



PHEVs as Dynamically Configurable Dispersed Energy Storage

Final Project Report

Power Systems Engineering Research Center

*Empowering Minds to Engineer
the Future Electric Energy System*



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Final Project Report

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Executive Summary

Studying the impact of Plug-in Hybrid Electric Vehicles (PHEVs) and Battery Electric Vehicles (BEVs) is complex because these technologies provide dispersed and yet mobile energy storage that can be aggregated at different scales. This report focuses on how PHEVs/BEVs, as dynamically configurable, dispersed energy storage, can create multiple benefits in electricity networks while playing a major role in transportation networks.

PHEVs/BEVs provide multiple benefits by serving in two modes: Grid-to-Vehicle (G2V) or “smart charging,” and Vehicle-to-Grid (V2G) or “smart discharging.” G2V charging mode can be used when demand is low and there is ample, low cost electric energy supply available. V2G discharging mode can be used as a supply source when demand is high or supply is lost.

Communications is essential to enable smart control in either mode. Controlled charging/discharging of PHEVs/BEVs in public parking spaces or parking garages in business districts would facilitate aggregation to provide ancillary services. There would be cost advantages arising from the high density of Electric Vehicle Supply Equipment in such parking areas, such as from the ability to spread communications equipment costs over a large number of vehicles. In contrast, aggregation of multiple home garage charging stations may be cost prohibitive because of the need to meter and communicate with individual vehicles at different locations.

There are various requirements for and challenges in providing ancillary services, such as the minimum threshold capacity requirements for battery charging, telemetry measurements requirements, and the representation of PHEVs/BEVs in power network models. A case study of benefits in several ISO regions shows that these benefits will vary significantly over time, between different ancillary services, and from locality to locality. The net benefits to the PHEV/BEV owner and the electricity system could be significant to the extent that the communications and telemetry costs are fairly small, and the effect of providing ancillary services on battery lifetime is negligible.

Two important issues addressed in this study for the development of PHEV/BEV infrastructure were the “smart garage location problem” and “charging station installation problem”. The first problem is determining the optimal location of the garage facility and the type of profit incentives to maximize profit. In this research, the smart grid location problem is formulated as a bi-level optimization program and solved using a genetic algorithm. The results of sensitivity analysis show that poor walkability or low incentive parameters will increase the influence of vehicle trip rates on parking.

The second problem is determining the optimal number of charging/discharging stations to be installed in an existing parking garage. This problem is formulated as a stochastic program with a simple recourse. The problem includes uncertain parameters, such as the PHEV/BEV penetration rate in the vehicle fleet and the PHEV/BEV charging rate. The problem is solved using a Monte Carlo sampling-based algorithm. Sensitivity analysis shows that the mean value of PHEV/BEV penetration rate and charging rate are important factors in making investment decisions.

A model was developed to investigate the impact of aggregated PHEV/BEV on electricity power networks and on the parking garage developer's decisions. The results show that high penetration of PHEVs/BEVs could affect power system operating conditions and locational marginal prices (LMP). Comparisons among the three cases, 'V2G with uniform price', 'V2G with LMP', and 'G2V with LMP', show that the business model of 'V2G with LMP' maximizes profit for a parking garage developer, thereby providing a relatively greater incentive for investment.

Future analyses could be advanced in several ways. Analysis of the impact of PHEVs/BEVs on electricity power networks and on a parking garage developer's decisions would benefit from more accurate estimates of market penetration rates of PHEVs/BEVs over time. The models of the dispersed energy storage system and smart garage used in this study could be expanded to account for uncertainty, modification of the model parameters from survey results, and addition of other potential revenue and cost components.

Project Publications

- [1] M. Kezunovic, S.T. Waller, I. Damnjanovic, "Framework for Studying Emerging Policy Issues Associated with PHEVs in Managing Coupled Power and Transportation System," 2010 IEEE Green Technology Conference, Arlington, Texas, April 2010.
- [2] C. Pang, P. Dutta, S. Kim, M. Kezunovic and I. Damnjanovic, "PHEVs as Dynamically Configurable Dispersed Energy Storage for V2B Uses in the Smart Grid". The 7th Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion, Cyprus, November 7-10th, 2010.
- [3] S. Kim, and I. Damnjanovic, "Smart Garage Projects: Optimizing for Vehicle-to-Grid Operations", Proceedings of Transportation Research Board (TRB) Annual Conference, 2011.

Doctoral Theses

Kim, Seok. Doctoral Candate. Department of Civil Engineering. Texas A&M University. Thesis topic: Models and Solution Approaches for Development and Installation of PEV Infrastructure. Thesis in progress.

Tuttle, David. Doctoral Candidate. Department of Electrical and Computer Engineering. University of Texas at Austin. Thesis topic: Time Variant Quantities of PEVs Required to Enable Grid Ancillary Services with One-Way Power Flow. Thesis in progress.

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1. Introduction

1.1 Overview

The use of electric energy as a propulsion fuel in transportation sector is rapidly growing. From this trend and recent announcements by carmakers, Plug-in Hybrid Electric Vehicles (PHEVs) and Battery Electric Vehicles (BEVs) are becoming an eventual reality that presents challenges and opportunities. Indeed, with the increase in volatility of the crude oil market and unimaginable price of oil, as well as the threat of global climate change increasingly acknowledged, the electricity and transportation sectors are investigating a number of new technologies that will enhance energy security by reducing the current dependency on oil-based fuels. The interest in PHEVs/BEVs has increased due to their impact on redistribution of the pollution from tail pipe to smoke stack, low-cost charging, and reduced petroleum usages. Compared with traditional Hybrid Electric Vehicles (HEVs), PHEVs/BEVs have an enlarged battery pack and an intelligent converter. PHEVs/BEVs represent a technology that will serve the consumers in both electricity and gasoline markets and address the pressing issues of fossil-fuel dependencies and climate change.

Studying the impact of PHEVs/BEVs is quite complex and identifies novel problems. No other approach before PHEVs/BEVs had the unique capability of acting as dispersed and yet mobile energy storage that may be aggregated at different scales. Keeping in mind incentive programs that can be developed as a new business model for exploring the role of PHEVs/BEVs as dynamically configurable (mobile) energy storage, the potential impacts on both electricity and transportation networks may become quite diverse. This study is focused on how PHEVs/BEVs as dynamically configurable dispersed energy storage can create multiple benefits in electricity networks while playing a major role in the transportation networks. Further, in such settings where electricity, transportation, and emerging carbon markets converge, it is of paramount importance to understand consumers' choices as they transcend traditional boundaries and include travel patterns, as well as future government regulations, aggregation opportunities, retailers' incentives, etc. With the growth in adoption of PHEVs/BEVs and utilization of dynamically configurable (mobile) energy storage units, the transportation market has the potential of becoming an upstream business component of the electric power industry.

In a scenario with high penetration rate of PHEVs/BEVs acting as dynamically configurable energy storage, many functions of the electricity network may be affected. While this study is focused on the impacts on the electricity network, it is clear that transportation networks may experience impacts simultaneously. Since the investment and returns are the main driving force behind the opportunities, the study is addressing the issue of how new business opportunities utilizing PHEVs/BEVs may be created to spur innovation and entice new investments.

1.2 Current Research Status

Many researchers have investigated the various potential benefits and implementation issues of V2G concept [1]-[13].

Kempton and Tomić studied the fundamentals of using PHEVs for load leveling, regulation, reserve, and other purposes [2]. They also discussed three vehicle types that can produce V2G power and the net revenue when selling V2G power to power markets [3]. Hadley and Tsvetkova analyzed the potential impacts of PHEVs/BEVs 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 PHEVs/ BEVs on electric power network components [5]. Farmer, et al. describes the PHEV distribution circuit model to estimate the impact of an increasing number of PHEVs/ BEVs on transformers and underground cables within a medium voltage distribution system [6]. Han, et al. proposed the optimal V2G aggregator for frequency regulation by applying the dynamic programming algorithm to compute the optimal charging control for each vehicle [7]. Shimizu, et al. [8] and Ota, et al. [9] also discussed power system frequency control by using V2G system. Anderson, et al. performed the case studies of Plug-in hybrid electric vehicles (EVs) if used by regulating power providers in Sweden and Germany [10]. Pillai and Bak-Jensen modeled the aggregated BEV-based battery storage for the use in long-term dynamic power system simulation when integrating V2G in the Western Danish power system [11]. Guille and Gross proposed a framework to integrate the aggregated battery vehicles into the electric power grid and presented the aggregated PHEVs/BEVs in a parking facility as one of the electric power sources. Their studies consider the role of a new parking facility for PHEVs/BEVs in electric power markets and systems, but not its core parking-transportation function.[12]. Mitra and Venayagamoorthy studied wide area control for improving stability of a power system with plug-in electric vehicles [13].

1.3 Problem Description

As recently defined by the Department of Energy, the Smart Grid has seven widely agreed upon characteristics [14]:

- Enabling informed participation by consumers
- Accommodating all generation and storage options
- Enabling new products, services, and markets
- Providing the power quality for the range of needs in the 21st century economy
- Optimizing asset utilization and operating efficiently
- Addressing disturbances through automated prevention, containment, and restoration
- Operating resiliently against all hazards

It is enlightening to briefly review how PHEVs/BEVs acting as dynamically configurable energy storage can affect the above seven characteristics of the Smart Grid:

- In this case the consumers are the owners of the energy storage and this potential can only be fully utilized if the car owners are informed of the opportunities and get actively involved.

- Accommodating all generation and energy storage options is also quite obvious; PHEVs/BEVs can act as both the dispersed energy storage and at the same time support effectively interfacing of alternative generation sources such as wind and solar.
- Enabling new products, services and markets is indeed possible with innovative ways of using PHEVs/BEVs. Acting in both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) modes, PHEV/BEV uses invite re-definition of ancillary services to allow for elaborate load participation, aggregation options, and energy trading products.
- Providing the power quality for the range of needs in the 21st century economy is what PHEVs/BEVs can support rather well. Dynamically configurable energy storage can offer uninterruptible power supply options for residential and business needs during emergencies by being massively distributed, as well as clean power by “buffering” the erratic behavior of some electricity sources through energy storage.
- Optimizing asset utilization and operating efficiently can be met by PHEVs/BEVs in several areas. The utilization of power plants may be better controlled through the trade-off between mobile-point and fixed-point sources of emissions, while charging of PHEVs/BEVs in off-peak periods can be optimized to assure minimal loss-of-life impact on existing distribution system assets.
- Addressing disturbances through automated prevention, containment, and restoration is another opportunity for PHEV/BEV utilization. The dynamically configurable energy storage can provide local source of energy in the network in the regions where aggregated support is feasible (large metropolitan areas) preventing the need to shed the load at critical times.
- Operating resiliently against all hazards is another grid support feature that PHEVs/BEVs can offer. By the nature of the dispersed phenomenon, PHEVs/BEVs acting as distributed and yet mobile energy storage can, if and when an attack or disaster strike, act as a ubiquitous source of electricity that can be moved around as needed, at least for the critical initial period.

To meet future challenges, the utility industry and the transportation sector in various regions (metropolitan, municipalities, rural) need to take a comprehensive, holistic view of the synergies between the transportation and electricity networks that will result from the large scale uses of aggregated PHEVs/BEVs. This systemic approach is typically referred to as the built environment planning. This brings a need to study both macro (state or multi-state utility grid and highway system) and micro (dispersed generation and transportation networks of local/regional interest) issues.

To offer sustainable solutions, the study will need to focus on the synergetic benefits rather than just the benefits that may come from PHEV/BEV uses in the electricity infrastructure. Indeed, understanding users’ behavior across the systems is the key to capitalize on emerging opportunities. For example, transportation choices and behavior can become a binding externality that could significantly affect the ability of the electric power industry to exploit full benefits from adoption of PHEVs/BEVs. At the same time,

such interdependency of consumer behavior can further help the industry. It is important to focus on a consumer that participates in both markets and therefore links them. A key modeling challenge is the combination of electrical and traffic models, with representation of charging and discharging activities.

Developers can make a profit from unique opportunities of smart garage, such as V2G and G2V operations. Smart garage would provide a charging service for PHEV/BEV drivers in G2V mode and an ancillary service for electricity power network in V2G mode. Smart garage developer can also earn a profit from traditional parking service such as the ones provided by conventional parking garages. Revenue from those services is closely related to a parking demand which varies depending on developer's decisions. For example, as smart garage is closer to final destination and parking fee is reduced, the garage demand increases, and vice versa. The 'smart garage development problem' suggested in this report will provide the optimal location and incentive structure to maximize developer's profit.

An increase in PHEV/BEV sales may force operators of existing parking garages to install charging stations. Uncertainties of future PHEV/BEV penetration and PHEV/BEV charging rate (i.e. number of PHEV/BEV users charging at the garage) make it difficult for the operator to decide a quantity of charging stations to be installed. If charging stations are installed in insufficient numbers, the garage operator will have additional cost derived from the loss of potential profit. On the other hand, if charging stations are excessively installed, the operator will incur the cost associated with the improper use of spaces and capital. Therefore, the garage operator should be conscientious in deciding on a number of charging stations to be installed. The 'charging station installation problem' in this report will address the problem of determining the optimal number of charging stations with accounting for uncertainties.

Aggregated PHEV/BEV in smart garage can perform as distributed generator or load on electricity power networks, and have an effect on power system operating conditions and locational marginal price (LMP). LMP is the basic cost of energy and is used to settle an electricity trade. Therefore, developer's decisions affect not only the demand of smart garage but also locational marginal price. The model in this report will show the impact of smart garage where PHEV/BEV are parked on electricity power networks and provide the developer's optimal decisions with considering the impact of smart garage.

1.4 Goals and Objectives

This research is focused on study of PHEVs/BEVs as dynamically configurable (mobile) dispersed energy storage in integrated transportation, energy, and built environments. The following goals and objectives are envisioned:

Goal #1: Investigating of PHEV/BEV large scale penetration scenarios and aggregation options

The objective of this task is to develop methodology for study of adoption rates and incentives for PHEVs/BEVs adoption across the nation. This information will provide feel for how dispersed the energy storage is and what are the logical aggregation options.

Goal #2: Evaluating existing controllable battery chargers to assess capabilities of controlled charging in providing load leveling, regulation, and other services

The objective of this task is to develop simulation environment to evaluate controllable battery charger/inverter technologies. The tests will be performed for obtaining estimated capabilities, from controlling charge and discharge rates, for PHEVs/BEVs to providing load leveling, regulation, and other services.

Goal #3: Studying impacts of PHEV uses in load leveling, regulation, reserve, emergency, efficiency, and renewable generation interfacing, particularly considering the mobility

The objective of this task is to take the data from Task #2 together with other available information about PHEV/BEV battery and battery charging capabilities to estimate the scale of contribution from a PHEV/BEV fleet to providing load leveling, regulation, and other services assuming full mobility of the storage.

Goal #4: Understanding of PHEV/BEV ancillary services, demand bidding options, and impact on unbundling market offerings.

The objective of this task is to understand the value of the ancillary services provided by PHEVs/BEVs, using both historical ancillary service price data and forecasts of costs in coming years.

Goal #5: Managing development of energy exchange stations in interfaced transportation and electricity networks.

The objective of this task is to develop short- and long-term strategies for development of PHEVs/BEVs infrastructure. This includes: a) the model formulation with a special emphasis on technology adoption and network effects, regulation uncertainty, and meta-system constraints, b) the solution approach, and c) development of a case study.

Goal #6: Analyzing synergy between electricity and transportation impacts of large scale uses of PHEVs/BEVs in aggregated mode

The objective of this task is to identify specifically how the mobility of storage by PHEVs/BEVs, the geographical and temporal variation in electricity price, and the geographical and temporal variation in road congestion all interact.

Goal #7: Assessing cumulative environmental benefits of dynamically configurable dispersed energy storage.

The objective of this task is to estimate the displacement of fossil emissions due to the use of PHEVs/BEVs.

1.5 Organization of Report

The report is organized into eight chapters. Chapter one presents the overview of the project. The background is given in chapter two. Chapter three presents the charging characteristics of PHEVs and BEVs. Chapter four discusses the control of PHEVs/BEVs charging. The strategies for development of PHEVs and BEVs infrastructure are presented in chapter five. Chapter six discusses the role of PHEVs/BEVs in electricity network. Chapter seven presents the synergy between electricity and transportation network. Conclusions are given in chapter eight.

2. Background

2.1 Introduction

This chapter presents the project background. The expected impact of PHEVs and BEVs is briefly discussed in section 2.2. The roadmap for PHEV/BEV development and the concepts of G2V and V2G uses are explained in detailed in sections 2.3 and 2.4 respectively. Section 2.5 discusses the vehicle utilization scenarios and section 2.6 gives the conclusion.

2.2 PHEVs and BEVs

With the price of oil peaking in the recent past close to the once unimaginable \$150 per barrel and the threat of global climate change increasingly acknowledged, the transportation sector is employing a number of new technologies that will enhance energy security by reducing the current dependency on oil-based fuels. Should the gasoline cost increase in the future, PHEVs and BEVs will become the economical choice for transportation. Widespread adoption of PHEVs/BEVs will also improve air quality and carbon footprint, since point source pollution is easier to control than mobile source pollution. This level of control is essential for effective implementation of carbon cap-and-trade markets, which should spur further innovation. In USA, sales of HEVs have grown 80% each year since 2000, proving that PHEVs/BEVs are likely an eventual reality that must be dealt with [15]. The implications of this reality will be highly dependent on the policies in place to use PHEVs/BEVs to the benefit of the transportation and power systems, as well as the drivers, industry, and public at large.

