVs and demand response scheduling: (a) in scenario A (with PV generation); (b) in scenario B (without PV generation).

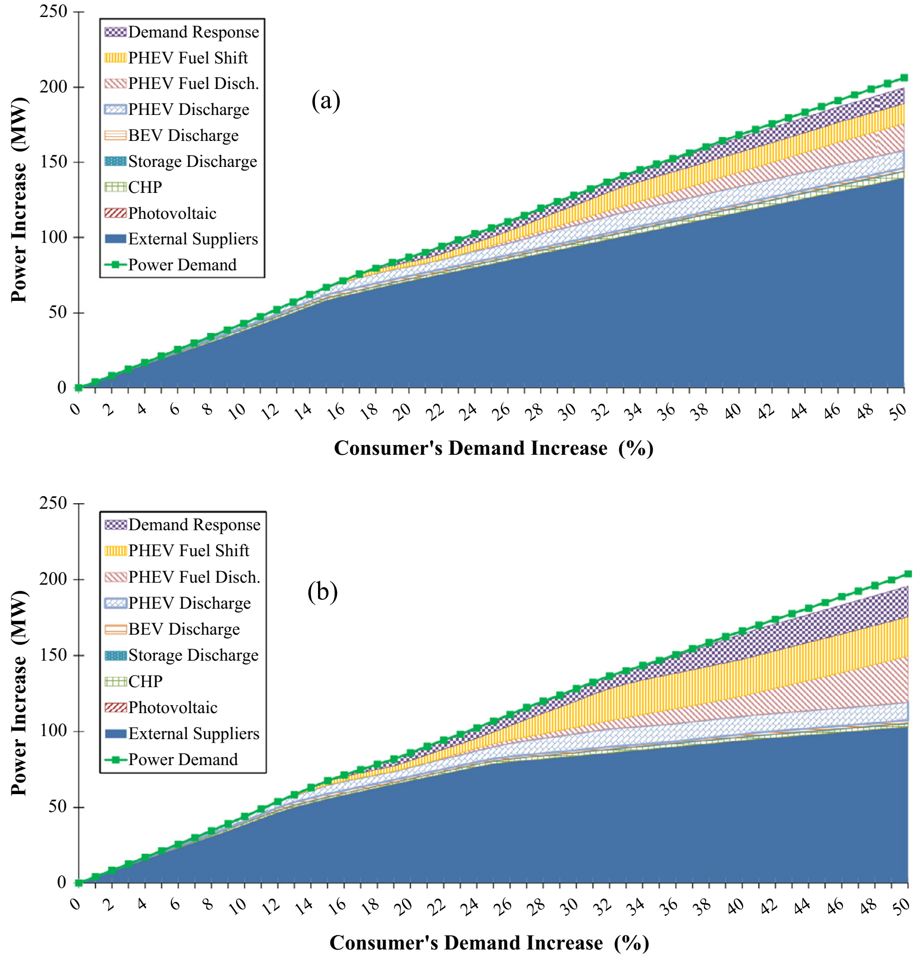

Fig. 7. Energy resources scheduling considering the consumefs demand increases: (a) in scenario A (with PV generation); (b) in scenario B (without PV generation).

This section is divided into three subsections. Subsection 4.1 presents a description about the distribution network and distributed energy resources used in this case study. In Subsection 4.2 the energy resources scheduling is presented considering high PV generation during the day in first scenario and any PV generation in the second one. In Subsection 4.3 a sensitivity analysis is presented considering the increase in the load, and the increase in the load, in BEVs and PHEVs. These analyses intend to show the operation points when each energy resource is necessary.

4.1. Case study description – 37 bus distribution network

The presented case study considers the distribution network presented in [54], and the energy mix in 2050 proposed in [55] considering a scenario with 80% of RES, 10% of CCS (carbon capture and storage) and 10% of nuclear is used. In the distribution network, the most relevant distributed generation units will be the combined heat and power (CHP) and mainly the photovoltaic (PV) units will be largely connected in medium and low voltage distribution networks. Furthermore, the distribution networks will integrate large quantities of electric vehicles, consumers with DR programs, and perhaps some storage capacity. Fig. 3 shows the 37 buses, an 11 kV distribution network connected to the high voltage network through two power transformers with 10 MVA each one. The distributed energy resources are represented by technology. In each consumption point, the DR programs are also considered. Table 1 provides complementary information of the technologies characteristics. The distribution network supply energy to 1908 consumers (1850 domestic consumers (DM), 2 industries (In), 50 commerce stores (Co), and 6 service buildings (SB)) [54]. Table 2 shows the consumption characteristics in each consumption bus. Five consumption profiles presented in Fig. 4 are implemented in order to create a more realistic scenario.

