PHEVs as Dynamically Configurable Dispersed Energy Storage for V2B Uses in the Smart Grid

C. Pang, P. Dutta, S. Kim, M. Kezunovic, and I. Damnjanovic

***Abstract*-- Vehicle-to-building (V2B) provides an option to use the battery energy in electric vehicles to support loads in the power grid. Many researchers have shown that vehicle-to-grid (V2G) has many potential benefits. But for various practical reasons wide application of this concept is envisioned on a 5-10 year time horizon. We have focused on V2B as a concept that is practically viable today and may be implemented on a 3-5 year time horizon. This paper aims at demonstrating the potential benefits of Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) as dynamically configurable dispersed energy storage acting at the convergence of transportation and power system. A new parking facility as an energy exchange station called "smart garage" is discussed in this paper. Based on the availability analysis of smart garages, the benefits of using BEVs/PHEVs as energy storage for demand side management (DSM) and outage management (OM) are discussed in detail. A strategy to adopting BEVs/PHEV uses in the V2B mode under the peak load and outage condition is studied and demonstrated with test cases.**

***Index Terms*—Battery electric vehicle, Plug-in hybrid electric vehicle, Demand side management, Outage management, Smart garage, Vehicle–to-building, Vehicle-to-grid**

I. Introduction

THE operational security, reliability and stability are among the most important requirements of a power system. With the growing number of distributed storage and generation units, power network structure becomes more complex. With the rapid load growth, power system becomes more stressed and hence more difficult to control. Currently, utilities in North America are adopting far reaching steps applying the new equipment and advanced technologies trying to meet the emerging requirements of the smart grid. Similar trends may be observed across the world. Maintaining the operational security, reliability and stability while expanding and developing the grid to meet the growing demand is still the main challenge in a power system.

With growing concerns about energy security, environment, and economics, interest in Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) has increased. BEVs/PHEVs have large-capacity batteries and an intelligent converter to connect to electric power grid. Using a plug, BEVs/PHEVs can charge the battery using electricity from an electric power grid, also referred to as "Grid-to-Vehicle" (G2V) operation, or discharge it to an electric power grid during the parking hours, also referred to as "Vehicle-to-Grid" (V2G) operation. Indeed, most of the time vehicles sit idle parked at homes, streets, parking lots, or garages; hence BEVs/PHEVs battery capacity can be fully utilized during such times. Therefore, BEVs/PHEVs could serve as decentralized energy storage in a smart grid and can act as either a load or a generator as needed. When aggregated in sizeable numbers, and operating both in the V2G and G2V modes, BEVs/PHEVs may be an attractive integral part of a smart grid.

Many researchers have investigated the various potential benefits and implementation issues of V2G [1-7] concept. Kempton and Tomić studied the fundamentals of using BEVs/PHEVs for load leveling, regulation, reserve, and other purposes [2, 3]. Hadley and Tsvetkova analyzed the potential impacts of BEVs/PHEVs on electricity demand, supply, generation, structure, prices, and associated emission levels in 2020 and 2030 in 13 regions specified by the North American Electric Reliability Corporation (NERC) [4]. Meliopoulos, et al. considered the impacts of BEVs/PHEVs on electric power network components [5]. Anderson, et al. performed the case studies of Plug-in hybrid electric vehicles as regulating power providers in Sweden and Germany [6]. Guille and Gross presented a proposed framework to effectively integrate the aggregated battery electric vehicles into the grid as distributed energy resources [7]. The combined impact BEVs/PHEVs make on both electric power system and transportation network has not been explored as much. When considering the role of BEVs/PHEVs as dynamically configurable (mobile) energy storage, the potential impacts on both electricity and transportation networks may become quite diverse. The flow of traffic is an important factor in deciding the flow of electric power that could be utilized from BEVs/PHEVs. Correlating the movement of people to the movement of the power load offers new opportunities in the smart grid.

This paper aims at demonstrate the potential benefits of BEVs/PHEVs that may be used to feed power back to home or office building , which is known as "Vehicle-to-Building" (V2B) operation. The new parking facility called "smart garage" is introduced and its eclectic power capacity is discussed. Based on the availability analysis of smart

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garages, a strategy to adopting BEVs/PHEV uses in the V2B mode under peak load and outage condition is proposed.