2.3 Road Map of PHEV and BEV Development

This section draws from [16] and provides a road map of several generations of PHEV/BEV technologies.

A. First Generation

The first generation of PHEV/BEV manufacturing is mainly focused on capturing the market leadership while maintaining the extremely high levels of reliability, safety, and convenience that conventional vehicles provide today. Meeting these expectations could be a challenge given that PHEV/BEV technology is new and unproven in large scale customer deployments, which tend to discover problems not easily found despite manufacturers' rigorous validation tests. The global vehicle manufacturers perceive enough safety and durability risks with these first generation vehicles that they are avoiding including two-way power flow capability (G2V and V2G) for the near term. The vast majority of vehicles include only G2V power flow and the driver has on-board vehicle programmability to manually set the charge window. Modest integrated communication capabilities are included, which enables diagnostics and status from the vehicle, limited charge control to set "grid-friendly" charging windows, and control of passenger cabin pre-heating or pre-cooling.

B. Second Generation

The second generation PHEVs/BEVs will be developed with far greater amounts of field and lab experience enabling improvements particularly in streamlining the cost. Enhancements in battery control and efficiency will improve all electric-range or maintain it at decreased costs.

AC Level-1 (120 Volt) and AC Level-2 (240 Volt) charging capability, which will be discussed in detail in chapter three, will remain but likely improved with more substantial communication capability such as power line communications (PLC) between Electric Vehicle Supply Equipment (EVSE¹) and PHEV/BEV, ZigBee wireless communications between the smart-meter and PHEV/BEV, vehicle integrated wireless capability typically over digital cell phone networks, or 802.11 WiFi wireless communications between the PHEV/BEV and a home area network (HAN). These enhanced communications will enable more sophisticated interactions between PHEV/BEV and grid, including the provision of vehicles participating in ancillary services.

C. Third Generation

The third generation PHEVs/BEVs may be providing an industry standard ultra-fast high-capacity interface to the vehicle (beyond AC Level 2) deploying an off-vehicle charger and two-way power flow capabilities. The next generation higher capacity charging infrastructure architecture is likely to be DC charging supporting a maximum power flow of approximately 100kW.

Over the first decade progressively more sophisticated communications, control, and power flow capabilities will be incorporated as vehicle manufacturers gain field experience with batteries, electronics, PHEV/BEV driving habits, and as clearer business models emerge that allow manufacturers to be profitably compensated for the costs and risks of more sophisticated V2G interactions.

The first “reverse” power flow configuration may be Vehicle to Load (V2L) [17]. V2L capability will enable the PHEV/BEV to act as a construction-site generator to an isolated load. An example of this configuration would be a PHEV/BEV pickup-truck which would include an on-board charger, converter, and bed mounted power outlets.

The PHEV/BEV could act as a home backup generator in a vehicle to home (V2H) configuration. Multiple PHEVs/BEVs acting in concert with a local coordinator could support a military mobile hospital in a Vehicle to Premise (V2P) configuration.

Basic V2G interactions could leverage the PHEV/BEV as a distributed storage node to capture locally generated energy from photovoltaic panels and wind generators, or store low-cost off-peak energy for later release back to the grid at higher peak rates through “net-metering.” Net-metering capability enables a home’s electric meter to effectively run backward to credit the customer’s account when their local sources (such as rooftop solar panels or backyard wind generators) produce more energy than their home demands. The excess energy in this case is fed back into the grid. Unlike residential photovoltaic panels which may provide excess power back to the grid simply based upon

¹ EVSE is composed of the conductors, including the ungrounded, grounded, and equipment grounding conductors, the electric vehicle connectors, attachment plugs, and all other fittings, devices, power outlets or apparatuses installed specifically for the purpose of delivering energy from the premises wiring to the electric vehicle.

total sunlight available and the local load, the increased communication and control of PHEV/BEV can provide greater coordination and optimization of reverse power flow to the grid.

D. Fourth Generation

With assured two-way communication and control, additional software, and grid aggregators, fourth generation PHEVs/BEVs may be enabled to generate revenue for the owner through the use of their onboard battery and gasoline generator. In this configuration, PHEVs/BEVs may act as a distributed storage node with their large battery storing less-expensive off-peak energy from the grid or locally generated renewable energy, releasing excess energy back to the grid during higher priced peak demand.

2.4 Concepts of G2V and V2G

When PHEVs/BEVs are plugged in, the power can flow both ways: when electric power stored in electric vehicles flows to power grid, it is called vehicle-to-grid (V2G); the opposite flow of electric power, which means charging batteries in EVs through EVSE, is referred to as grid-to-vehicle (G2V). Figure 2.1 shows the two operation modes.

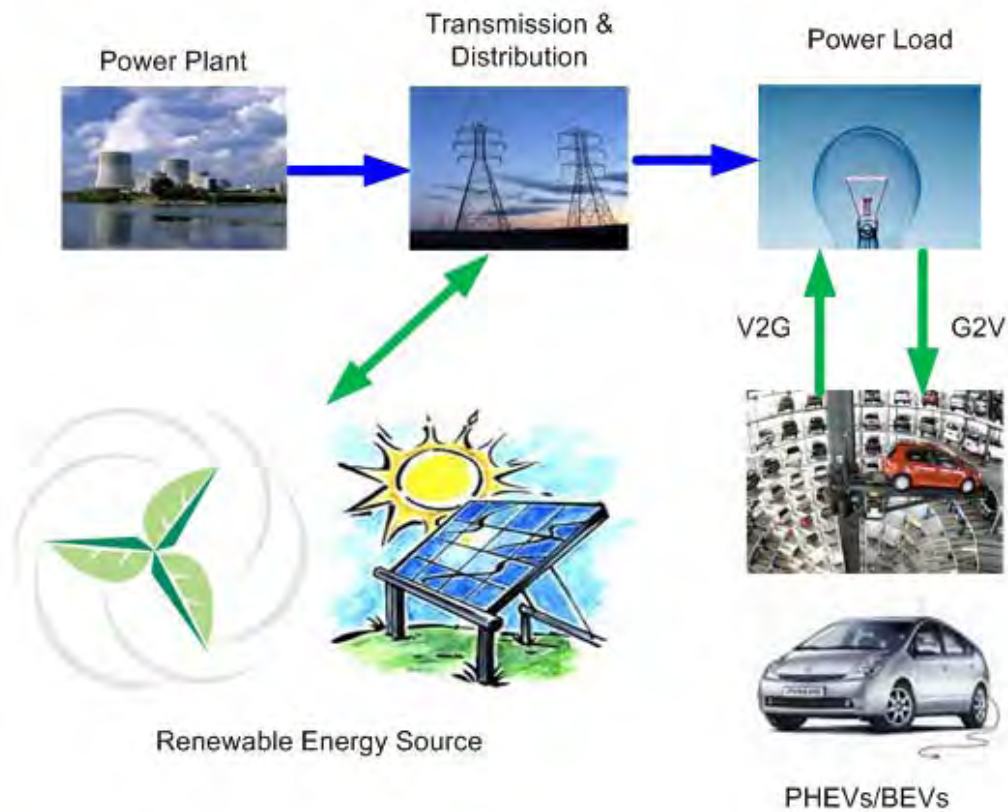


Figure 2.1 Framework of G2V and V2G Connections

The concept of V2G is first proposed by Dr. Willett M. Kempton in 1997 [18]. He explored the potential economic and system potential of electric vehicles connected to the

power grid. The fundamental calculations for costs and power related to V2G technology and the potential markets that V2G users can access are discussed in [2][3].

In general, by serving in two modes: G2V and V2G, PHEVs/BEVs can provide benefits to the power system operation. The G2V mode can be used to charge PHEVs/BEVs at reduced cost when the power system load is reduced and generation capacity is abundant, such as during night time. The V2G mode may be used when demand is high or supply is accidentally lost since the stored electric energy can be released from PHEVs/BEVs in an aggregated way, which will offer major contributions to regulation service and spinning reserves, as well as load-shedding prevention. The mobility of the energy storage in PHEVs/BEVs allows for strategic placement of the distributed generation source to optimize power system needs.

2.5 Utilization Scenarios

2.5.1 Ancillary Services

Based on the Federal Energy Regulatory Commission (FERC) Order 888, several ancillary services are needed to facilitate provision of open access transmission service to a customer. These services range from actions taken to put the transaction into effect (such as scheduling and dispatching services) to services that are necessary to maintain the integrity of the transmission system during a transaction (such as load following and reactive power support). Other ancillary services are needed to correct for the effects associated with undertaking a transaction (such as energy imbalance service) [19]. Order 888 proposed six services that are needed for open access operation of a transmission system. They are:

- Scheduling, System Control and Dispatch Service;
- Reactive Supply and Voltage Control from Generation Sources Service;
- Regulation and Frequency Response Service;
- Energy Imbalance Service;
- Operating Reserve - Spinning Reserve Service; and
- Operating Reserve - Supplemental Reserve Service.

FERC did not specify technical details of the services, and the costing methods for the services vary from one independent system operator (ISO) or regional transmission organization (RTO) to another. For example, in so-called organized markets, energy imbalance service is provided through the “real-time” market, involving clearing of energy offers against demand. Typically, commitments to provide some of the other ancillary services such as regulation and operating reserves are also arranged in a market process. Outside of organized markets, these services are provided pursuant to cost-based rates.

The North American Electric Reliability Council (NERC) followed up on FERC’s initiative by conducting its own more technical study to identify ancillary services [20]. Together with the Electric Power Research Institute (EPRI), they identified 12 Interconnected Operations Services (IOS) [21]:

- Regulation;
- Load Following;
- Energy Imbalance;
- Operating Reserve – Spinning;
- Operating Reserve – Supplemental;
- Backup Supply;
- System Control;
- Dynamic Scheduling;
- Reactive Power and Voltage Control from Generation Sources;
- Real Power Transmission Losses;
- Network Stability Services from Generation Sources; and
- System Black Start Capability.

Different ISOs have slightly different selections of the ancillary and interconnected operations services that they provide. For example, the ancillary services in the Electric Reliability Council of Texas (ERCOT) in the case of zonal market were as follows:

- Balancing Energy Service;
- Regulation Service - Down;
- Regulation Service - Up;
- Responsive Reserve Service;
- Non-Spinning Reserve Service;
- Replacement Reserve Service;
- Voltage Support;
- Black Start Service;
- Reliability Must-Run Service;
- Out of Merit Capacity Service;
- Out-Of-Merit Energy Service;
- Zonal Out-of-Merit Energy (Zonal OOME) Service; and
- Emergency Interruptible Load Service (EILS).

Some of these services were provided for the zonal market solely by ERCOT, like Balancing Energy Service, and others were provided in part by ERCOT and in part by Qualified Scheduling Entities (QSEs). Each QSE could self-arrange to cover its Obligation assigned by ERCOT for each of the following Ancillary Services: Regulation Up, Regulation Down, Responsive Reserve, and Non-Spinning Reserve. Any of the ancillary services that were not self-arranged would be procured as a service by ERCOT

on behalf of the QSEs [22]. In the case of the nodal market, which started in December 2010, some services are still the same as in the zonal market, such as the self-arranged services; and some of the services have changed, for example Out-of-Merit Capacity, Out-of-Merit Energy and Zonal Out-of-Merit Energy Services are included in the Reliability Unit Commitment Service [23].

Historically, most ancillary services besides EILS were actually provided by generators, or by entities that own both generation and have local demand. However, ISOs/RTOs typically also allow for demand-side provision of ancillary services. Pioneering work by Kempton and others [24] has shown the potential for using V2G power flow for PHEVs/BEVs to provide energy and ancillary services to grid. Furthermore, even in the context of one-way power flow under G2V, it is possible for PHEVs/BEVs to provide ancillary services through the ability to control the battery charging rate. The control of charging will be discussed in more detail in chapter 4, while the general role of PHEVs/BEVs in the electricity system will be discussed in more detail in chapter 6.

2.5.2 Outage and Demand-side Management

Most of the time vehicles sit idle parked at homes, streets, parking lots, or garages; hence PHEVs/BEVs battery capacity can be fully utilized during such times. PHEVs and BEVs could serve as decentralized energy storage in a smart grid and can act as either a load or a generator as needed. PHEVs/BEVs may be an attractive integral part of a smart grid, when aggregated in sizeable numbers and capable to operate in the V2G mode.

The V2G approach considers batteries in PHEVs/BEVs as a generation resource for the buildings via bidirectional power transfer through energy exchange stations (chargers/dischargers) at certain periods of time, which could increase the flexibility of the electrical distribution system operation. It is expected that V2G 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 [25]. Chapter 6 will discuss the role of PHEVs and BEVs in distribution system in detail

2.6 Conclusions

This chapter discusses the road map of several generations of PHEV/BEV technologies. The concepts of G2V and V2G operation are also presented. PHEVs/BEVs offer limited or zero emissions to improve air quality. The increasing cost of gasoline eventually will make PHEVs/BEVs the economical choice for transport. With the help of advanced control and communication methods, PHEVs and BEVs can work as a generation resource connected to the power grid via bidirectional power transfer through energy exchange stations. This could increase the flexibility of the electrical distribution system operation since the additional storage will allow for more widespread use of solar and wind generation, which are currently underutilized due to lack of storage. By participating in the ancillary services market, PHEVs/BEVs based V2G will improve the grid's stability and reliability.

3. Charging Characteristics of PHEVs and BEVs

3.1 Introduction

This chapter discusses the charging characteristics of PHEVs and BEVs. The market penetration of PHEVs/BEVs is estimated in section 3.2. The types of charging levels are discussed in section 3.3. Section 3.4 discusses the aggregation of PHEVs/BEVs. Conclusion is given in section 3.5.

3.2 Estimated Levels of Penetration of PEHVs and BEVs

It has been reported that the number of motor vehicles registered in the United States in 2006 is 244.2 million. And there were 111.6 million occupied houses in the US and 91.2% of these houses have at least one vehicle. [26] With the increasing penetration rate of PHEVs, there will be a huge number of the PHEVs which are available for use as the dynamically configurable energy storage.

The penetration rate of PHEVs/BEVs, which have a drastic impact on the smart grid, is expected to continuously increase after the wide spread market introduction is made in 2011 and beyond. Many researchers have assumed the PHEV/BEVs penetration rate in their research to vary in the range of 5% - 50% in the future and multiple studies use either statistical or predictive models to determine the penetration of PHEVs/BEVs. Hadley and Tsvetkova [4] estimate that by 2030 the market share of PHEVs/BEVs could reach 25%. Sullivan, Salmeen, and Simon have researched the PHEVs/BEVs marketplace penetration by the agent based simulation and estimated that the market share in optimistic scenarios could reach around 20 % by 2040 [27]. N.Y. ISO published a technique report for the potential impacts of PHEVs/BEVs on New York State's electricity system. They assumed 25% of the fleet will be PHEVs/BEVs by 2030 [28]. Figure 3.1 shows the cumulative millions of PHEVs in U.S. estimated by The California Cars Initiative [29].

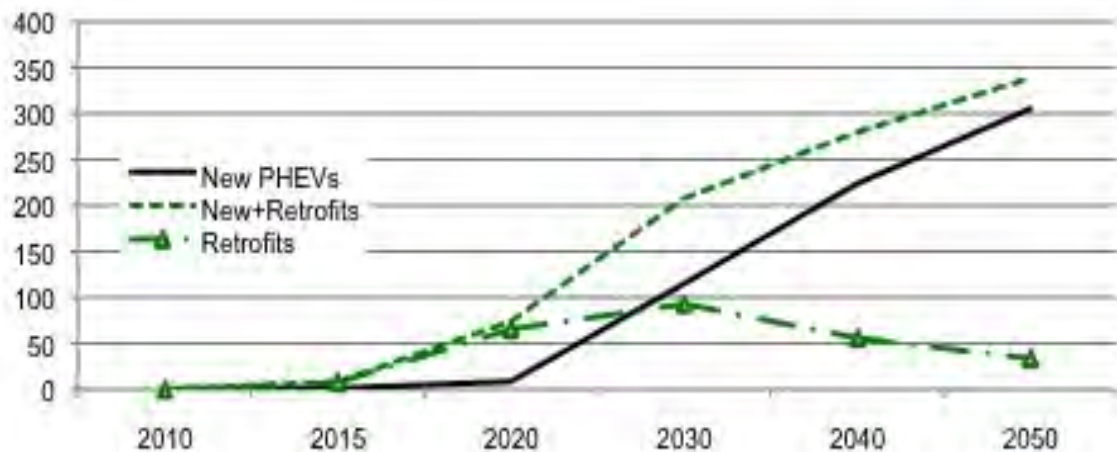


Figure 3.1 Cumulative Millions of PHEVs in U.S. [29]

While all these projections are showing large penetration of PHEVs/BEVs not to occur before 20-30 years from now, gas price, tax rebates, electric vehicle subsidies, and sales tax exemptions may accelerate the adoption and create a significant impact on PHEVs/BEVs penetration levels. However, 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 5-10 years from now. In those major cities, the penetration rate should be higher than other areas, which will provide the feasibility of PHEVs/BEVs serving in electricity markets.