Regarding the electric vehicles, it was considered a penetration of 65% of the total number of vehicles (55% PHEV and 10% BEV) making 2430 electric vehicles (2060 PHEVs and 370 BEVs) [56]. The penetration of EVs is highly dependent by the incentives created by the governments and also by the technological developments. In the present study are considered the ‘high scenario’ described in [56]. A detailed description of the electric vehicles for each consumer is presented in Table 3.

The BEVs and PHEVs characteristics were defined based on the information available for commercial models. The driving pattern was obtained using the EVeSSI simulation tool [57]. The energy price in each hour for the external suppliers was obtained considering the average price in day-ahead Nordpool market during the year 2013 in working days. The prices for electricity energy and for fuel (gasoil and gasoline) are based on the average prices in Europe.

In the present case study, the network is operated near its boundaries. The high voltage/medium voltage power transformer has 20 MVA of capacity, and the maximum consumers demand is of 23.76 MVA (only considering the normal consumption without EVs charge).

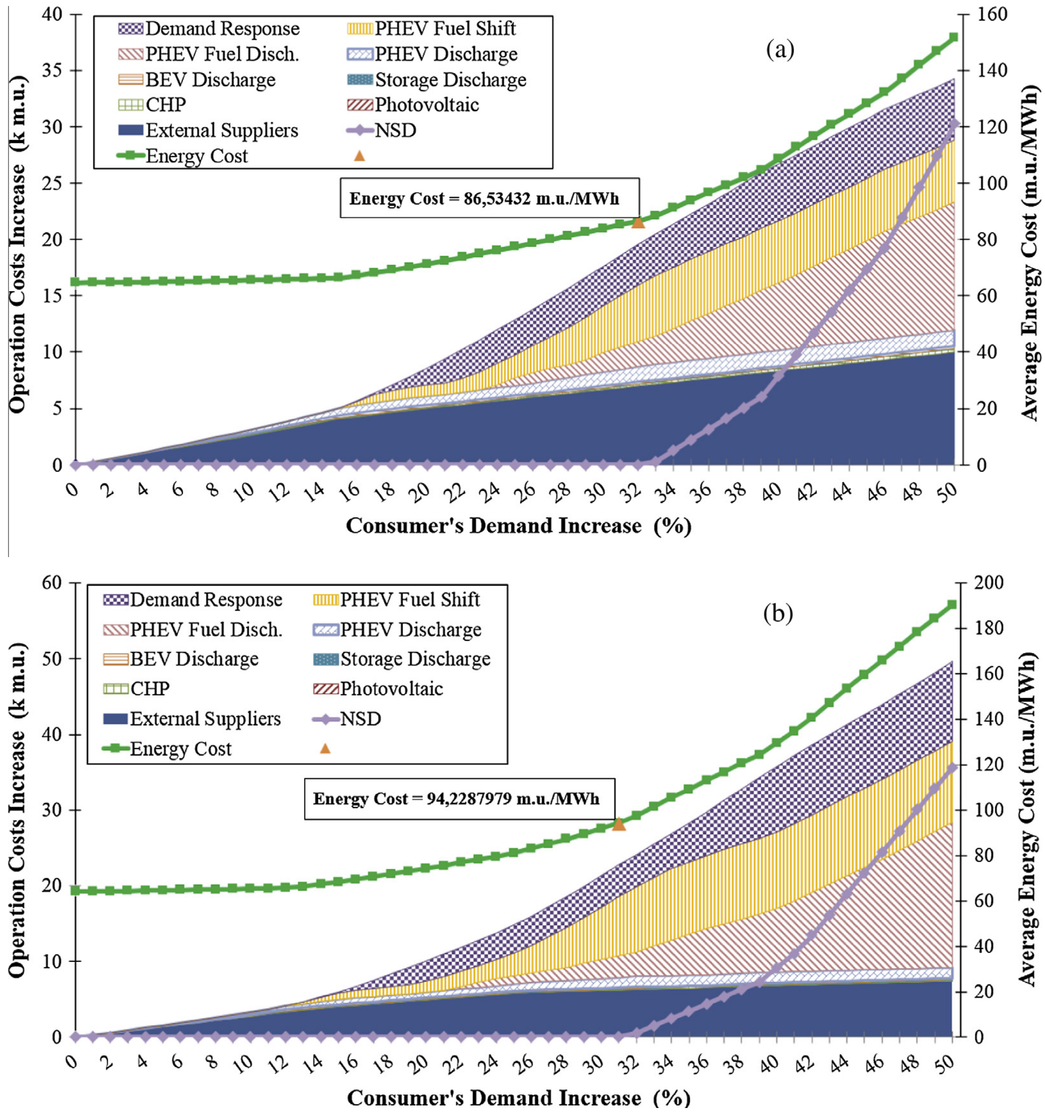

Fig. 8. Operation costs considering the consumers' demand increases: (a) in scenario A (with PV generation); (b) in scenario B (without PV generation).

4.2. Energy resources scheduling results

This subsection presents the day-ahead energy resource scheduling results, namely the operation cost and the scheduling energy of each resource. Two scenarios are considered: in the first one, scenario A, the high generation of PV units is considered; in scenario B the PV generation is zero, simulating a day with no sun. Fig. 5 shows the global energy resources scheduling for both scenarios and also the considered market price. Fig. 6 shows the scheduling of storage systems, BEVs, PHEVs, and demand response programs. The proposed method has an execution time highly dependent of the number of resources mainly the number of EVs. In this sense, all the vehicles in the same bus at the same period are aggregated, representing a significant reduction of the number of variables in each period. Even so, the execution time of the scheduling process is around 15 min. This value represents more time and computational effort than the algorithms normally used. However, the method intends to be used in day-ahead scheduling, meaning that mentioned execution time doesn't represent a problem.