This paper is organized as follows: Section II introduces the benefits of using BEVs/PHEVs in the V2B integration. The smart garage and V2B implementation issues are discusses in Section III. Section IV presents the test cases and results. Conclusions of this paper are given in Section V.

II. Benefits of Using BEVs/PHEVs in Power System

V2B approach considers BEVs/PHEVs as a generation resource for the buildings at certain periods of time via bidirectional power transfers, which could increase the flexibility of the electrical distribution system operation. It is expected that V2B operation will improve the reliability of the distribution system, provide extra economic benefits to the vehicle owners, and reduce the home or building electricity purchase cost based on the demand side management (DSM) and outage management (OM) programs with customer incentives.

A. Demand Side Management (DSM)

For electric utility, DSM is defined as “the planning, implementation, and monitoring of distribution network utility activities designed to influence customer use of electricity in ways that will produce desired changes in the load shape”, which includes peak clipping, valley filling, load shifting, strategic conservation, strategic load growth, and flexible load shape [8]. However, for utility end-user (customer), DSM is often understood to include two components: energy efficiency (EE) and demand response (DR). EE is designed to reduce electricity consumption during all hours of the year; DR is designed to change on-site demand for energy in intervals and associated timing of electric demand by transmitting changes in prices, load control signals or other incentives to end-users to reflect existing production and delivery costs [9]. By cooperative activities between the utility and its customers to utilize DSM, it will provide the benefits to the customer, utility, and society as a whole, which is summarized in Table I [10].

TABLE I
DSM Benefits to Customer, Utility and Society [10]

Customer benefits	**Societal benefits**	**Utility benefits**
Satisfy electricity demands	Reduce environmental degradation	Lower cost of service
Reduce / stabilize costs	Conserve resources	Improved operating efficiency,
Improve value of service	Protect global environment	Flexibility of operation
Maintain/improve lifestyle and	Maximize customer welfare	Reduced capital needs

In the V2B option, the owners will plug in their vehicles during the day at their final destination for a given time frame. As an example, this may be either at their workplace (central business district) or at the place of their study (university). The destinations, either parking lots or parking garages, are assumed to be equipped with a bi-directional charger and controller. The parking facility should allow either charge or discharge mode for the car batteries when necessary. The idea is that the parking facility can offer an aggregation service for charging the batteries when the building demand is lower than its peak load and discharge the batteries to partially supply the building to reduce the peak demand during a high demand. This mode will be considered as DSM by V2B. Considering the electricity rate when the vehicle batteries were charged is lower than when the batteries are discharged, the battery storage may be used to offset high cost during the peak demand.

B. Outage Management (OM)

Another important benefit of V2B is using the battery energy storage in BEVs/PHEVs as an emergency back-up power for the commercial facility/building, which increases the reliability of the power supply for that load.

An outage is typically caused by several unplanned events and a timely detection and mitigation of such situations is a real concern for the utility. Outage management system helps the operators to locate an outage, repair the damage and restore the service. Outage management must be performed very quickly to reduce outage time. Recently completed project proposes an optimal fault location scheme which will help the operator to find the faulted section very quickly [11]. In this paper we will focus mainly on the restoration strategy under an outage.

We can consider the following types of outages and study the impact of BEVs/PHEV adoption under these conditions:

a) *Outage beyond the distribution system*: These may be caused by generator failure, fault in transmission line or substation busbar. Usually spinning reserves are kept for these circumstances. From the previous studies it is concluded that BEVs/PHEVs can be a candidate solution for spinning reserves (as the traditional fastest acting spinning reserve generators are highly costly while BEV/PHEV qualifies for fast response with lesser cost). One may consider using a real-time security constrained optimal power flow under the contingencies to calculating amount of BEV/PHEV generation required for a certain location at a specific instance.

b) *Outage in distribution system*: These may be caused by fault inside the distribution system and can be mitigated by precise spatial adjustment of BEV/PHEV generation that may be fed locally during and after outage.

To propose the restoration strategy where BEVs/PHEV is used to mitigate an outage condition, we need to correlate the information about events (where the fault is located and how the impact will propagate) and the location of the storage. Thus a spatial as well as temporal analysis should be performed.