3.3 Charging Stations

3.3.1 Charging Infrastructures

The primary electric vehicle charging station is expected to be located at the residence, business, or fleet facility where the vehicle is garaged. There are also a number of public charging sites that will be available. In North America, standards for installation and functional requirements of electric vehicle infrastructure are provided in the National Electrical Code (NEC) Article 625 [30] and by the Society for Automotive Engineers (SAE) J1772 [31]. SAE J1772 defines the electrical rating of charging methods for conductive charger coupler. The key requirements of Article 625 have been summarized in [32] as:

- Wiring methods, including electric vehicle coupler design, construction, and functionality;
- EVSE coupler requirements, including polarization, non-interchangeability, construction and installation, unintentional disconnection, and grounding pole requirements;
- EVSE construction requirements, including rating, markings, means of coupling, cable, interlock, and automatic de-energization of the charge cable;
- EVSE control and protection, including over-current protection, personnel protection, disconnecting means, loss of primary source, and interactive systems;
- EVSE location requirements, including hazardous (Classified) locations, indoor sites and ventilation requirements for indoor installations (where applicable), and outdoor site requirements.

Based on the SAE J1772 standard [31], conductive charging is a method for connecting the electric power supply network to the PHEV/BEV for the purpose of transferring energy to charge the battery, establishing a reliable equipment grounding path, and exchanging control information between the PHEV/BEV and the supply equipment. In the most fundamental sense, there are three functions, two electrical and one mechanical, which must be performed to allow charging of the PHEV/BEV battery from the electric supply network. The electric supply network transmits alternating current electrical energy at various nominal voltages (rms) and a frequency of 60 Hz. The PHEV/BEV battery is a DC device that operates at a varying voltage depending on the nominal battery voltage, rate-of-charge, and charge-discharge rate. The first electrical function converts the AC to DC and is commonly referred to as rectification. The second electrical

function is the control or regulation of the supply voltage to a level that permits a managed charge rate based on the battery charge acceptance characteristics, i.e., voltage, capacity, electrochemistry, and other parameters. The combination of these two functions is the embodiment of a charger. The mechanical function is the physical coupling or connecting of the PHEV/BEV to EVSE and is performed by the user. The conductive charging system consists of a charger and a coupler. The conductive system architecture is suitable for use with electrical ratings as specified in Table 3.1 and as shown in Figure 3.2.

Table 3.1 Different Charge Method [31]

Charge Method	Nominal Supply Voltage (Volts)	Maximum Current (Amps-continuous)	Branch Circuit Breaker Rating (Amps)
AC Level 1	120 V AC, 1-phase 120 V AC, 1-phase	12 A 16 A	15 A (minimum) 20 A
AC Level 2	208-240 V AC, 1-phase	≤ 80 A	Per NEC 625
DC Charging	Under Development		

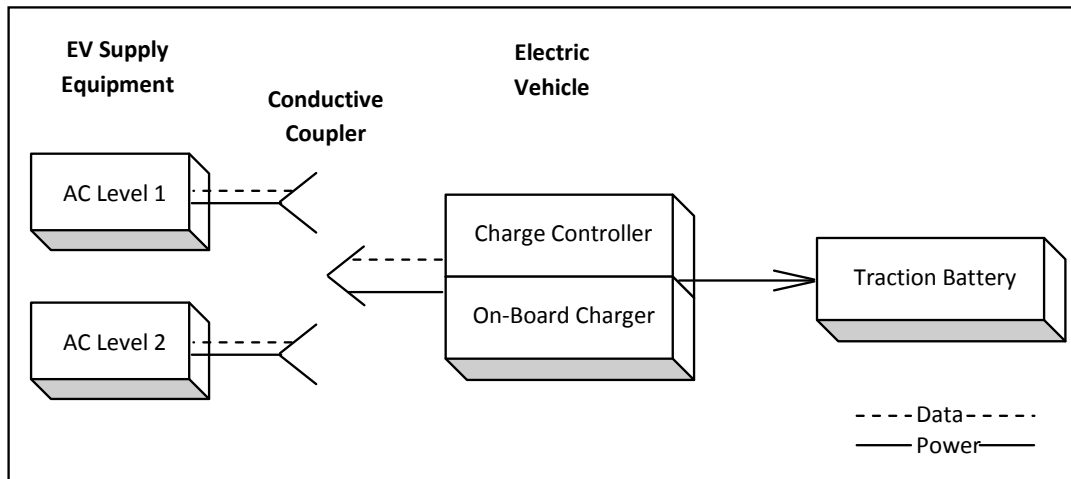


Figure 3.2 Conductive EV/PHEV Charging System Architecture [31]

The conductive coupler consists of a connector/vehicle inlet set with electromechanical contacts imbedded in an insulator and contained within housing for each of the mating parts. The contacts provide a physical connection at the vehicle interface for the power

conductors, equipment grounding conductors, and control pilot conductor between the PHEV/BEV and charge connector. The interface consists of 5 contacts that perform the interface functions as shown in

Figure 3.3 and specified in Table 3.2.

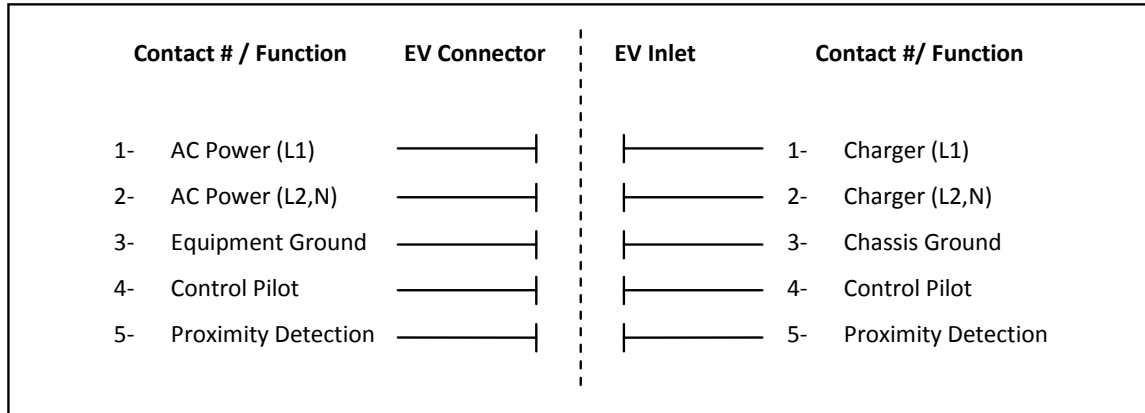


Figure 3.3 AC Level 1 and Level 2 Conductive Coupler Contact Interface Functions [31]

Table 3.2 AC Level 1 and AC Level 2 Conductive Coupler Contact Function [31]

Contact #	Connector Function	Vehicle Inlet Function	Description
1	AC Power (L1)	Charger 1	Power for AC Level 1 and 2
2	AC Power (L2,N)	Charger 2	Power for AC Level 1 and 2
3	Equipment Ground	Chassis Ground	Connect EVSE equipment grounding conductor to EV/PHEV chassis ground during charging
4	Control Pilot	Control Pilot	Primary control conductor
5	Proximity Detection	Proximity Detection	Allows vehicle to detect presence of charge connector

The control pilot circuit is used to verify proper vehicle connection, grounding, and ventilation. After the EVSE verifies that everything is connected properly and that the EV is ready to begin accepting charge the control pilot will commence the charging. As the vehicle charges, the control pilot monitors the connections and will interrupt charging if there is an issue with EVSE or EV connection or if utility power becomes unavailable [33].

Based on the SAE J1772 standard, the EVSE communicates the maximum available continuous current capacity to the PHEV/BEV by modulating the control pilot duty cycle. The EVSE may accept an external signal to vary the duty cycle for supply or premises power limitations, and this can also be used to modulate the charge rate for other purposes such as providing ancillary services. Under the standard, the delay from an external load management signal to the time when the EVSE modifies the pilot signal state, duty cycle or other required response should be at most 10 seconds. The vehicle's on-board charger is used in Level 1 and Level 2 charging to convert the AC input from EVSE into DC power to charge the battery. Under the standard, PHEV/BEV should modify the on-board charger AC current drawn from the line in response to the control pilot duty cycle modification in at most 5 seconds. That is, the delay could in principle be as long as 15 seconds from external load modification to change in charging rate; however, this worst case may significantly over-estimate the typical response times.

3.3.1.1 Level 1

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 only provides a small amount of power with maximum of up to 1.44 kW, and it results in prolonged charge times. So Level 1 is only intended to be an entry level voltage and not the ultimate solution. And also a new dedicated circuit is recommended when using Level 1 charging because of the installed overload protection by the single circuit breaker.

3.3.1.2 Level 2

The Level 2 method uses a 208-240 VAC, single-phase, up to 80-Amp branch circuit. It is the primary and preferred method for the battery electric vehicle charger for both private and public facilities. The typical charging time for a 10 kWh battery pack will be 1 to 2 hours. Two types of Level 2 equipment has been used so far: Conductive and Inductive charging systems. With major auto manufactures dropping inductive charging system, the conductive charging system has prevailed for now. Due to the small battery size installed in most EBVs now, some chargers at Level 2 will be limited to as low as 15 Amp, providing a maximum charging power of 3.3 kW. With the development of high capacity batteries in PHEVs, Level 2 charging system could support up to 80-Amp and has the ability of faster charging.

3.3.1.3 Fast Charging

The Level 3 method is one method for fast charging. Faster charging methods are still under development, which includes the DC charging method. SAE J1772 listed DC charging as being under development. There is no agreed upon current standard for the faster charging or related connector. Literature [31] discusses Level 3 charging method, which uses an offboard charge system serviced by a 480-VAC, three-phase circuit. It is the preferred method for fast charging for both commercial and public applications and is intended to perform similar to a commercial gasoline service station. Most typically equipment sizes varied from 60 to 150 kW and can provide a 50% charge in 10 to 15 minutes for the battery electric vehicles.

Considered the properties of the three charging levels, Level 3 charging for PHEVs is not considered requisite in a residential environment, but may be used in the commercial charging

3.3.2 Smart Charging

Based on the charging infrastructures introduced above, the time needed to recharge 10 kWh of energy to a vehicle battery will typically be only 2–5 hours. Plug-in vehicles will presumably usually be charged at night or at work. Most vehicles are driven only one or two hours a day on average and are parked for the rest of the time. That is, given charging infrastructure, most vehicles can potentially be plugged in for 10–15 hours a day (more for vehicles that are regularly plugged in both at home and at work). The difference between the elapsed time needed for actual charging and the time that the vehicle is plugged in results in timing flexibility that can be harnessed to provide grid services while at the same time meeting the needs of the driver [34]. We call this “smart charging.” In contrast, we say “dumb charging” for the situation in which a vehicle plugs in and then derives the maximum available charge current from the grid until charging is complete or the vehicle is unplugged.

Smart charging is more than just charging at off-peak times. It involves fine-grained control of the charging of each vehicle to meet both the needs of the vehicle owner (charging the vehicle by a certain time) and the needs of the grid (matching generation and load, providing ancillary services, and perhaps also avoiding overloads in distribution networks from many vehicles being charged at the same time). Some vehicles will have tighter constraints on charging than others. A Plug-in Hybrid Electric vehicle (PHEV), which can be viewed as an electric vehicle with an onboard “range extender” that uses a conventional fuel (e.g., gasoline) to provide energy when the battery has been discharged, has enormous flexibility in charging: if the battery is not completely charged when the vehicle is needed, the vehicle will simply use a little more onboard fuel, with the opportunity cost being the difference between the cost of fuel and the cost of charging with electricity. A battery electric vehicle (BEV) will likely have tighter constraints on charging, depending on its range and its owner’s driving patterns [34].

3.4 Aggregation of PHEVs and BEVs

Vehicle charging can be managed by either simple on and off type of charging or by modulating the charging rate over the time. Modulating the charging rate can be viable indirectly through EVSE or directly through PHEV/BEV (Figure 3.4). For indirect control, a signal would be sent to the EVSE for controlling the charge rate. Then, the EVSE modulates the pilot duty cycle and the PHEV/BEV modifies its load impedance to adjust charging current accordingly. However, for direct control the signal would be sent directly to PHEV/BEV and it then modifies its load impedance to adjust charge current. An important issue for any kind of charging management is communication between grid operator and the vehicle. This communication can be, and in some cases should be, done through a third party like an aggregator or a retailer. For example, in ERCOT, the aggregator would be a “qualified scheduling entity.”

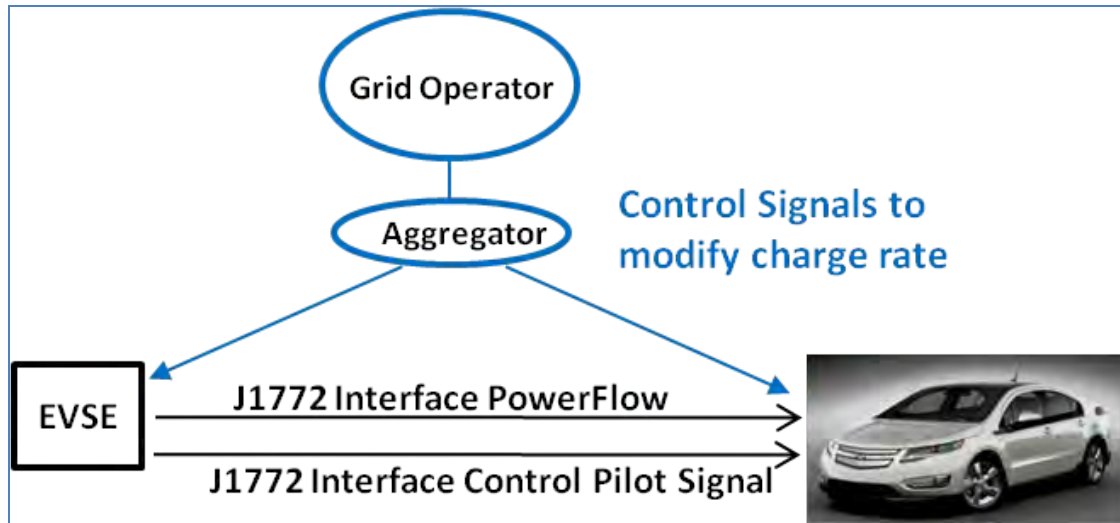


Figure 3.4 Two Different Ways of Modulating the Charging Rate

Different plug-in vehicles generations will have different capabilities for interaction with the grid based on their technologies. An aggregator will coordinate the application of multiple PHEVs/BEVs to meet product or service commitments to the ISO while also achieving targeted charge levels regarding commitments to the vehicles. As with any load resource, an aggregator will need to sign up a sufficient number of PHEVs/BEVs to provide the product or service and meet the requirements to participate in the market. Participation in the market is viable if it has a value for the PHEV/BEV owners. PHEV/BEV owners will need to balance the desire for payments associated with participating in ISO-related products against concerns about battery life impacts or charging convenience. Future customer preferences, energy rates, social pressures, and other factors will foster or discourage the growth of PHEVs/BEVs as a participant in the electricity markets [35].

3.5 Conclusions

The chapter discussed the charging infrastructure for PHEVs and BEVs. SAE J1772 standard defines the electrical rating of charging methods for conductive AC charger coupler at level 1 and 2. The household circuit capacity with 120V is capable of charging the PHEV/BEV battery, which is defined as AC Level 1. AC Level 2 charging system could support up to 80-Amp and has the ability of faster charging if needed in the future. DC faster charging method is still under development, but it has a bright future, which could finish the charging procedures in half hour if DC chargers are available. Charging/discharging in public parking spaces or parking garages in business districts would allow for easier aggregation of PHEV/BEV to provide ancillary services.

4. Control of Charging

4.1 Introduction

Plug-in vehicles are being developed by almost all major automakers and as discussed earlier in this report will be introduced in volume in the near future [34]. The daily energy use for driving 30 miles electrically for a typical passenger car will be on the order of 10 kWh, making plug-in vehicles one of the biggest energy-consuming devices in a household [34]. If the market for plug-in vehicles grows rapidly then there will also be a rapid increase in charging load. Consequently, the challenges and opportunities that large electric vehicle penetration presents to the utility grid should be investigated, even if absolute numbers will remain low for many years compared to the total vehicle fleet [36]. The rest of this section is organized as follows. Section 4.2 describes the battery and charging system. Section 4.3 discusses PHEV/BEV interface with the grid. The individual garage versus parking lot charging is presented in section 4.4. Conclusion is given in section 4.5.

4.2 Battery and Charging System

4.2.1 Battery System

This section draws details from [33]. The battery systems of PHEVs/BEVs have two main components: the battery management system (BMS) and the battery pack. The BMS monitors the battery state and health, and provides an interface between the battery and the rest of the vehicle including the onboard charger. The BMS may also handle energy management while the vehicle is operating based on the power and energy needs of the drive train.

A PHEV/BEV battery pack includes several interconnected battery modules, which in turn are comprised of individual battery cells connected in series and parallel. The battery chemistry which is most viable for PHEV/BEV applications is currently lithium-ion (Li-Ion).

Although the battery pack is rated for a certain energy capacity, this overstates the energy that can be withdrawn between recharging since there is a minimum allowable state-of-charge (SOC) to prevent damage to the battery and to prolong battery lifetime. The difference between the maximum and minimum allowable SOC is referred to as the usable state-of-charge. Depending on the battery design and vehicle design this usable SOC will typically be in the range of 50% to 80%.