As one can see in Figs. 5 and 6, the lack generation of PV panels is mainly compensated by external suppliers. In both scenarios, the BEVs and PHEVs are scheduled in the off-peak hours, mainly in the hours with lower price, increasing the significantly the consumption in periods 3 and 4. After the trips of the first vehicles in the morning (usually from the houses to the workplaces), it is necessary to charge again the batteries in the BEVs and PHEVs. The charge process in these periods is directly affected by the PV generation. In fact, in scenario A the vehicles' (BEVS and PHEVs) peak charge occurs in period 14, and in scenario B occurs in period 16. This means peak consumption in peak PV generation which shows the effectiveness of the proposed method. However, in period 20 (with higher consumption) the available generation resources (PV, CHP, and external suppliers) are not enough to supply all the demand, because in scenario B the PV generation was zero. In this scenario, the storage systems are used to compensate the lack of PV generation.

The operation costs are similar in both scenarios. In scenario A the operation cost is of 26,603 monetary units (m.u.), and in scenario B is of 26,442 m.u. This happens because the PV units has a higher generation cost than the CHP and external suppliers. The PV generation is scheduled due to the existence of "take-or-pay" contracts imposing the dispatch of all generated energy. The cost of storage system is insignificant because only 6.3 kW h are discharged.

In sum, it is possible to conclude that the network is operating in its limits concerning the balance between the generation and consumption capacity. Thus, any special DR event or vehicles discharge are required in normal operation, even when the PV generation is zero. This happens in the peak periods with a consumption power higher than generation power (external suppliers + CHP + PV).

4.3. Sensitivity analysis

In this section two sensitivity analyses are presented considering the increase in the consumers demand and the joint increase of the consumer demand, the number of electric vehicles (BEVs + PHEVs), and the capacity of the storage systems (Load/EVs/Storage). The increase is made proportionally in all periods and in all consumers, electric vehicles and storage systems. In the consumers, it is considered the increase of the active and reactive power consumption in each consumer and in each period, and also the participation in I/C demand response events. Concerning the electric vehicles, several parameters are proportionally increased, namely the initial state of the batteries, the trip requirements, the batteries capacity, and the charge and discharge rates. In the case of the PHEVs, the fuel discharge rate and the fuel shifting opportunities are also increased. In the case of the electric vehicles, it is assumed that the new electric vehicles have the same behavior of the initial ones. The storage systems are increased the charge and discharge rates and the batteries capacity.