The restoration strategy can be executed in the following steps:

1) Detect a fault;
2) Estimate the location of the fault;
3) Analyze the amount of generation required and the availability of BEV/PHEV that can provide an alternative generation support in the vicinity of the faulted area until the faulted section is repaired. This will also consider the generation time requirement (i.e. time to repair the faulted section).
4) Schedule the aggregated BEV/PHEV generation optimally. This is a multi-objective optimization problem which can be formulated to minimize the distance

between location of the fault and available BEV/PHEV generation locations as well as minimize the operating cost under system operation and security constraints.

III. Implementation Issues

Penetration rate of BEVs/PHEVs is expected to continuously increase after their wide spread market introduction is made in 2010 and beyond. Hadley and Tsvetkova [4] estimate that by 2030 the market share of BEVs/PHEV could reach 25 percents. Sullivan, Salmeen, and Simon have researched the BEV/PHEV marketplace penetration by the agent based simulation and estimated that the market share in optimistic scenarios could reach around 20 percents by 2040 [12]. While such projections are showing large penetration of BEVs/PHEVs not to occur before 20-30 years from now, it is assumed in this paper that a focused availability of such vehicles in major cities due to early adopters will create a critical mass of vehicles for aggregated use to be available 3-5 years from now. Under this consideration, the infrastructures for G2V and V2B operation would be available widely making the proposed idea viable and economically attractive. Three implementation issues are discussed in this section.

A. Garage Location and Charging/Discharging Infrastructure

Commercial and public parking garages in a central business district (CBD) provide thousands of parking spaces for commuters and visitors. After penetrating the conventional vehicle market, owners of EBVs/PHEVs will be using these parking garages, which ma provide an aggregated service to act as an electric power source or storage.

Figure 1 shows a simple transportation network with smart garage building. As a smart garage is constructed, BEV/PHEV drivers have two options: proceed to final destination directly or park at the smart garage and walk to the destination along walking links. Drivers in transportation network select parking garage based on the location and financial incentives (less parking fee), which can be modeled as traffic assignment problem. Demand of smart garage (number of parked BEVs/PHEVs) calculated from the traffic assignment problem would vary by the location and incentive of the smart garage.

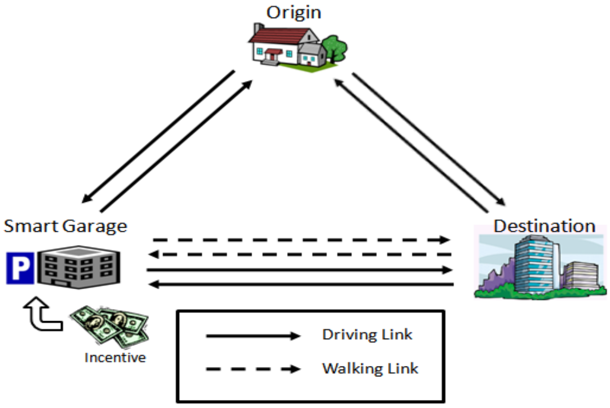

Fig. 1. Simple transportation network with smart garage.

Electric power capacity of smart garage is estimated based on demand of smart garage. Demand of smart garage building is not constant. Generally, the demand of smart garage building during the day would be higher than during the night, similar to the demand structure for a conventional garage as shown in Figure 2. Due to the versatility, electric power capacity needs to be defined in two parts: for periodic service and for continuous service as in Figure 2. The available electric power estimated based on the demand of smart garage can be used for determining the support service that can be provided during outage management and demand side management in vehicle-to-building (V2B) mode.

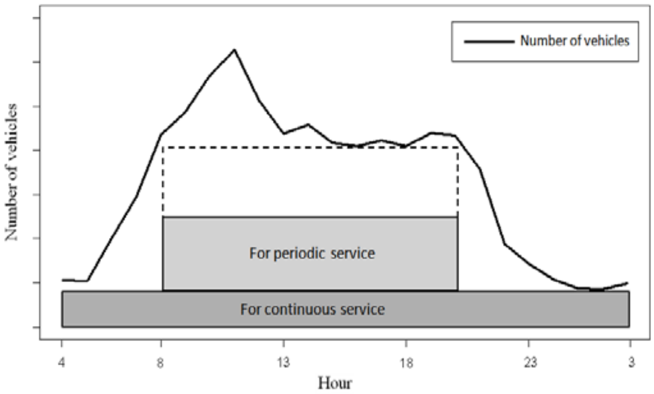

Fig. 2. Demand of smart garage for a day.