A PHEV/BEV will typically operate in charge-depleting mode until the usable SOC has been consumed and in terms of discharge/charge cycles would be considered a deep cycle. Battery systems currently being developed for PHEVs/BEVs are designed to have a cycle life of about 3,000 deep cycles or more. This means that if a vehicle uses all of its electric-range nearly every day and charges fully overnight, the battery system should last for about 10 years or more. A battery's useful lifetime for PHEV/BEV applications is typically measured at the point where its usable SOC is less than 80% compared to a new battery, or when it is able to supply less than 80% of the peak power required for vehicle operation. A related parameter that is commonly used when discussing batteries is the

depth-of-discharge (DOD) expressed as a percentage. The DOD is not determined directly, but is calculated by subtracting the state-of-charge from one hundred.

4.2.2 Battery Charging Profile

This section draws details from [33]. The energy needed to charge a PHEV/BEV will vary based on the specific battery pack and charging equipment. The charge rate will vary depending on the charge profile, for instance a battery pack may be charged using a simple constant current or constant voltage profile. However in general a combination of these will be used, and will vary by battery technology and manufacturer. In addition different charging strategies may be used throughout a single charge session as battery parameters reach thresholds or to improve the health of the battery.

Lithium-Ion batteries are typically charged using a combination of constant current and constant voltage profiles, denoted CC/CV. To begin, a constant current is applied while the voltage rises to its upper limit after which the voltage must be held constant to avoid damaging the battery. During the constant voltage segment the charge current will begin to decrease as the battery approaches a full state of charge. Finally, charging will be cutoff when the current has reached a minimum threshold, for instance 3% of the rated current. A sample charge profile illustrating constant current/constant voltage charging is shown in Figure 4.1. The charging current could, in principle, be reduced from the maximum levels indicated in the figure in order to modulate the charging rate, but currents should not exceed these levels.

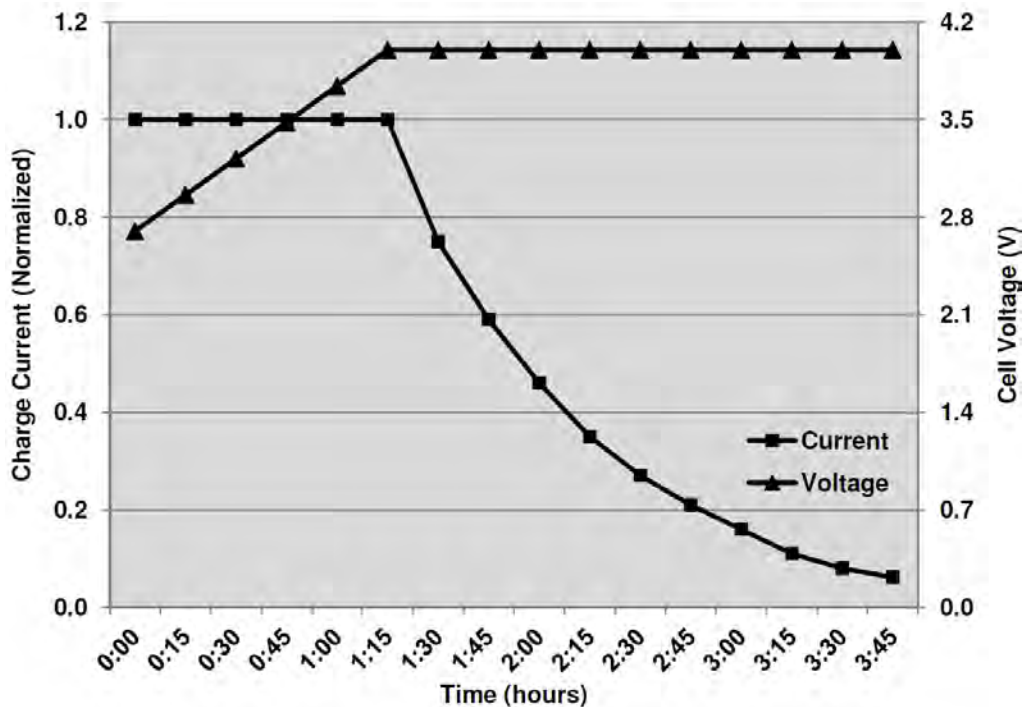


Figure 4.1 Sample Charge Profile for Lithium-Ion Batteries [33]

For a single Lithium-Ion cell the maximum charging voltage will typically be limited to about 4 volts or less, depending on the particular chemistry. An entire PHEV/BEV

battery pack will have a nominal voltage of several hundred volts. The values for charge current in Figure 4.1 are normalized to show the general charge current trend, since the actual charge current will depend on the specific charge. In addition the charge time and cutoff current are somewhat arbitrary and will vary based on the actual charge rate and manufacturer specifications. These characteristics have implications for the control of charging.

4.3 PHEVs/BEVs Interaction with the Grid

4.3.1 Introduction

Research on the impact of electric vehicle charging goes back to the 1980s. In an early paper, Heydt discusses typical driving profiles and concluded that the charging will likely coincide with overall peak demand and therefore that load management should be applied to avoid overloading [37]. Heider extended this analysis and found that the increase in peak demand is much higher if no infrastructure to support charging at work and throughout the cities is deployed [38]. However, the severity of this effect depends on the time of the existing peak demand in the day and the charging habits of drivers. If the peak charging load is allowed to coincide with the time of the existing peak load then this could cause a significant increase in peak load.

In contrast, Schneider et al. suggests that the utility grid in the United States is not used nearly to its full capacity during the night time and that the demand of electric vehicles should therefore be shifted to night [39]. According to a related study, with only modestly well-behaved charging, the existing U.S. energy grid can support 84% of the light duty vehicles in U.S [40]. The only real constraint on the existing generation and transmission system supporting this massive number of PHEVs/BEVs in the U.S. is the avoidance of charging during the most extreme periods of peak demand on the grid [4][41]. An example is late in the afternoon on a very hot summer day with extreme air-conditioning loads. The critical charge avoidance periods will vary by region, weather, and year but likely constitute less than a few hundred hours of an 8760 hour year for generation, transmission, and distribution, with the possible exception of clustering of PHEVs/BEVs on some distribution feeders. The key to avoiding these periods is the implementation of modest coordination of charging windows, staggered charge starting, and avoiding critical peak demand aggravation [42].

The most important function when vehicles are parked and plugged in is battery charging, and currently this is the primary interaction between PHEV/BEV and the power grid [33]. As mentioned in section 2.4, another possible interaction between PHEV/BEV and the grid is providing some services to the grid by either feeding power from the vehicle into the electrical grid (V2G) or by providing a controllable rate of charging of power from the grid, principally to provide ancillary services and other load management functions. The SAE Recommended Practice J2847 establishes requirements and specifications for communication between plug-in electric vehicles and the electric power grid, for energy transfer and other applications. Where relevant, J2847 notes, but does formally specify, interactions between the vehicle and vehicle operator [43].

4.3.2 PHEVs/BEVs for V2G

The limitations to using the PHEVs/BEVs for advanced V2G will likely be related to the challenge of implementing assured and secure communications particularly between the aggregator and the large number of PHEVs/BEVs, the amount of the potential income, the additional wear on the PHEV/BEV battery, and the degree of inconvenience to the driver. The use of PHEV/BEV range extending engines to generate energy (and create compensating revenues for the PHEV/BEV owner) which is then fed back to the grid to reduce grid peak demand has questionable likelihood of achieving mass adoption given the complexities of control, unattractive economics and emissions compared to traditional very large scale grid generation.

One important consideration is the cost of the PHEV/BEV battery itself. It will take some real incentives to induce the vehicles owner to participate in V2G if the owner has to face the warranty constraints. The warranty for both the Volt and LEAF battery is 8 years/100K miles [44][45]. Cycle life of 3,000 is often quoted for Li batteries, but in the case of the LEAF with a real range of maybe 75 miles per cycle, the warranty really only covers about 1,333 cycles. Assuming Li costs is about \$750/kWh today and the battery can only be discharged to 80%, the calculated battery cost alone is as high as \$0.70 / kWh. It may not be acceptable in a case of a private single owner. But it may be acceptable in a V2B or V2G environment where a hefty demand change can be offset with the PHEV/BEV, and where battery warranty could be consumed by the aggregator.

Another concept is to use coordinated PHEVs/BEVs as a grid feeder backup. The need for assured communication and the complexity of coordination also make the use of PHEVs/BEVs for feeder backup extremely challenging. Orchestration of this concept would require coordinated isolation of the feeder through grid protection and isolation devices such as relays, breakers, and fuses. It would also require real time estimation of cold start load conditions and cold start coordination across multiple vehicles (given it is likely that multiple coordinated vehicles will be needed to serve an entire feeder) and estimation of the load on the feeder and generation capability of the combined set of vehicles. Algorithms to address issues from different feeder configurations (single-phase or multiple phase feeders, for example) would also need to be created.

Coordination of frequency, voltage, and reactive power support across multiple vehicles would be required. Graceful coordination of shutdown of PHEV/BEV generation and resumption of grid supplied power would also be required. These functions are unlikely to appear in the near future.

4.3.3 Grid Capabilities, Infrastructure, and Concerns

To first implement rudimentarily intelligent PHEV/BEV charging, G2V power flow will likely be controlled by the driver manually setting the charge window in the PHEV's on-board computer. "Grid advised", automated, or real time charge window control could be sent from the system operator, aggregator, or retailer to the PHEV/BEV by a variety of communication pathways discussed in previous section. Vehicle to Load (V2L) construction site generator configurations are "off-grid" and hence have no communications or coordination requirement with the grid. V2H or V2P, where the reverse power flow is only to an isolated premise requires only communication between

the off-vehicle EVSE, outlet, transfer switch device(s) and the vehicle(s) and no external communication functions beyond the premise.

PHEV-Grid communications capabilities are essential to enable advanced interactions but may also be important for mitigating the impacts of very large numbers of PHEVs/BEVs charging from the grid. Initially, however, the volumes and energy consumption of the first generation PHEVs/BEVs will likely be inconsequential to the grid. Simple driver entry of a cooperative charge window will likely be sufficient to avoid significantly exacerbating peak loads and should be acceptable to early adopters. As increasing numbers of PHEVs/BEVs are sold, local grid to vehicle communications broadcasting will be useful for emissions and price signaling. Later, two-way communications that transmit the present and desired state-of-charge (SOC), power flow, and other parameters will be useful in enabling Demand-side Management (DSM), Opportunistic charging, Load Acting as Resource (LaaR), and various forms of ancillary services. Advanced interaction to create income from providing services to grid is a sophisticated concept that would require assured communications and coordination, aggregating entities to control large numbers of participating PHEVs/BEVs, and sufficient economic incentives to provide those services.

With the diversity of utilities, of utility deployed technologies, and of utility technical capabilities it is likely that PHEV-OEM-Utility communication will likely be the first mechanism implemented through vehicle-integrated wireless pathways such as GM's On-Star, and this will happen before PHEV-ZigBee/PLCSmartmeter-UtilityBackhaul communications pathways are broadly implemented [46]. These vehicle manufacturer controlled solutions will likely provide a secure portal for utilities to indirectly connect to a particular vehicle but with unknown incremental costs and communication assuredness. Technologically sophisticated PHEV/BEV manufacturers can certainly implement indirect PHEV-Grid communications, but the latency, liability, security, ownership, and costs may not be acceptable to utilities, ISOs, or PHEV/BEV drivers.

The control strategy used by ISOs will have to adapt to mass numbers of controllable PHEVs/BEVs. ISOs presently centrally control a relatively small numbers of large devices (such as large scale generators). But with large numbers of relatively small distributed devices, such as PHEVs/BEVs, the control strategy may need to use decentralized control through price or emissions signaling particularly if the vehicle can receive local real time price, CO₂, and generation information over a variety of methods such as FM radio RDS sub-bands or HD/Digital radio airwaves. In addition, local frequency measurements may also be necessary to augment ISO signals and to ensure that variable charging rates are always utilized to enhance grid conditions. In particular, local modulation of charging rate based on measurements of frequency would enable vehicles to implement the equivalent of governor droop control, increasing charge rate when frequency increases and decreasing charge rate when frequency decreases.

Given the thousands of utilities each with the freedom to choose their own technologies and multiple technical solutions possible, it is likely that vehicle manufacturers, owners, and utilities will all benefit from PHEVs/BEVs providing a commonly used configurable communications socket or a common PHEV/BEV-EVSE communications interface where the EVSE is then used as a bridge to the required residence HAN/SmartMeter-AMI interface. With a standardized interface, individual communication interface

modules can be installed that support the many potential standards such as ZigBee™, 802.11 Wi-Fi™, WiMax™, cell phone, or PLC which could be selected based on regional needs, terrain, cost, or utility preferences. This will be essential for matching the scale of car manufacturing, where hundreds of thousands or millions of cars are built, to the disparate arrangements across utilities and ISOs in North America.

4.4 Individual Garage versus Parking Lot Charging

Public and workplace charging infrastructure will be developed over time; however, the most used charging location is likely to remain the residential garage. PHEV/BEV buyer clustering is likely under these circumstances, which will require distribution analysis and occasional upgrades. Commercial fleets with home-base charging will develop as PHEV/BEV costs improve over time and become economically attractive. Given longer refueling/recharging times required for PHEVs/BEVs compared to conventional vehicles, public charging infrastructure may be better suited for locations not traditionally used for conventional vehicle refueling. Instead of conventional gas stations where drivers tend to want to spend the least amount of time possible, the PHEV/BEV public charging location paradigm will likely be locations that drivers desire to spend considerable time such as shopping malls, restaurants, movie theatres or where the vehicles are regularly parked for long periods such as employer, mass-transit, or airport parking lots. As employers provide daytime charging stations in their parking lots, intelligent charging capabilities will be needed to avoid aggravating high-peak charge periods over the course of the year.

Shopping center public charging stations with free AC Level-1 or AC Level-2 charging may become a tool for retailers to attract PHEV/BEV drivers to their stores, shop longer, and purchase more goods. The energy cost is likely minimal for AC Level-1 or AC Level-2 charging. By making the charging free, these particular EVSEs could be lower in cost since they do not require authentication and secure transaction processing capability. These EVSEs would likely not be ultra-fast high-capacity for a number of years given increased energy costs, unsettled standards, and increased EVSE costs and safety concerns.

Multifamily residences and street based parking present an infrastructure investment challenge which likely will not be addressed at a large scale until PHEVs/BEVs achieve substantial market adoption. PHEV drivers who live in multifamily dwellings or park on the street may strongly prefer range-extended PHEVs (over BEVs) combined with access to charging at their workplace or where they shop. If these drivers do not have an opportunity to charge, then the extended-range PHEV can still simply and beneficially operate similar to a conventional HEV.

Some of the greatest challenges to building a public charging infrastructure will be the initial costs, sitting for convenience, reserving parking spaces, long charge times, and the potential for low or negative returns on investment for owners of public charging stations. For the first decade if not more, AC Level-1 and AC Level-2 public charging stations will likely dominate. Later, ultra-fast high capacity public charging stations may become more pervasive as large numbers of PHEVs/BEVs are on the road. These ultra-fast high-capacity charging stations will create heavy, sporadic loads on the distribution network which may have a meaningful effect on feeders and may require local storage to condition the distribution feeder to maintain power quality [47]. Most high power public

stations will likely need to include authentication and secure transaction capabilities for commerce.

Public or place of business parking garage based charging would allow for easier aggregation of PHEV/BEV charging loads to provide ancillary services, since the large number of charging stations in close proximity would allow for metering of and control of a fairly large number of EVSEs, with telecommunications costs amortized over a large number of vehicles. In contrast, aggregation of multiple home garage charging stations will involve metering of and communication with the individual cars to coordinate their charging.

4.5 Conclusions

This section has discussed the control of and communication with battery chargers, including discussion of the battery and charging system, the EVSE, and the evolution of interaction of the PHEV/BEV with the grid. PHEV/BEV-to-Grid communications capabilities are essential to enable advanced interactions. The large number of charging/discharging stations in close proximity of each other would allow for metering and control of a fairly large number of EVSE, with telecommunications costs amortized over a large number of vehicles. In contrast, aggregation of multiple home garage charging stations will involve metering of and communication with the individual cars to coordinate their charging, which may be cost prohibitive.

There are some requirements and challenges for providing ancillary services, such as the minimum threshold capacity, telemetry measurements requirements, and the representation of PHEVs/BEVs in power network models. The control strategy used by ISOs will have to adapt to massive numbers of controllable PHEVs/BEVs. The case study of benefits in several ISO regions shows that these benefits will vary significantly over time, between different ancillary services, and from locality to locality. To the extent that the communications and telemetry costs are fairly small, and the effect of providing ancillary services on battery lifetime is negligible, the net benefits to the PHEV/BEV owner and the electricity system could be significant.