These analyses attempt to evaluate the points when each resource is used, mainly the demand response programs, storage systems, and the electric vehicles based services. On the other perspective, this analyses shows the point when the system stops being able to supply all the demand resulting in non-supplied demand (NSD). Figs. 7 and 9 show the differences in the resources scheduling comparing with initial scenarios (with and without PV generation) for load increase and load/BEVs/PHEVs/storage increase, respectively. In the same way, Figs. 8 and 10 show the differences in the operation cost.

By analyzing Figs. 7–10 it is possible to see that the external suppliers are the main source to supply the load increase. However, the external suppliers are not able to provide more energy during the peak periods. Therefore, the use of other resources is necessary to supply energy in these periods. Table 4 presents the points (increase percentage) when each resource is necessary in each scenario and in the sensitivity analysis.

In Table 4, it is possible to see that the storage systems are the first resource scheduled when the load increases only 2%. The PHEV and BEV normal discharge are scheduled at 4/5%, and the PHEV fuel shift and I/C demand response are scheduled between 14% and 18% of load increase. This means that the storage systems have very little capacity to support the variations in the system. On the other hand, the PHEV and BEV discharge can support an increase of the total load around 10%. Comparing scenarios A and B it is possible to see that the lack of PV generation increases the necessity of energy and the PHEV fuel shifting and the I/C demand

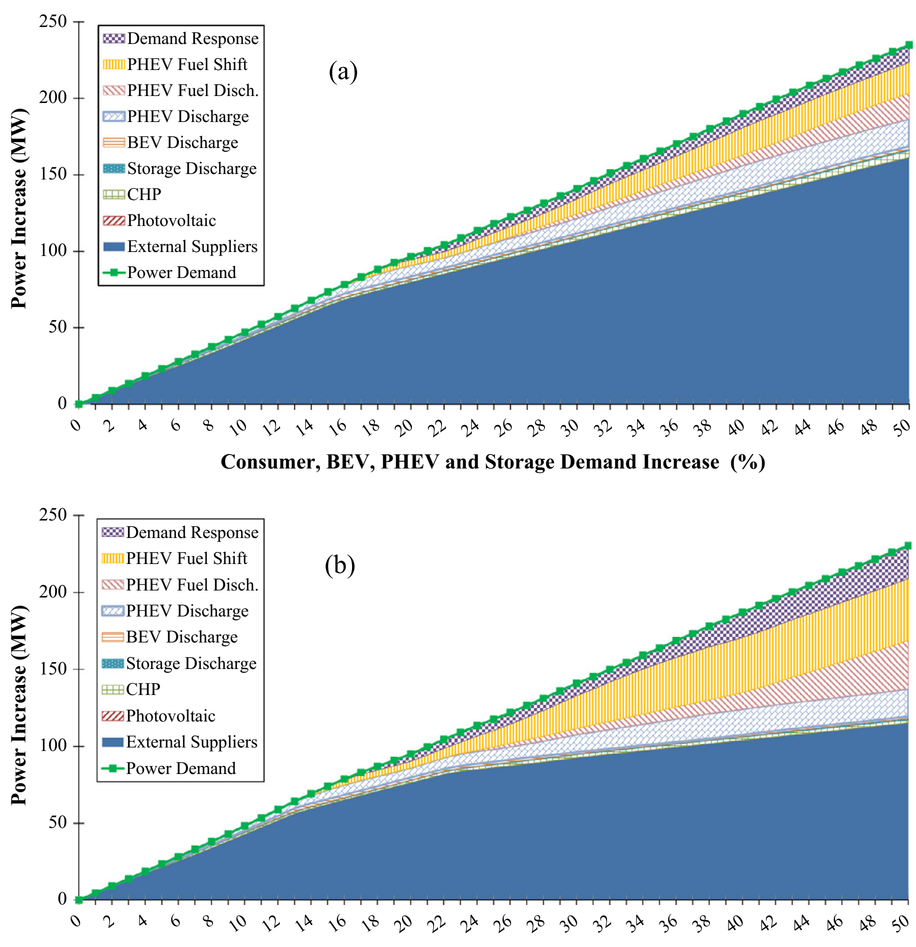

Fig. 9. Energy resources scheduling considering the consumers' demand, the electric vehicles and the storage systems increase: (a) in scenario A (with PV generation); (b) in scenario B (without PV generation).