B. BEV/PHEV Integration

In [5], a security constrained optimal power flow to schedule BEV/PHEV generation is proposed and tested using an IEEE test systems. In that approach the operating cost is minimized under normal system operation.

Our restoration strategy consists of scheduling BEVs/PHEVs by optimizing a multiple-objective problem. The problem can be stated as:

$$Min \;\; f_i(\underline{x}, \underline{u}, \underline{p}) \tag{1}$$

$$s.t \;\; g_i(\underline{x}, \underline{u}, \underline{p}) = 0 \qquad i = 1, 2, ..., m$$

$$h_i(\underline{x}, \underline{u}, \underline{p}) \le 0 \qquad i = 1, 2, ..., n$$

Where

$f_i(\underline{x}, \underline{u}, \underline{p})$: The functions to be minimized;

$\underline{x}$: The vector of state variables;

$\underline{u}$: The vector of control variables (location and amount of BEV/PHEV generations here);

$\underline{p}$: The vector of fixed parameters;

$\underline{g}$: Equality constraints;

$\underline{h}$: Inequality constraints.

The objective functions can be cost minimization, real power loss minimization, minimization of time of outage (depending on the discharge rate of the chosen vehicles).

Presently we are considering only the cost minimization objective. The objective function can be formulated as:

$$f(\underline{x}, \underline{u}, \underline{p}) = \sum_{i=1}^{N_G} \beta_G[i].P_G[i] \tag{2}$$

Where

$P_G[i]$: Active power generation of i^th^ BEV/PHEV generation;

$\beta_G[i]$: Cost coefficient of i[th] BEV/PHEV generation: depends on the type of vehicle as well as type of parking garages.

The equality constraints will be the power flow equations. The inequality constraints will be the BEV/PHEV generation limits, bus voltage limits, line overload limits.

The restoration strategy will be executed using the following procedure. A fault location scheme detects and locates the fault. Depending on the location of the fault, an analysis is performed to determine amount of load affected and location of Smart Garage near the islanded area. Now, depending on the availability and state of charge of the aggregated vehicles and the maximum generation and price of discharging for garages, total cost will be minimized. While this procedure is a spatial analysis, a temporal analysis which will take care of the discharge rate and availability of vehicles, as well as the time to repair the fault will also be performed.

C. BEV/PHEV Charging/discharging

It is assumed that the primary electric vehicle charging station is located at the residence, business, or fleet facility where the vehicle is parked. Also, it is assumed that there are also a number of public charging sites that are available. In North America, standards for installation and functional requirements of electric vehicle infrastructure are provided in the National Electrical Code (NEC) Article 625 [13] and by the Society for Automotive Engineers (SAE) J1772 [14]. SAE J1772 defines the electrical rating of charging methods for conductive charger coupler. Based on the available charging infrastructures, BEVs/PHEVs may be charged by either Level 1 or Level 2 charging method.

Table II shows the detailed information about the different charging methods specified in North American [13, 14]. The Level 1 method uses a standard 120-VAC, 15-Amp (12 Amp useable) or 20-Amp (16 Amp useable) branch circuit that is the lowest common voltage level found in both residential and commercial buildings in the United States. Level 1 charging only provides a small amount of power (maximum of up to 1.44 kW), and results in prolonged charging time. The Level 2 method uses a 208 to 240-VAC, single-phase, up to 80-Amp branch circuit. Since the typical charging time for a 10 kWh battery pack will be 1 to 2 hours, it is the primary and preferred method for the battery electric vehicle charger for both private and public facilities. The faster charging methods are still under development. No current standard for the faster charging or connector. Table II shows two typical cases used for faster charging.

TABLE II
ELECTRICAL RATINGS OF DIFFERENT CHARGING METHODS IN NORTH AMERICA

Charging Method	Nominal Supply Voltage	Maximum Current	Typical Charge Time
AC Level 1	120 V, 1-phase	12 A or 16 A	5-8 hours
AC Level 2	208 to 240 V, 1-phase	Up to 80 A	1-2 hours
AC Level 3	208 to 600 V, 3-phase	400 A	10-15 mins.
DC Charging	Up to 600 V	400 A	10-15 mins.