5. The Strategies for Development of PHEV/BEV Infrastructure

5.1 Introduction

This chapter aims to address the problem of developing a smart garage and the problem of installing charging stations at an existing parking garage. In this chapter, we assume: a) that developer of parking garage will construct a new parking garage for PHEVs/BEVs, or b) operator will install charging stations at an existing parking garage. The scope of the study is limited to project planning phase. The rest of this section is organized as follows. Section 5.2 describes the development of novel smart garage. Section 5.3 discusses the installation of charging stations in existing parking garage. Conclusion is given in section 5.4

5.2 Development of New Smart Garage

This section provides mathematical formulations to find optimal decisions for parking garage developers. The smart garage development problem (SGDP) provides the optimal location and incentive structure to maximize developer's profit. Last, sensitivity analysis shows the marginal influence for each parameter and suggests some important implications for smart garage management.

5.2.1 Overview

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 PHEVs/BEVs will be using these parking garages, which may provide an aggregated service to act as an electric power source or storage.

Smart garage represents an interface between the transportation network and electric power systems. Figure 5.1 shows the roles of smart garage as the interface between two networks. Smart garage will provide a charging service for PHEV/BEV drivers, which indicates G2V operation, and an ancillary service for electricity power network, which indicates V2G operation. For these operations, smart garage operator will communicate with independent system operator (ISO) to obtain electricity trade prices or to notify the amount of available electricity power.

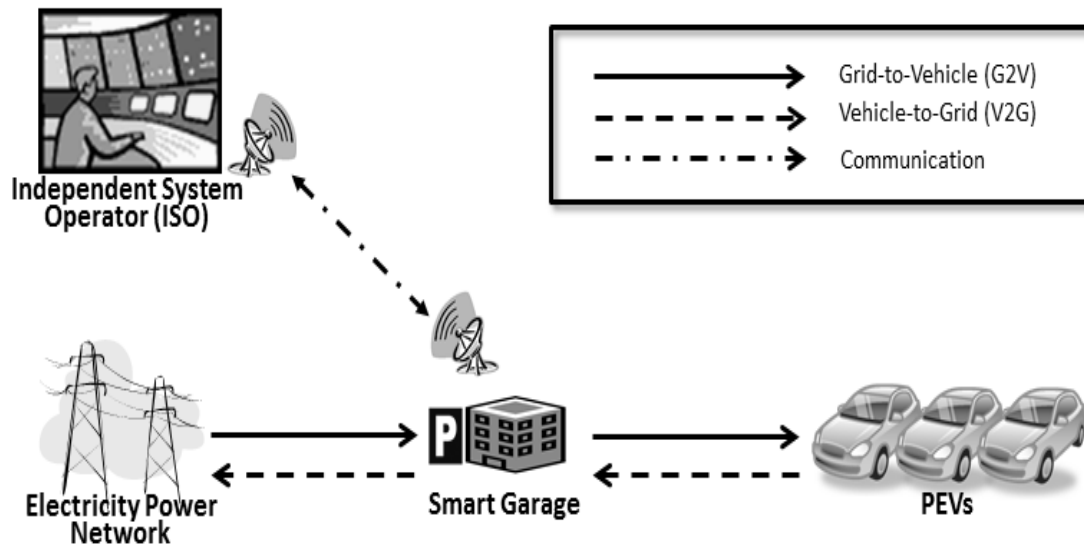


Figure 5.1 Smart Garage Interfaces

Figure 5.2 shows a simple transportation network with smart garage building. As a smart garage is constructed, PHEV/BEV 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 multiple factors including cost of parking at all locations, congestion level, and walking distance. In this study, the location of smart garage and fee structure are considered as decision variables of parking garage developer. Demand of smart garage (number of parked PHEVs/BEVs) can be calculated by these two decision variables.

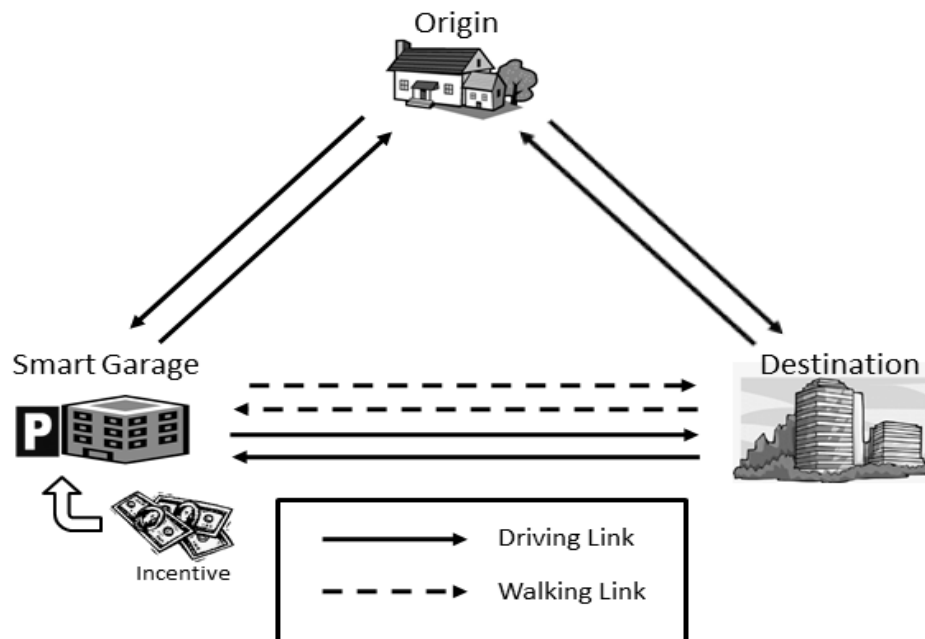


Figure 5.2 Simple Transportation Network with Smart Garage

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 5.3. Due to the versatility, electric power capacity needs to be defined in two parts: for periodic service and for continuous service as in Figure 5.3. 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.

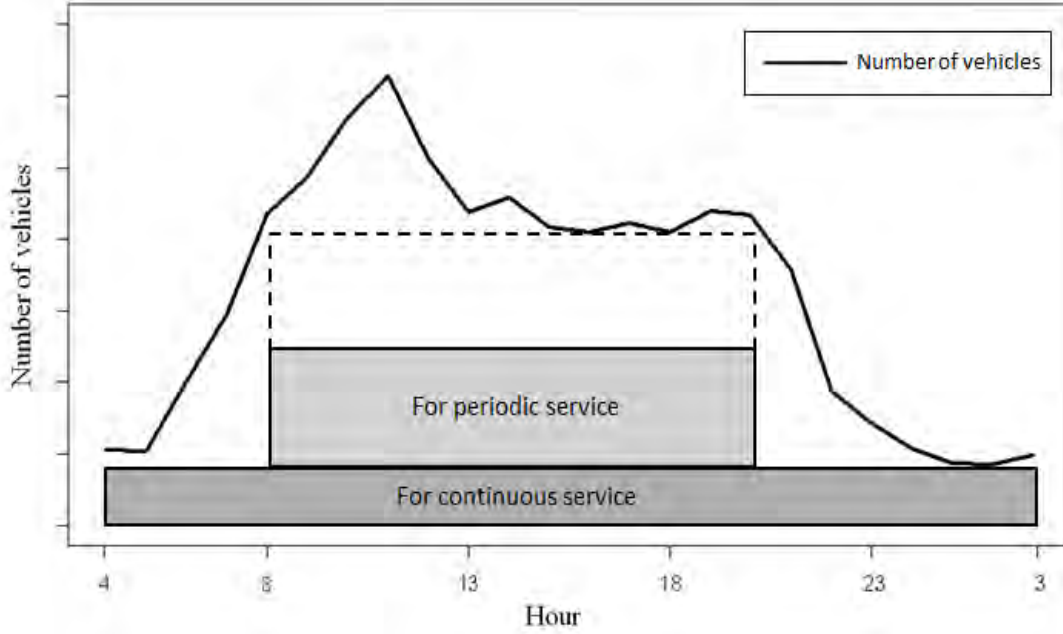


Figure 5.3 Example of Demand of Smart Garage Building for One Day

In order to clarify the presented model, we consider three more key assumptions:

Assumption 1: When choosing travel paths, users follow the user equilibrium principle [48]. Wardrop's first principle implies that drivers choose the routes in a greedy manner. User equilibrium is obtained when no driver can find a lower transportation cost as a result of changing his or her route choice.

Assumption 2: The garage users return from the destination to the origin directly. Again, for simplicity, we do not consider trip chaining.

Assumption 3: The time interval is defined as one hour and all trips as less than an hour. Traffic flow from the origin to the destination and from the destination to the origin is generated every hour, and parking duration is defined in units of one hour.

5.2.2 Mathematical Formulation

Consider a directed network $G(N, A)$ of N nodes and A links, where set A consists of two subsets of links: driving (roadway) and walking (sidewalk) links, A_d and A_w ,

respectively. The network includes k origin-destination pairs (r_i, s_i) , $r_i, s_i \in N$, $i = 1, \dots, k$, and θ mode transfer nodes.

SGDP in this study is formulated to determine optimal location and (dis)incentive structure on a pre-specified link. The SGDP has two levels. The upper-level objective function specified in Equation (5.1) consists of three revenue components: parking fee (disincentive), regulation service fee, and peak demand service fee. Equations (5.2) and (5.3) define the location and incentive decision space. Equation (5.4) defines the demand for the smart garage based on the results from the user equilibrium problem. The lower-level problem is the user equilibrium problem with two user classes (PHEVs/BEVs and Internal Combustion Engine-ICE vehicles), time-dependent trip rates, and walking link costs. The notations of parameters, variables, and sets used in the model are listed in Appendix 1.

$$\max_{l,i} r_{Total}(l,i) = r_{PF}(l,i) + r_{RS}(l,i) + r_{PH}(l,i) \quad (5.1)$$

$$s.t. \quad 0 \leq l \leq L \quad (5.2)$$

$$0 \leq i \leq I \quad (5.3)$$

$$d_h(l,i) = \sum_{u=1}^N (x_b)_h^u + \sum_{u=2}^N (x_b)_{h-1}^u + \dots + \sum_{u=n}^N (x_b)_{h-(n-1)}^u \quad \forall b \in A_W \quad (5.4)$$

$$\min \sum_{A_D} \int_{\omega=0}^{\omega=x_a} (t_a(\omega, l, i))_h d\omega + \sum_{A_W} \int_{\omega=0}^{\omega=x_b} (t_b(\omega, l, i))_h d\omega \quad (5.5)$$

$$s.t. \quad \sum_j (f_j^{rs})_h = (q_j^{rs})_h \quad \forall r \in N, \forall s \in N \quad (5.6)$$

$$\sum_k (f_k^{rs})_h = (q_k^{rs})_h \quad \forall r \in N, \forall s \in N \quad (5.7)$$

$$\sum_w (f_w^{sr})_h = (q_w^{sr})_h \quad \forall r \in N, \forall s \in N \quad (5.8)$$

$$\sum_y (f_y^{sr})_h = (q_y^{sr})_h \quad \forall r \in N, \forall s \in N \quad (5.9)$$

$$(f_j^{rs})_h, (f_k^{rs})_h, (f_w^{sr})_h, (f_y^{sr})_h \geq 0 \quad \forall r \in N, \forall s \in N, \forall j \in J \quad (5.10)$$

$$\forall k \in K, \forall w \in W, \forall y \in Y$$

$$(x_a)_h = \sum_r \sum_s \sum_j (f_j^{rs})_h \delta_{a,j}^{rs} + \sum_r \sum_s \sum_k (f_k^{rs})_h \delta_{a,k}^{rs} \quad (5.11)$$

$$+ \sum_r \sum_s \sum_w (f_w^{sr})_h \delta_{a,w}^{sr} + \sum_r \sum_s \sum_y (f_y^{sr})_h \delta_{a,y}^{sr} \quad \forall a \in A_D$$

$$(x_b)_h = \sum_r \sum_s \sum_k (f_k^{rs})_h \delta_{b,k}^{rs} + \sum_r \sum_s \sum_y (f_y^{sr})_h \delta_{b,y}^{sr} \quad \forall b \in A_W \quad (5.12)$$

5.2.2.1 Lower-Level Problem

Construction of a smart garage changes the topology of a transportation network and drivers' behavior. The existing driving and walking link cost functions can be modified to account for changes in network topology and financial incentive. The modified driving and walking link cost functions are discussed in the Modified Link Cost Functions section.

In this section, origin-destination (O-D) trip rates and parking hours are deterministic, while destination-origin (D-O) trip rates are calculated from the result of the O-D assignment problem and the assumed parking hours. Based on Assumption 2, D-O trip rates consist of two types: "proceed to origin directly" and "walk to the smart garage and drive to origin." The details for trip rates are discussed in the Trip Rates section.

Modified Link Cost Functions

A Bureau of Public Roads (BPR) function [49] has been widely used by researchers and engineers to model travel time/cost on roadway links. A similar function was developed by Fox and Associates [50] for modeling pedestrian travel on walking links. Free-flow driving and walking time is derived from the lengths of the driving and walking links (l_a and l_b) and the average speeds of vehicles and pedestrians (s_a and s_b). Equation (5.13) and (5.14) present modified link cost functions, where the walking link cost function in Equation (5.14) includes the effect incentive ($-\gamma \cdot i$) on the travel time.

$$t_a = \frac{l_a}{s_a} \left[1 + \alpha_a \left(\frac{x_a}{c_a} \right)^{\beta_a} \right] \quad a \in A_D \quad (5.13)$$

$$t_b = \frac{l_b}{s_b} + \alpha_b \left(\frac{x_b}{c_b} \right)^{\beta_b} - \gamma \cdot i \quad b \in A_W \quad (5.14)$$

where x_a is the vehicle flow on the driving link, a , and x_b is the pedestrian flow on the walking link, b ; c_a and c_b are the practical capacity; the quantities α and β are model parameters; and i is the incentive provided by the smart garage building.

In Equation (5.14), γ is an incentive parameter that indicates the amount of time people are willing to walk with financial incentive (one dollar per hour). For example, an incentive parameter γ of 20 means that people will walk for, at most, 20 minutes with an incentive of \$1/hour. This incentive parameter will be affected by the walkability of the walking links. For example, people prefer to walk on better walking links, which means the incentive parameter γ increases with an increase in the quality of walking links.

Trip Rates

This study considers bi-directional trips: O-D and D-O. The total O-D trip rates (q_{Total}^{rs}) are divided into two categories: the trip rates of ICE vehicles (q_j) and the trip rates of

PHEVs/BEVs (q_k) defined by the penetration rate of PHEVs/BEVs (τ). The trip rates are assumed to be generated in intervals of one hour and are defined as follows:

$$(q_{Total}^{rs})_h = (q_j^{rs})_h + (q_k^{rs})_h = (1-\tau)(q_{Total}^{rs})_h + \tau(q_{Total}^{rs})_h \quad \forall r \in N, \forall s \in N \quad (5.15)$$

While total O-D trip rates are divided by types of vehicles, total D-O trip rates (q_{Total}^{rs}) are divided by whether or not drivers use the smart garage building. Hence, there are two D-O trip rates: the rate for the vehicles that have not parked at the smart garage building (q_w^{sr}) and the rate for the vehicles that have (q_y^{sr}). The D-O trip rates are defined as follows:

$$(q_{Total}^{sr})_h = (q_w^{sr})_h + (q_y^{sr})_h \quad \forall r \in N, \forall s \in N \quad (5.16)$$

The D-O trip rates are determined from the results of the previous O-D assignment problem. That is, drivers assigned to a smart garage building in the previous O-D trips should walk back to the parking building in the D-O trip, and drivers assigned to a conventional parking garage in previous O-D trips should return to their origins directly in the D-O trip.

The link flows on A_w are composed of drivers who want to park their vehicles for different parking hours, which is defined in Equation (5.17). The link flows $(x_b)_h$ are part of $(q_k^{rs})_h$ and are obtained from the assignment problem.

$$(x_b)_h = (x_b)_h^1 + (x_b)_h^2 + \dots + (x_b)_h^U \quad \forall b \in A_w \quad (5.17)$$

D-O trip rates, q_w^{sr} and q_y^{sr} , are calculated based on link flows $(x_b)_h$. Trip rate q_y^{sr} is derived from the pedestrian flows, x_b , of PHEV/BEV drivers who parked their cars in the smart garage building. As discussed above, x_b could be divided into $(x_b)^u$'s, depending on parking hours, u . The parking hours, u , should be less than or equal to U . Drivers who have parked their vehicles for specific hours will leave the parking building after their stay at the destination node expires. Therefore, $(q_y^{sr})_{h+1}$ is defined as follows:

$$(q_y^{sr})_{h+1} = \sum_{u=1}^h (x_b)_{h+1-u}^u \quad \forall b \in A_w, \forall r \in N, \forall s \in N \quad (5.18)$$

Finally $(q_w^{sr})_{h+1}$ is computed by subtracting $(q_y^{sr})_{h+1}$ from D-O trip rates. It is defined as follows:

$$(q_w^{sr})_{h+1} = \sum_{u=1}^h \left[(q_j^{rs})_{h+1-u}^u + (q_k^{rs})_{h+1-u}^u - (x_b)_{h+1-u}^u \right] \quad \forall b \in A_w, \forall r \in N, \forall s \in N \quad (5.19)$$

5.2.2.2 Upper-Level Problem

Much like Kempton and Tomic [3], we consider that the garage operator has an option to partially discharge the stored power from parked PHEV/BEV batteries during parking hours. The total amount of available power is dependent on the number of parked PHEVs/BEVs, or, in other words, on the demand for a smart garage building (d_h).