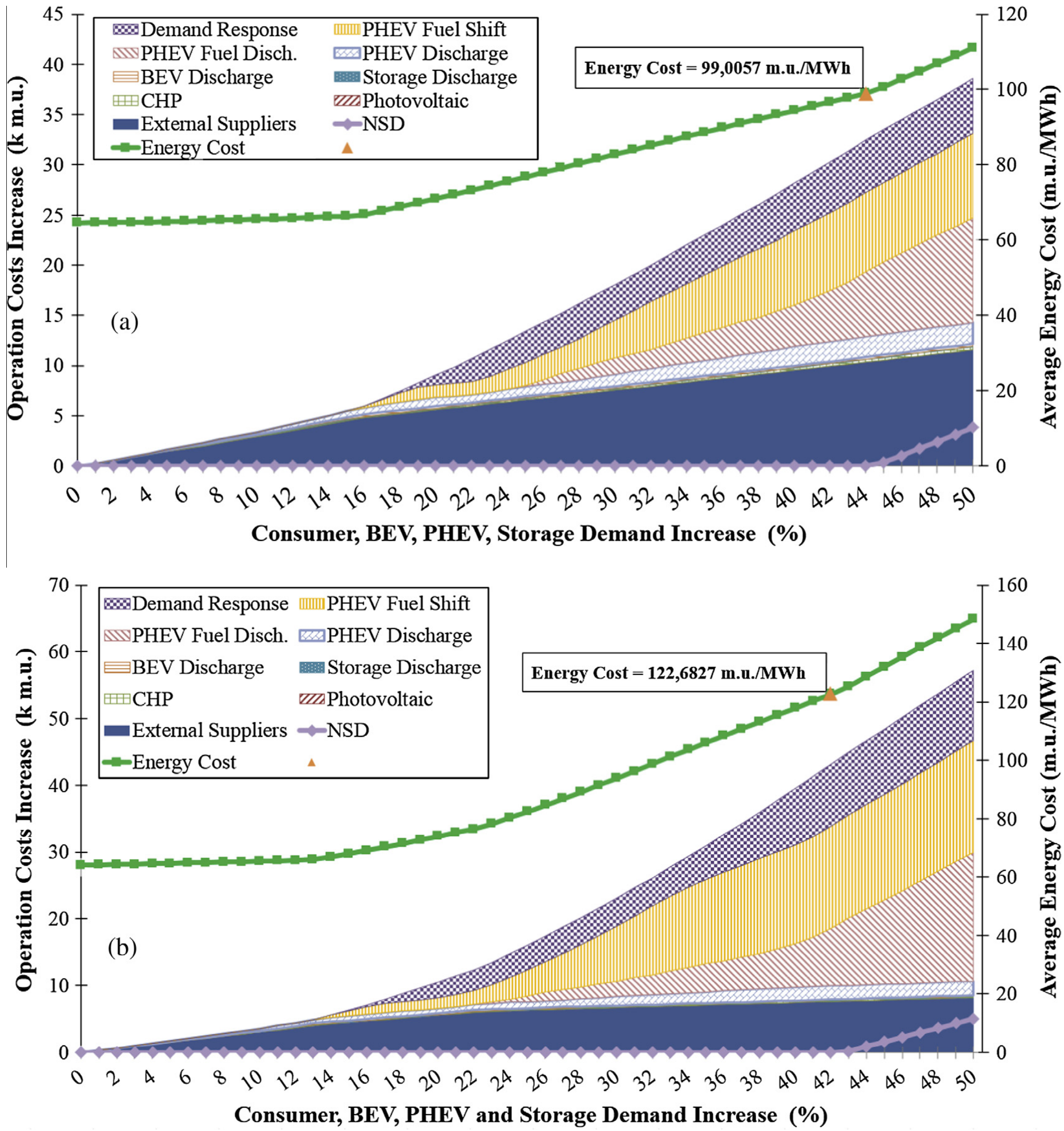

Fig. 10. Operation costs considering the consumers' demand, the electric vehicles and the storage systems increase: (a) in scenario A (with PV generation); (b) in scenario B (without PV generation).

Table 4
Use of each energy resource considering the sensitivity analysis.