IV. CASE STUDY FOR USING BEVS/PHEVS IN V2B

Test cases for two scenarios are studied: demand side management using V2B mode during peak power demand and outage management using V2B mode during faults.

A. Demand Side Management during Peak Power Demand

In this case, a large commercial building is analyzed to demonstrate the potential savings using demand side management based on V2B operation. Iron, Inc. prepared a technical survey for the California Energy Commission (CEC), which modeled difference commercial sectors, including large office building [15]. The load shapes include typical day, hot day, cold day, and weekend for each of four seasons. According to the definition used in this report, large office buildings are defined as premises with total floor area equal or larger than 30,000 square feet. The largest electric end uses in this building type are interior lighting, cooling, office equipment, and ventilation [15].

The summer typical load shape for a large office building is selected for our case study. The single building demand is obtained from the results reported in the literature [15]. The following assumptions are taken:

- The studied building is 450,000 sq ft;
- There are up to eighty BEVs/PHEVs that arrive at 8 AM and are available for the entire day;
- Maximum capacity of each vehicle is 10 kWh;
- The batteries in BEVs/PHEVs are drained by an average of 4.0 kWh by the driving cycle used.

When BEVs/PHEVs are on site, the building can charge the batteries during the morning hours (lower electricity price) and drain the batteries by an equal amount during afternoon hours (higher electricity price). Thus the owner of BEV/PHEV will have the required energy in his/her battery to make sure the driving cycle to return home can be met. Figure 3 shows the impacts of charging BEVs/PHEVs by faster charging methods (AC Level 3 or DC charging). It will elevate the peak demand to 1.86 MW of the office building since the faster charging method will cause a large load in a short period (10-15 mins), which is not recommend for either utilities or customers.

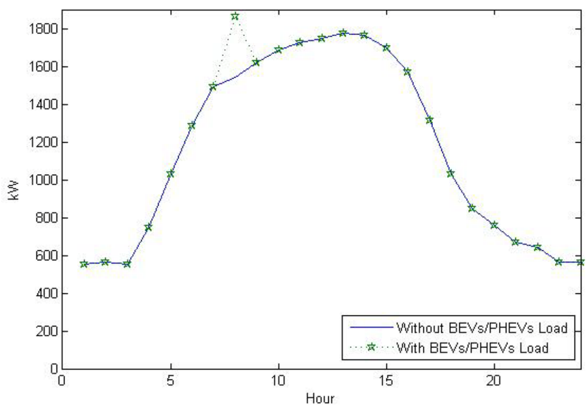

Fig. 3. Impacts of faster charging BEV/PHEVs on load demand.

Figure 4 shows the change in the load shape for the typical summer day by using the AC Level 1 charging method. The load curve was changed by shifting the afternoon peak load to the morning off-peak load when charging and discharging the BEVs/PHEVs. Considering the rate structures for peak and off-peak load in commercial buildings, peak load shifting using V2B mode may provide the electricity bill saving. Further study could be conducted to show the total saving expressed in dollars.

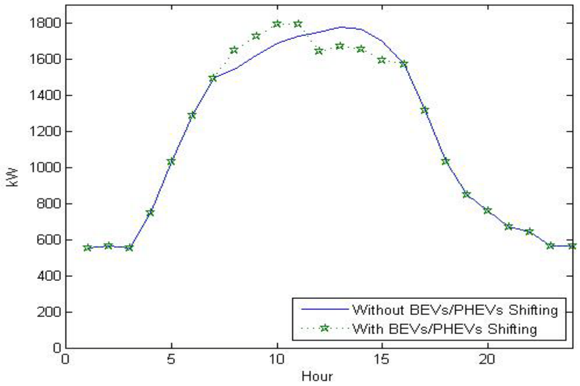

Fig. 4. Peak load shifting with BEVs/PHEVs for a typical summer daily load.

B. Outage Management during Faults

The proposed restoration scheme was tested on a small distribution system (IEEE 37 node radial test feeder [16]).

This is an actual feeder located in California, which consists of several unbalanced spot loads. The nominal voltage is 4.8kV.

Figure 5 shows the test feeder with smart garages at some nodes.