Demand for a PHEV/BEV garage building is not constant. Generally, the demand for a smart garage building during the day would be higher than during the night, similar to the demand for a conventional garage. This is shown in Figure 5.4.

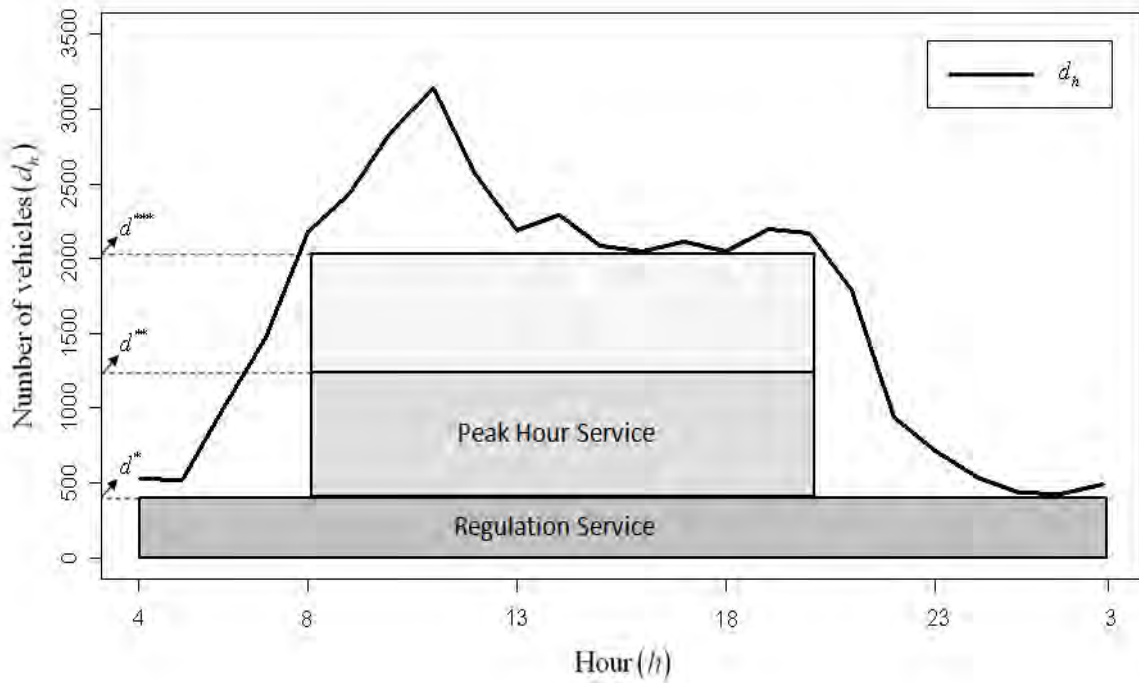


Figure 5.4 Example for Demand of SG and V2G Services.

Revenue from Parking Fee

As previously mentioned, this study considers an upper-level objective based on three revenue components: the parking fee, the regulation service, and the peak hour service. Here, the incentive that smart garages could provide can be considered as a cost, or a negative value of the parking fee. Hence, in an upper-level objective, there is a tradeoff between the cost of attracting more PHEVs/BEVs to park and get the value from ancillary services fees, and the parking fee. When a smart garage building is constructed at location and provides incentive to users, the revenue model from the parking fee is defined as follows:

$$r_{PF}(l,i) = \sum_{h=1}^{24} (d_h(l,i) \cdot f') \quad (5.20)$$

where f' is the parking fee at a smart garage building, and is the difference between the parking fee at a conventional parking garage (f) and the incentive provided by a smart garage building (i).

Revenue from Regulation Service

In addition to the revenue from parking fees, a developer receives revenue from V2B operations. Utilizing the PHEVs/BEVs in the smart garage, the developer contracts with an aggregator (or independent system operator) provision of power regulation storage and peak hour services.

The regulation service—one of the key ancillary services—corrects unintended fluctuations of power generation in order to meet a load demand. If a load demand exceeds power generation, PHEVs/BEVs discharge power from the battery, and if power generation exceeds a load demand, PHEVs/BEVs charge power from the power grid. The smart garage building can provide regulation service for 24 hours at the level of $d^*(l,i)$, as shown in Figure 5.4. Kempton and Tomic [3] suggested a revenue model for regulation service as follows:

$$r_{RS}(l,i) = \sum_{h=1}^{24} d^*(l,i) \cdot (p_{cap} \cdot P + P \cdot R_{d-c} \cdot \hat{Z}_h) \quad (5.21)$$

where P is the power limited by the vehicle's stored energy, $d^*(l,i)$ is the minimum amount of vehicles for 24 hours, \hat{Z}_h is the forecast power price, p_{cap} is a capacity price, and R_{d-c} is the dispatch-to-contract ratio, as defined below:

$$R_{d-c} = \frac{E_{dis}}{P_{con} \cdot t_{con}} \quad (5.22)$$

where E_{dis} is the total energy dispatched over the contract period, P_{con} is the contracted capacity (MW), and t_{con} is the duration of the contract.

Revenue from Peak Hour Service

The peak hour demand market is another source of revenue for a smart garage. The extracted power from the PHEVs/BEVs parked during the day can provide electric power, with the PHEVs/BEVs basically functioning as a distributed generator. The operator of the garage can contract with the independent system operator (ISO) to sell power for a specific period. In this study, the specific period is defined as 8:00 a.m. to 8:00 p.m., when demand for the smart garage building is high. The smart garage building can extract power up to d^{***} , which would be the point that the battery in a PHEV/BEV

is drained. Therefore, defining a proper power extraction ratio (λ) is essential. The revenue model for the peak hour services is defined as follows:

$$r_{PH}(l,i) = \sum_{h=8}^{20} (P \cdot d^{**}(l,i) \cdot \hat{Z}_h) \quad (5.23)$$

where $d^{**}(l,i) = \lambda(d^{***}(l,i) - d^*(l,i))$ and $d^{***}(l,i)$ is the maximum amount of vehicles between 8:00 a.m. and 8:00 p.m.

5.2.3 Numerical Example

5.2.3.1 Case Study

A numerical example to illustrate the application of the developed bi-level smart garage development model is presented next. The example network shown in Figure 5.5 consists of four nodes and 12 links. It is assumed that node 2 and node 3 have a conventional parking garage and a smart garage building is constructed at distance l from node 2. The links are divided into two types: driving links and walking links.

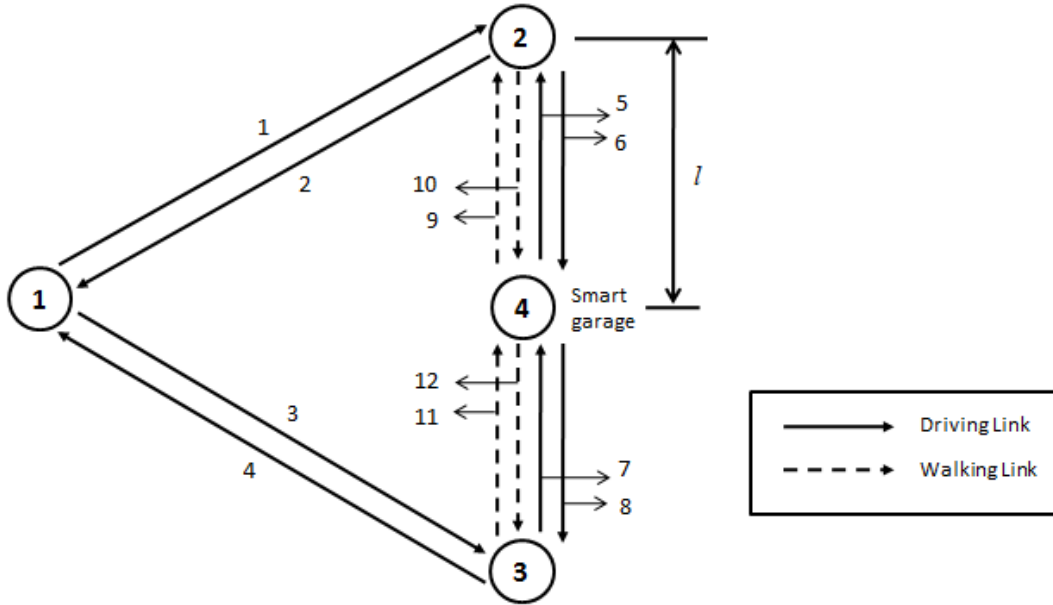


Figure 5.5 Simple Network

The driving links and walking links each have a link cost function (Equations (5.13) and (5.14)). Lengths and capacities for each link are given in Table 5.1. Pedestrian trips are generally considered as less than 1.6 km [51] and can extend to 3.0 km in a central business district [52]. Based on the pedestrian trips in a central business district, the distance between node 2 and 3 is defined as 3.0 km.

Table 5.1 Link Data for Example Network

Link	Length l (km)	Capacity c (veh/h)	Link	Length l (km)	Capacity c (veh/h)
1	16	600	7	$3-l^*$	300
2	16	600	8	$3-l^*$	300
3	15	600	9	l^*	Inf.
4	15	600	10	l^*	Inf.
5	l^*	300	11	$3-l^*$	Inf.
6	l^*	300	12	$3-l^*$	Inf.

For link cost functions, the average speed of cars and pedestrians (s_a and s_b) are assumed as 0.632 km/min and 0.1167 km/min, respectively [53]. Parameters α_a and β_a in the cost function of the driving link are assumed as 0.15 and 4, respectively.

The sidewalk capacity in the cost function of walking links can be measured in a real network but, for simplicity, is assumed to be infinity in this numerical example. The incentive parameter (γ) is assumed as 40, while the parking fee at a conventional parking garage at nodes 2 and 3 (f) is assumed as one dollar per hour.

The example network has two O-D pairs and four O-D and D-O trip rates, depending on the type of vehicles or whether or not they are parked in the smart garage building. As previously discussed, D-O trip rates are derived from the O-D trip rates and drivers' parking duration. Further, the trip rates on each O-D pair ($(q_{Total}^{rs})_h$) are assumed to be deterministic.

The ratio of PHEVs/BEVs to all vehicles of traffic flow would be different every hour, on every link, and on each origin-destination pair. However, for simplicity, the ratio is assumed as being constant in this example. The ratio of PHEVs/BEVs to all vehicles (τ) is assumed as 25% [54]. With trip rates and the penetration ratio of PHEVs/BEVs, the PHEV/BEV flows are calculated. Finally, the forecasted power prices (\hat{Z}_h) are summarized in Table 5.2.

Depending on the location, l , and incentive level, i , the optimal link flows vary. In the upper-level problem objective function (e.g., revenue), we assumed values based on Kempton and Tomic's study [3]. The power limited by a vehicle's stored energy (P) is assumed as 20 kWh, and the capacity price (p_{cap}) is assumed to be 30 \$/MW-h. The dispatch-to-contract ratio (R_{d-c}) is assumed as 0.1, and the power extraction ratio (λ) is assumed as 0.5.

5.2.3.2 Results

Figure 5.6 shows the demand patterns for the smart garage building (d_h) depending on l and i . In the figure's legend, the first value indicates the amount of incentive and the

second value indicates the location of the smart garage. The various garage demand patterns are calculated by using combinations of the location and the incentive. It can be observed from the figure that as the incentive increases and the location is centered between the two nodes, the demand for the smart garage building increases as well.

Table 5.2 Forecasts of Power Price used for Numerical Example

Hour	Power Price (\$/MW-h)	Hour	Power Price (\$/MW-h)	Hour	Power Price (\$/MW-h)
4	14.74	12	23.72	20	25.50
5	15.08	13	23.80	21	23.65
6	17.70	14	23.49	22	23.06
7	23.81	15	22.74	23	20.51
8	25.12	16	22.50	24	17.51
9	24.90	17	22.51	1	15.51
10	24.07	18	25.50	2	15.51
11	24.00	19	26.50	3	15.51

As a bi-level nonlinear programming problem is an NP-hard problem [55], to find the optimal solution, we rely on a genetic algorithm (GA) to search for the global optimum. A genetic algorithm is a method of searching the fitness landscape for a highly fit solution. This algorithm is inspired by evolutionary biology, so that the population (solution) is increasingly better adapted, as in the evolutionary process [56]. The simple form of a genetic algorithm typically consists of three types of operators, including selection, cross-over, and mutation. For the numerical example, basic GA operators are defined in Table 5.3.

The GA process is terminated by a stopping criterion. In this study, the stopping criterion is evoked if the successive best solutions no longer produce higher fitness (more than 1 dollar) during 10 generations.

Graph (a) in Figure 5.7 shows the best fitness and average fitness for all generations. At the initial generation, GA explores decision space to find better fitness values. Then, at the end of generation, GA finds the best fitness value, which is around \$14,000. The maximized total revenue is obtained at \$14,817, and the optimal incentive and location are approximately 0.44 dollars per hour and 1.53 km from node 2, respectively.

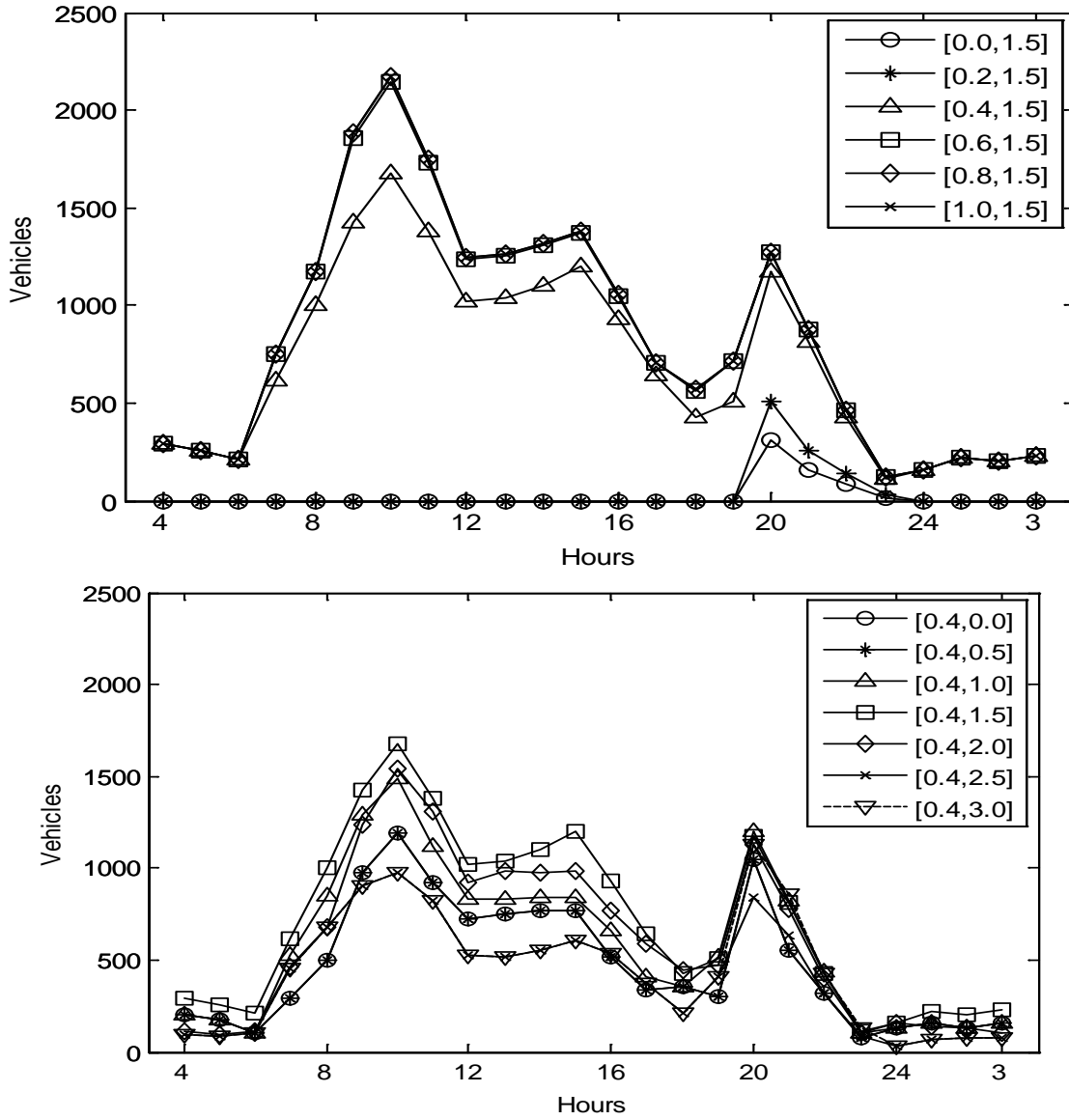


Figure 5.6 Demands of Smart Garage Building depending on Location and Incentive

Table 5.3 Methods and Parameters of GA Operators

Operator	Method	Parameter
Selection	Binary Tournament Selection	1. Population size: 10 2. Elites: 2
Cross-over	Simulated binary cross-over	1. Rate of cross-over: 0.8 2. Distribution index (η): 2
Mutation	Gaussian Mutation	1. Rate of mutation: 0.8 2. Standard deviation: • 0.05 (for incentive) • 0.15 (for location)

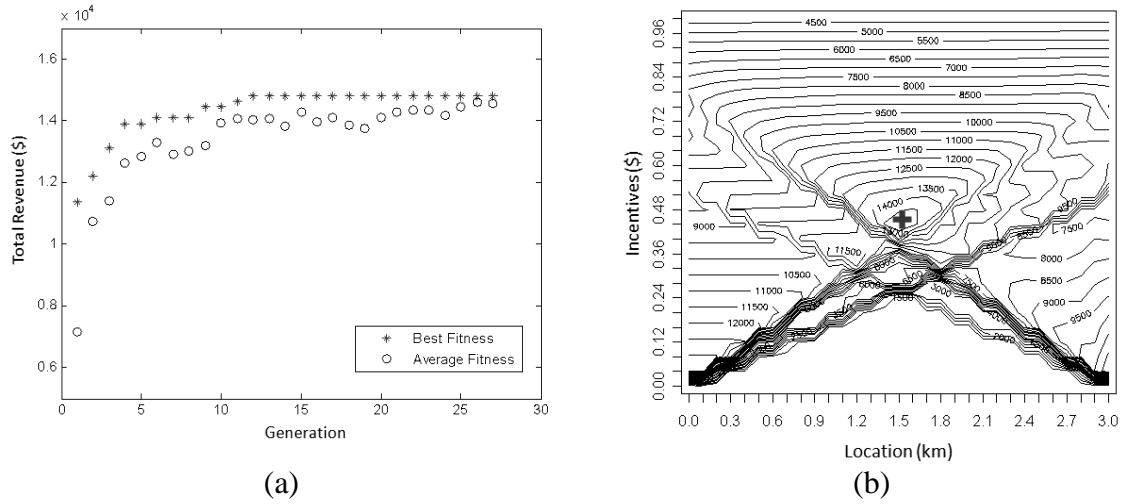


Figure 5.7 Fitness and Contour Graph for Total Revenue

Graph (b) in Figure 5.7 presents a contour graph for total revenues, which is calculated from 801 combinations using the enumeration method. The optimal point (“+” mark in the figure) is obtained from the GA operation. Graph (b) shows that, as incentive increases, location becomes a less important factor. In fact, drivers are incentivized to park in the smart garage and walk to their final destination. However, there is an optimal level of incentive at the point where the marginal increase in electric power generating potential (e.g., smart garage demand) is equal to the marginal opportunity cost of charging for parking.