Distributed energy resources	Load increase analysis (%)		Load/BEVs/PHEVs/storage increase analysis (%)	
	Scenario A	Scenario B	Scenario A	Scenario B
External supplier	0	0	0	0
PV	0	X	0	X
CHP	0	0	0	0
Storage discharge	2	0	2	0
BEV discharge	5	4	5	4
PHEV discharge	4	4	4	4
PHEV fuel discharge	25	23	26	24
PHEV fuel shift	17	14	17	15
I/C demand response	17	15	18	16
NSD	34	33	46	44

response has the capability to compensate that. These two resources support a demand increase of 8%. The PHEV fuel discharge is used when the demand increases 23/26%. A significant difference is verified between the two sensitivity analyses concerning the use of the PHEV fuel discharge. In the first analysis, the NSD (load curtailment without any contract) occurs when the load increases 33%. In the load/BEVs/PHEVs/Storage increase analysis, the NSD only occurs at 44/46%. This happens due to the increase of PHEV fuel discharge capacity, but mainly of the PHEV discharge rate in the second analysis. Therefore, an increase of the discharge rate in the discharge station/inverters can increase the reliability of the distribution network. In general, it is possible to conclude that the proposed PHEV DR services can support a significant increase in the total power demand between 20% and 30%. If the V2G capacity of BEVs and PHEVs and I/C demand response were included, the increase can reach 46%.

In Figs. 8 and 10 the differences in the operation costs are presented considering the loads and the loads/EVs/Storage increase. The NSD costs are represented in a separate trend due to the high impact in the final costs. An additional trend was included showing the average energy cost. Excluding the NSD (points represented in the graphics), it is possible to conclude that in scenario A (with PV generation) the cost increases more or less in the same proportion of the load, namely 30.62% to 83.46 m.u./MW h when the consumers' demand increases 33% and 47.96% to 94.53 m.u./MW h when the loads/EVs/storage increases 45%. In scenario *B* (without PV generation), the operation costs increase more sharply, namely 41.32% (89.37 m.u./MW h) to an increase of 43% in the consumers' demand and 79.23% (113.34 m.u./MW h) to an increase of 43% in the loads/EVs/storage. These values are relatively high, yet still acceptable considering the average energy selling price. Other important aspect to be considered is the initial operation conditions defined in this case study very close to the network boundaries. In general, it is possible to verify the adequacy of the proposed programs having a medium impact in average operation costs.

5. Conclusion

The future distribution network will be managed under a large penetration of distributed energy resources, such as DG units, consumers with demand response programs, storage systems, and electric vehicles, mainly BEVs and PHEVs. The high fossil fuel prices and the environmental concerns are one of the major reasons behind the investment in the massive use of electric vehicles in the transportation sector. However, the use of electric vehicles that will be connected into the distribution network will comprise several changes in the power systems management and operation. Virtual power players that aggregate the distribution energy resources at a distribution level are essential for improving the management in future distribution networks considering a hierarchical management.

This paper proposes the use of two fuel shifting demand response programs in the PHEVs to improve the flexibility of day-ahead energy resource management. Basically, the fuel shifting DR services is the replacement, fully or partially, of the use of electric energy by other type of fuel. In the case of PHEVs, the other fuel can be the gasoil or gasoline depending of the vehicle characteristics. The first fuel shifting DR program remunerates the PHEVs owners that replace the use of the battery by the ICE in the daily trips. The second fuel shifting DR program remunerates the PHEVs owners that inject electric energy in the distribution network from the ICE. The use of this program should be avoided in covered car parks but can be used in the open ones. These new DR programs for the PHEVs are included in an optimization methodology to solve the day-ahead energy resources management problem, which considers the management of a large set of distributed energy resources in a distribution network that are aggregated by a virtual power player.

As shown in the paper, mainly in the case study, the adoption of the proposed methodology, including the fuel shifting services, improve significantly the operation flexibility. This means that the distribution system can accommodate more consumption, more distributed generation and more electric vehicles. The sensitivity analysis showed that storage systems only support approximately 2% of the increase in the consumption power. On the other hand, the PHEV and BEV discharge can support an increase of the total load around 10%, and the PHEV fuel discharge is used to support around 25% of the increase in the consumption power.

Other interesting conclusion is that the PHEVs can support their own developed. In fact, the use of the smart charging and the proposed fuel shifting demand response strategies allows a high level of flexibility avoiding the significant increase of consumption in peak periods. On the other hand, the coordination of EVs services can be made based on the available generation from renewable sources.

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