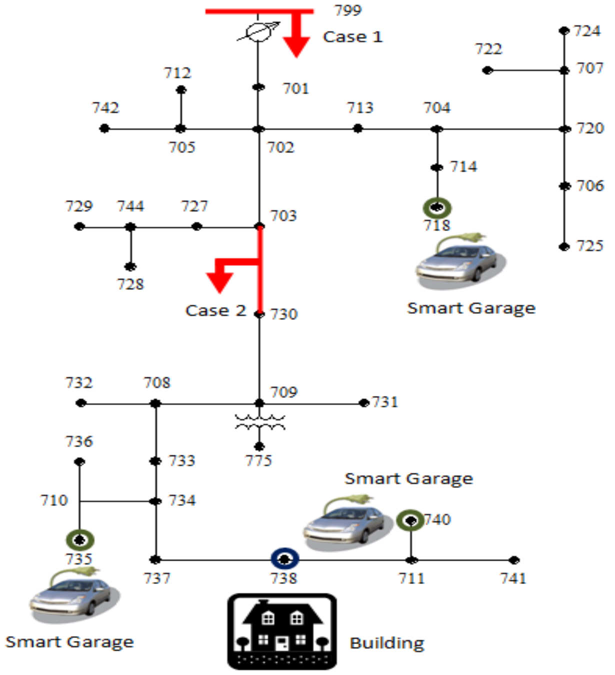

Fig. 5. Diagram of test feeder with smart garages.

The following assumptions are taken:

- Three nodes are specified as smart garages (nodes 718,735 and 740);
- Maximum capacity of each vehicle is 10 kWh;
- Discharge vehicles with state of charge (soc)>70%;
- BEV/PHEV tariff for charging is 5c/kWh and for discharging is (15-40) c/kWh (depending on different garages). Discharging tariff for node 718 is 40 c/kWh, for node 735 is 30c/kWh, for node 740 is 25 c/kWh.

Under normal operating condition, node no. 799 acts as an infinite bus and all the loads are fed through it. We have studied two different outage cases:

1) Case 1: Fault on or beyond node 799: BEVs/PHEVs at nodes 718,735 and 740 were scheduled to satisfy all the loads on the feeder. Table III shows the case results.

TABLE III
CASE STUDY 1: RESULTS FOR BEV/PHEV GENERATION SCHEDULING

Node 718			Node 735			Node 740		
Ph-1 (kW)	Ph-2 (kW)	Ph-3 (kW)	Ph-1 (kW)	Ph-2 (kW)	Ph-3 (kW)	Ph-1 (kW)	Ph-2 (kW)	Ph-3 (kW)
0	0	411	300	300	300	427	339	380

Total cost for three phases is 733.2$/hr.

2) Case 2: Fault on line segment 703-730: Node 799 will supply all the loads beyond this line segment. BEVs/PHEVs at nodes735 and 740 will be scheduled to satisfy the island created by a fault on line 703-730. Table IV shows the case results.

TABLE IV
CASE STUDY 2: RESULTS FOR BEV/PHEV GENERATION SCHEDULING

Node 735			Node 740		
Ph-1 (kW)	Ph-2 (kW)	Ph-3 (kW)	Ph-1 (kW)	Ph-2 (kW)	Ph-3 (kW)
300	127	300	51	0	81

Total cost for three phases is 221.35$/hr.

V. CONCLUSIONS

This paper discusses the potential benefits of using BEVs/PHEVs as dynamically configurable dispersed energy storage that can serve as load or generation in a power system as needed. If serving in G2V as well as V2B mode and if aggregated, BEVs/PHEVs may play a major role in both the electricity the transportation networks. Based on the discussions presented in this paper, the following conclusions can be drawn:

- Selecting garage location and charging/discharging infrastructure needs special attention from the transportation system demand point of view;
- For demand side management in electricity networks, the use of BEVs/PHEVs to create a peak load shifting strategy can reduce the electricity purchase cost for the customer and vehicle owner;
- For outage management in electricity networks, the use of BEVs/PHEVs to generate power during outage restoration stage is envisioned by solving a multi-objective optimization problem of merit-order scheduling of BEV/PHEVs under operating constraints;
- Case studies used to demonstrate the feasibility of the proposed demand side management and outage management strategies suggest that with enough available BEVs/PHEVs, the aggregated batteries could be used to support the electricity demand of a typical building if the transportation demand is controlled accordingly.

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VII. BIOGRAPHIES

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