5.2.4 Sensitivity Analysis

The suggested model is based on a number of empirical variables and parameters, including the battery limitation (i.e., power limited by the vehicle’s stored energy), ratio of extraction, and trip rates. As the value of these parameters is largely uncertain, sensitivity analyses are conducted to understand the extent of the marginal influence.

Figure 5.8 shows the results of a sensitivity analysis. The penetration rate of a PHEV/BEV (τ) and the power limited by the vehicle’s stored energy (P) have the most significant effect on the total revenue when contrasted with the other parameters. The change of trip rate from node 1 to node 2 is sensitive to total revenue, but the change of trip rate from node 1 to node 3 is much less sensitive.

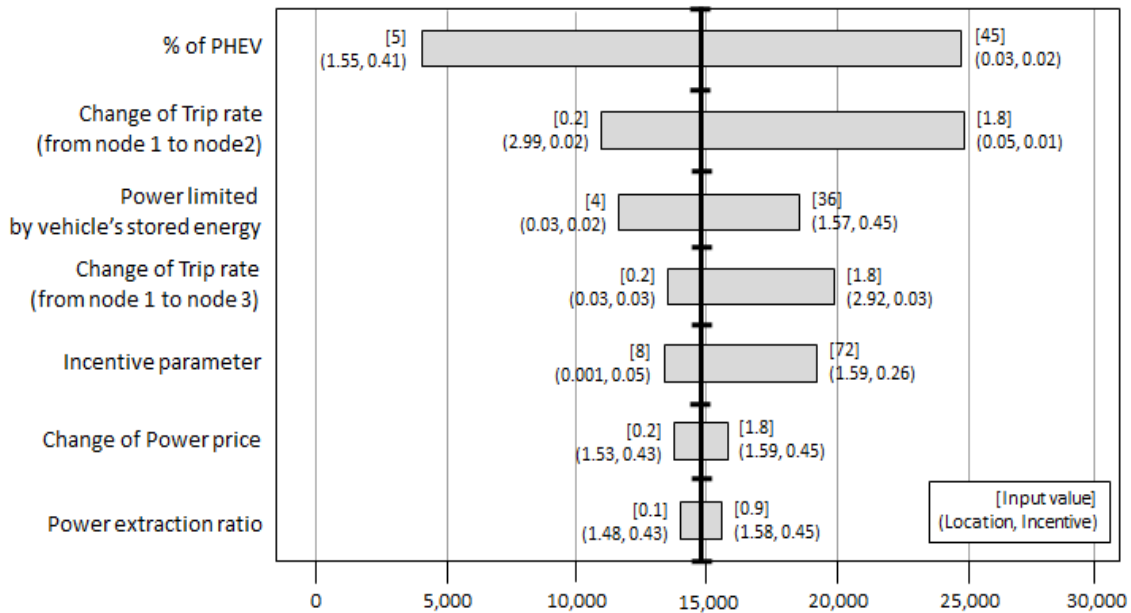


Figure 5.8 "Tornado" Diagram

The sensitivity analysis also shows that the change of trip rate and incentive parameter could affect the optimal location and incentive. The optimal location is determined near the node where a greater trip rate is allocated, and the optimal incentive decreases as the location of the smart garage building moves closer to the node with the conventional parking garage. Like the sensitivity analysis in total revenue, the trip rate with more traffic flow has more influence on the optimal location and incentive.

The results and sensitivity analysis give important implications for smart garage management. First, in the planning stage, the developer of the smart garage should consider long-term changes in future traffic flow and construct a smart garage closer to the node with the highest destination trip rate. Second, to attract more parking users, the developer needs to consider the walkability of walking links. For example, even if the operator of the smart garage provides much incentive, pedestrians do not want to walk through a dangerous area with poor walkability. Third, the operator of the smart garage can control the demand of the smart garage by manipulating the incentive structure (parking fee). For example, when there is an excessive demand for a smart garage, the operator can readjust the incentive and reduce the demand of the smart garage, or vice versa.

5.3 Installation of Charging Stations in Existing Parking Garage

Demand for PHEV/BEV is increasing with growing concerns about environment pollution, energy security, and economy. Different studies estimate different PHEV/BEV penetration rates, but they all agree that PHEV/BEV in a future will constitute a notable portion of all vehicles [4], [27] and [57]. To meet the demand of PHEV/BEV, GM and Nissan have already introduced PHEV/BEV models. Other manufacturers, such as Ford

and Toyota, have also announced their plans for massive PHEV/BEV release in the near future.

Stochastic models can help parking garage managers to evaluate the optimal number of charging stations to be installed. Garage operators want to know how many charging stations are appropriate to serve PHEV/BEV drivers and how much to spend for installing the charging stations. These decisions are associated with many uncertain parameters such as PHEV/BEV penetration rate and PHEV/BEV charging rate.

The model will explain these uncertain situations and help the operator make a decision on how many charging stations should be installed in a single parking garage. The model is formulated in the form of a two-stage stochastic problem with simple recourse. The case study for installation of plug-in infrastructure considers Northgate garage on Texas A&M University campus in College Station.

5.3.1 Overview

Installation of charging stations in single parking garage could affect drivers' parking choices. Figure 5.9 shows the influence of installation of charging stations at one garage only. Figure 5.9 (a) illustrates drivers' behavior without charging stations. Drivers park their cars in the parking garage closest to their destinations. However, if parking garage C installs charging stations, portion of PHEV/BEV drivers who used to park their vehicles at the other garages will change their parking choice as shown in Figure 5.9 (b).

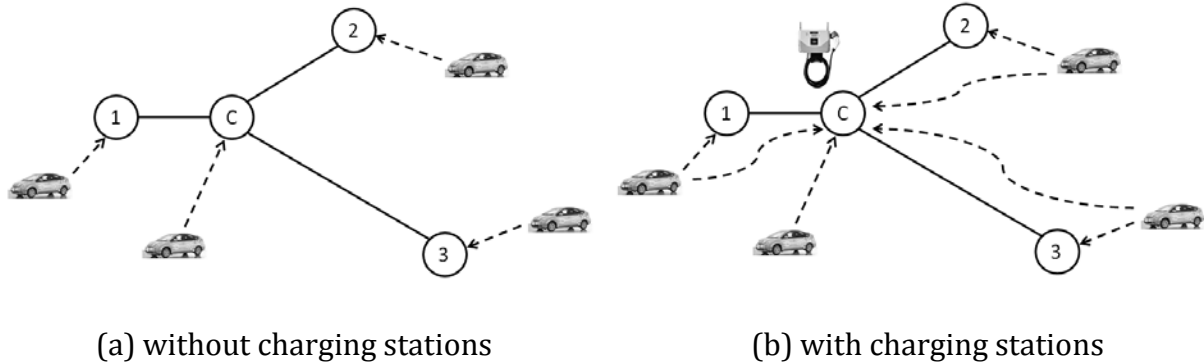


Figure 5.9 Influence of Installation of Charging Stations

PHEV/BEV demand for parking garage C with charging stations can be calculated based on the current parking demand and the attracted demand from the other garages. In order to calculate PHEV/BEV demand from other garages, we need to consider the total demand, parking users' willingness to walk further, and the uncertainties associated with these estimations. In this study, PHEV/BEV charging rate (rate of willingness to charge PHEV/BEV while parked) and PHEV/BEV penetration rate are considered uncertain.

The objective of this model is to determine the optimal number of charging stations to be installed. Figure 5.10 shows a model framework. The objective of the facility operator/manager is to minimize the sum of installation cost and the utility cost. Here, installation cost depends on the number of charging stations installed, while the utility cost represents a measure of utility (i.e. happiness) with the differences in the supply of charging stations and the PHEV/BEV charging demand. As mentioned above,

PHEV/BEV parking demand is calculated based on the demand for the garages, users' willingness to walk, and the two PHEV/BEV uncertain parameters, such as PHEV/BEV penetration rate and PHEV/BEV charging rate.

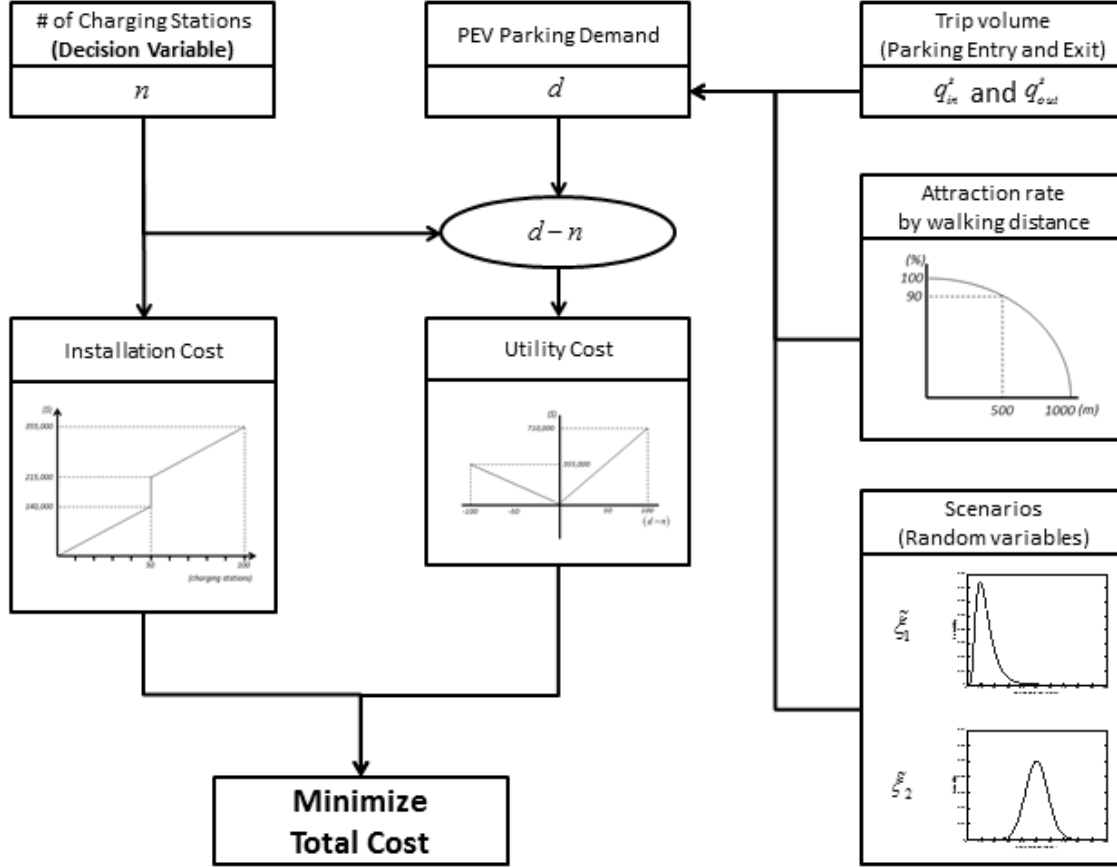


Figure 5.10 Model Framework

5.3.2 Mathematical Formulation

A two-stage stochastic model considers the first stage with allocates the spaces for charging stations, and the second stage that assesses the consequences (operator's utility). The objective of this problem is to minimize the sum of installation cost and utility cost (Equation (5.24)). The constraints associated with first-stage represent space capacity for charging stations (Equation (5.25)). The model is discussed below and the notations of parameters, variables, and sets used in the model are listed in Appendix 2:

$$\min f(n) + E[Q(d-n)] \quad (5.24)$$

$$\text{s.t. } 0 \leq n \leq N \text{ and integer} \quad (5.25)$$

$$\text{where } E[Q(d-n)] = \sum_{\omega_1 \in \Omega_1} \sum_{\omega_2 \in \Omega_2} P^{\omega_1} \cdot P^{\omega_2} \cdot Q(d-n) \quad (5.26)$$

$$d = \frac{1}{24} \sum_{h=1}^{24} d_h \quad (5.27)$$

$$d_1 = (x_c)_1 - (x_d)_1 \quad (5.28)$$

$$d_h = d_{h-1} + (x_c)_h - (x_d)_h \quad h = 2, \dots, 24 \quad (5.29)$$

$$(x_c)_h = \sum_{s \in N_p} (q_{in}^s)_h \cdot \tilde{\xi}_1 \cdot \tilde{\xi}_2 \cdot W(l^s) \quad h = 1, \dots, 24 \quad (5.30)$$

$$(x_d)_h = \sum_{s \in N_p} (q_{out}^s)_h \cdot \tilde{\xi}_1 \cdot \tilde{\xi}_2 \cdot W(l^s) \quad h = 1, \dots, 24 \quad (5.31)$$

$Q_j(d - n)$ represents the utility cost generated based on an initial charging stations n when PHEV/BEV demand of parking garage is d . The PHEV/BEV demand of parking garage is defined as average of hourly PHEV/BEV demands within one day as in Equation ((5.27)).

Random variables of $\tilde{\xi}_1$ and $\tilde{\xi}_2$ are used to model uncertainty in scenarios. Here, $\tilde{\xi}_1$ represents future penetration rate of PHEV/BEV and $\tilde{\xi}_2$ represents rate of PHEV/BEV to be charged. The sum of trip rates of PHEV/BEV entering to and exiting from parking garage, $(x_c)_h$ and $(x_d)_h$, are derived from the original trip rates, random variables, and attraction rate function. This model is also referred to as plug-in infrastructure installation problem (PIIP) in the rest of this report

5.3.3 Solution Method

The stochastic program with continuous distributions is usually impossible to be solved exactly, and the approximation approach could be used to solve the problem [58]. Mak et al. [58] proposed Monte Carlo sampling Method to solve the stochastic problem with continuous distribution in 1999. Basically, Monte Carlo bounding technique gives confidence intervals which account for the difference between optimal and candidate solutions. The PIIP in this report is solved based on the Monte Carlo bounding method. Abstract equations for Monte Carlo bounding method are listed above. Detail for this method can be found in [58].

5.3.3.1 Upper Bounds

Upper bound can be estimated by the standard sample mean estimator as following:

$$\bar{U}(n_u) = \frac{1}{n_u} \sum_{i=1}^{n_u} f(\hat{x}, \tilde{\xi}^i) \quad (5.32)$$

where \hat{x} is a candidate solution, $\tilde{\xi}^i$ are independent and identically distributed from the distribution of $\tilde{\xi}$. n_u is the number of samples.

Upper bound error is defined as following:

$$\tilde{\varepsilon}_u = \frac{t_{n_u-1, \alpha} s_u(n_u)}{\sqrt{n_u}} \quad (5.33)$$

where $s_u(\cdot)$ is the standard sample variance estimator of σ_u .

5.3.3.2 Lower Bounds

Lower bound can be estimated as following:

$$\bar{L}(n_l) = \frac{1}{n_l} \sum_{i=1}^{n_l} \min_{x_i \in X} \left[cx_i + \frac{1}{m} \sum_{j=1}^m f(x_i, \tilde{\xi}^{ij}) \right] \quad (5.34)$$

where n_l is the sample size and m is the batch size.

Lower bound error is defined as following:

$$\tilde{\varepsilon}_l = \frac{t_{n_l-1, \alpha} s_l(n_l)}{\sqrt{n_l}} \quad (5.35)$$

where $s_l(\cdot)$ is the standard sample variance estimator of σ_l .

5.3.3.3 Confidence Interval

The following equation is an confidence interval for optimality gap at \hat{x} .

$$\left[0, \bar{U}(n_u) - \bar{L}(n_l) + \tilde{\varepsilon}_u + \tilde{\varepsilon}_l \right] \quad (5.36)$$

5.3.4 Case Study

5.3.4.1 Area Scope

There are many parking garages and open parking lots at Texas A&M University campus at College Station. This case study considers only five parking garages and six surface parking lots as shown in Figure 5.11. The capacity of parking spaces for each parking garage and open space lots is shown as in Table 5.4.

This case study considers Northgate garage as the garage where charging stations will be installed. Some PHEV/BEV drivers who used to park their vehicles in the other parking garages or lots will have a choice to use Northgate garage to charge their cars. Therefore, in this case study, walking distance is an important factor to decide whether they will use Northgate garage for charging a car. The walking distance from the Northgate parking garage to other garages and open space lots are shown as in Table 5.5.

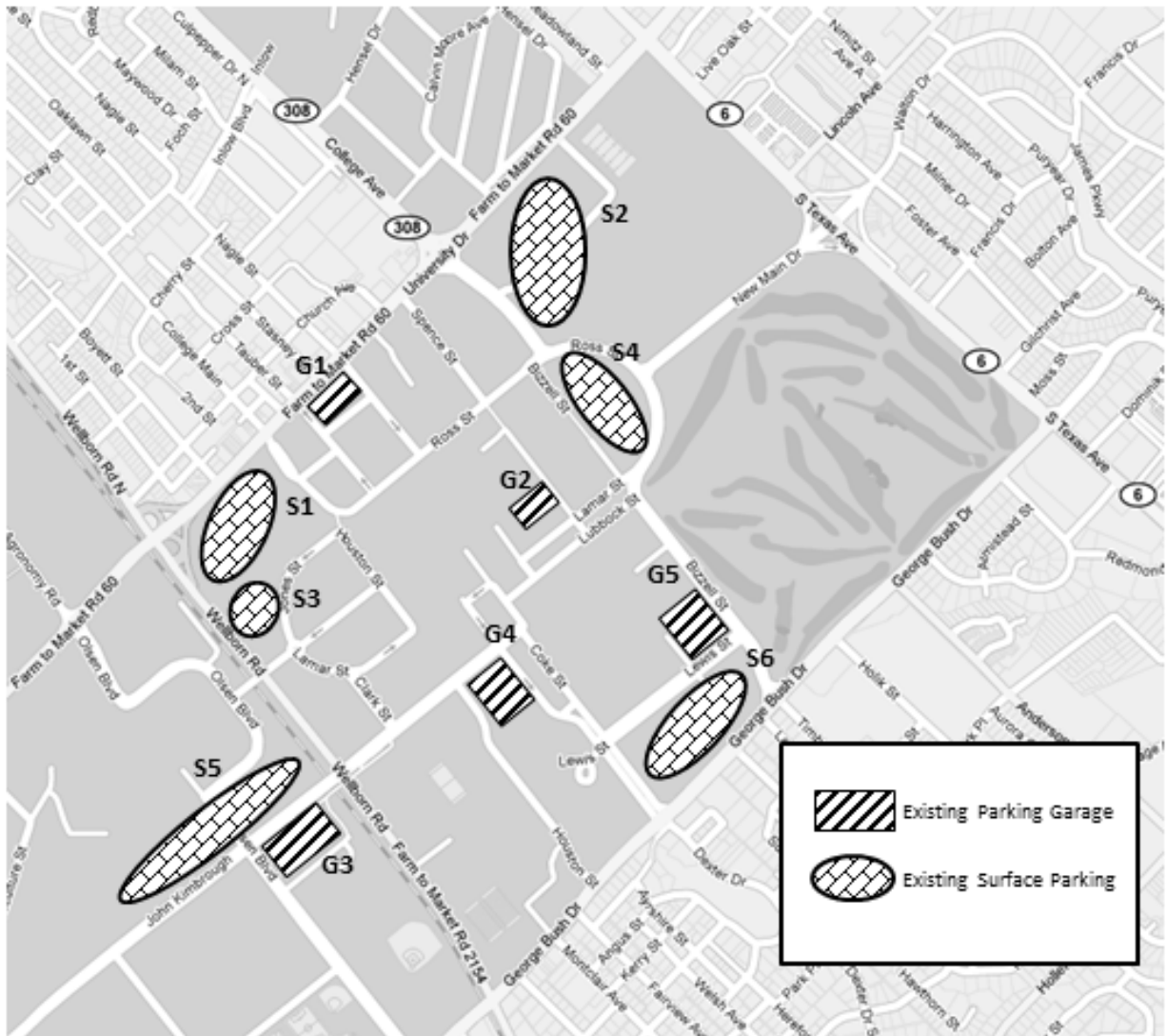


Figure 5.11 Existing Parking Garages and Surface Parking Lots

Table 5.4 Parking Spaces

Parking ID	Spaces	Parking ID	Spaces
S1	775	G1	2000
S2	2300	G2	510
S3	370	G3	3100
S4	640	G4	1630
S5	2350	G5	2250
S6	1180		

Table 5.5 Walking Distances from Northgate Garage

Parking ID	Walking distance from G1 (km)	Parking ID	Walking distance from G1(km)
S1	0.5	G1	0
S2	0.75	G2	0.6
S3	0.65	G3	1.3
S4	0.65	G4	0.9
S5	1.5	G5	1.1
S6	1.3		

Using this data, plug-in infrastructure installation problem (PIIP) can be applied for the analysis of the benefit/risk associated with installation of charging stations at the Northgate garage. PIIP seeks to answer the questions such as what is the optimal number of charging stations to be installed in Northgate garage.

5.3.4.2 Data

Installation Cost

Installation cost ($f(n)$) is determined based on the number of charging stations to be installed. The installation cost is a piece-wise linear function of the number of charging stations (Figure 5.12). When 50 charging stations are installed, extra installation costs are added due the need for a new transformer. The unit installation cost of a charging station is assumed to be \$2,000, and the cost of charging station switchgear (CSS) is \$10,000. The CSS is installed when 10 charging stations are installed.

$$f(n):$$

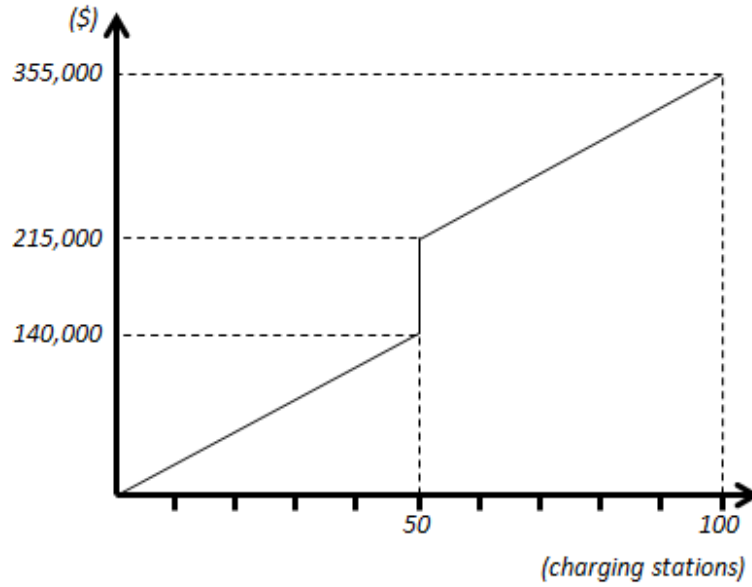


Figure 5.12 Installation Cost

Utility Cost

The utility cost ($Q_j(d-n)$) represents the cost associated with either over-estimated or under-estimated demand. Positive value at the difference ($d-n$) means insufficient charging stations so that manager will have additional cost derived from the loss of potential profit. On the other hand, negative value at the difference ($d-n$) means excessive charging stations are installed, so the manager will incur the cost associated with the improper use of spaces and capital. For this case study, utility cost is defined as shown in Figure 5.13.

$$Q(d - n):$$

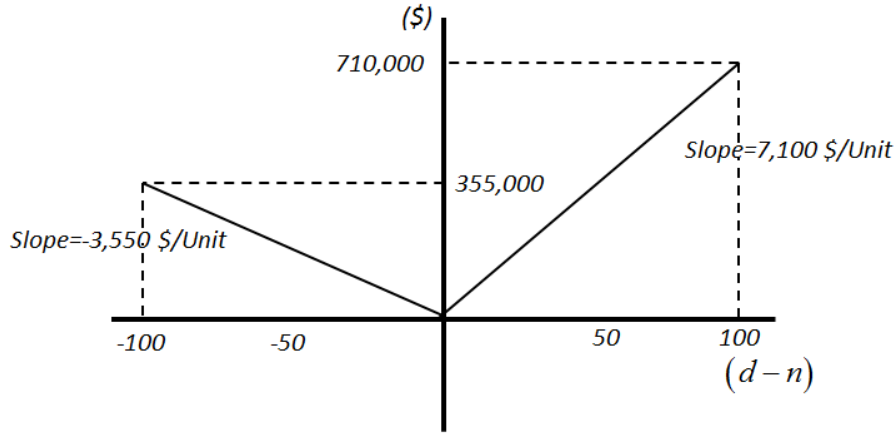


Figure 5.13 Utility Cost

The utility cost in Figure 5.13 shows the assumed cost for which parking facility operator/manager may have over-estimated or under-estimated demand. For example, excessive 100 charging stations mean that manager should not have installed the 100 charging stations. Therefore, the utility cost at excessive 100 charging stations is defined as \$355,000 which equals the amount of installation cost of 100 charging stations. For the perspective of parking garage manager, the utility cost derive from the loss of potential profit could be higher than the utility cost from improper use of spaces. Therefore, in this case study, the utility cost of insufficient 100 charging stations is defined as twice as much as that of the excessive charging stations. However, these can be specified based on manager preferences to capture the cost associated with either under-estimated demand (PHEV/BEV drivers want to charge, but there is no charging stations) or over-estimated demand (manager spends money on the charging station installation, but there is no demand). Note that the values of the parameters in utility functions can be changed to reflect future preferences.

Attraction Rate by Walking Distance

The attraction rate ($W(\cdot)$) is determined based on walking distance from Northgate garage to the other garages. Figure 5.14 shows the attraction rate for this case study. For example, when walking distance is over 1,000m, no PHEV/BEV drivers want to park their cars at Northgate garage. 90% of the PHEV/BEV drivers within 500m want to park their cars at Northgate garage. This rate can be specified based from the results of the customized survey.

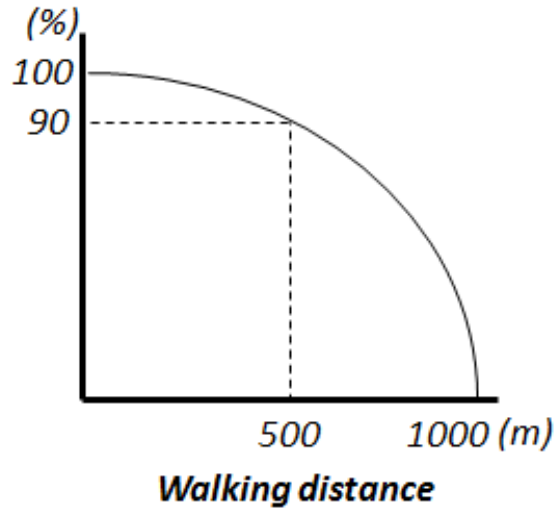


Figure 5.14 Attraction Rate by Walking Distance

Uncertainties

PIIP includes two uncertain parameters: PHEV/BEV penetration rate and PHEV/BEV charging rate. For this case study, two uncertain parameters are assumed as log-normal distribution and truncated normal distribution, respectively, as shown in Figure 5.15.

PHEV/BEV penetration rates are derived from log-normal distribution ($\mu=2.5$ and $\sigma=0.5$) as in Figure 5.15 (a). The log-normal distribution shows the mean value of PHEV/BEV penetration rate 13.8%. This mean value is assumed based on the forecasted results for other studies ([4], [27], and [57]). The PHEV/BEV penetration rate is assumed not to exceed 50%. PHEV/BEV charging rate is defined in the form of truncated normal distribution ($\mu=50$ and $\sigma=8$) as shown in Figure 5.15 (b). The mean value of the distribution is defined as 50%. PHEV/BEV charging rate will be determined in the range from 20% to 80%.

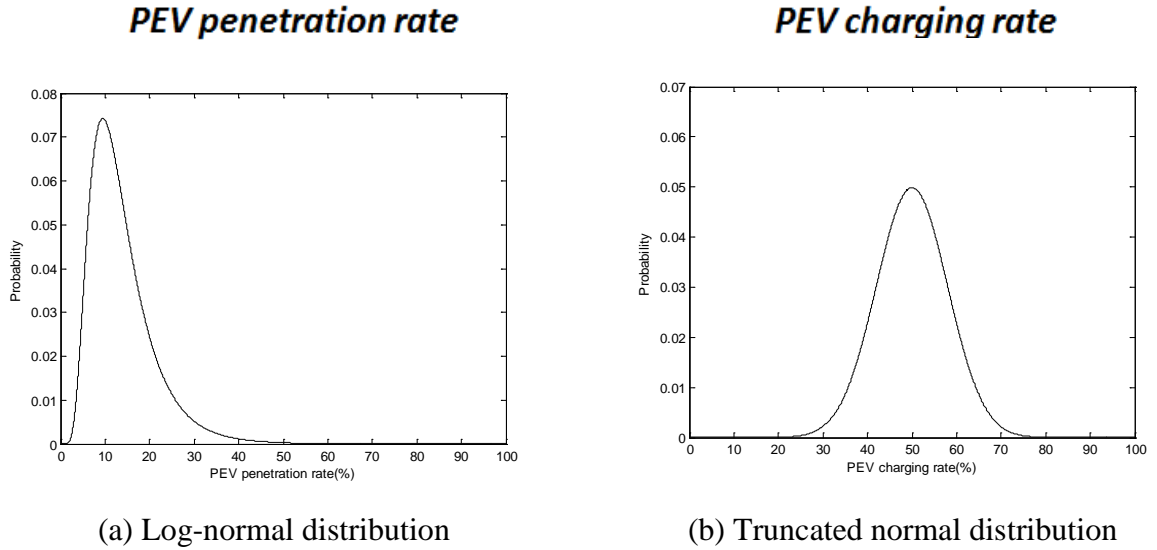


Figure 5.15 Distributions for Uncertainties

5.3.4.3 Results

Monte Carlo sampling based algorithm [58] is used for determining the solution of PIIP. The basic information of the algorithm, such as the batch size, the number of batches and the sample size, is presented in Table 5.6.

Table 5.6 also shows the computational results of the PIIP for Northgate garage. The analysis result given the assumed parameters indicates that the optimal number of charging stations is approximately 25. The upper and lower bounds are \$139,930 with \$2,033 ($\alpha=0.95$) and \$139,550 with \$2,752 ($\alpha=0.95$).

5.3.5 Sensitivity Analysis

As the value of parameters in the model is uncertain, the sensitivity analysis is conducted to understand the extent of the marginal influence. Figure 5.16 shows the results from the sensitivity analysis. In Figure 5.16, a “tornado” diagram shows the effect of parameters on the total cost and the number of charging stations. The bar at the top of the diagram indicates the most significant effect on the total cost. The bold line in the middle of bars indicates a result based on the parameters defined in previous sections. The values at the end of bars indicate the input values and the number of charging stations.

For example, the value for mean of PHEV/BEV penetration rate was initially assumed to be 13.8%. To do sensitivity analysis, the PHEV/BEV penetration rate is modified to 12.4% and 15.2% as the values at the end of a bar. The result with 12.4% PHEV/BEV penetration rate shows decrease in the total cost to around \$127,000, and the optimal number of charging stations decreases as 23. On the other hands, the result with 15.2% shows increase in the total cost to around \$155,000 and the optimal number of charging stations increases as 28.

Table 5.6 Case Study Results

Optimal Solution (\hat{x})	25
Lower Bound	
Batch size	30
Number of batches	30
Point estimate	139,550
Error estimate	2,752
Upper Bound	
Sample size	1,000
Point estimate	139,930
Error estimate	2,033
CPU Time (sec.)	239

Additional findings from the study are:

- Mean of PHEV/BEV penetration rate and PHEV/BEV charging rate show the most significant effect on total cost and the number of charging stations, respectively.
- The utility cost and the mean of PHEV/BEV charging rate show the significant effect on both of total cost and the number of charging stations.
- The unit installation cost shows moderate effect on both the total cost and the number of charging stations.
- SD of PHEV/BEV penetration rate shows the moderate effect on total cost, but no effect on the number of charging stations.
- SD of PHEV/BEV charging rate shows the slight effect on both the total cost and the number of charging stations.

Some managerial implications can be suggested based on the results of the sensitivity analysis. First, the parking facility operator/manager should focus more on forecasting the mean values of two random variables (PHEV/BEV penetration rate and PHEV/BEV charging rate) at the planning stage. These are critical values in determining the total cost and the number of charging stations. Second, in order to reduce the total cost, it is recommended to reduce the utility cost and unit installation cost. Unlike the uncertain rates, two costs may be manipulated by the parking facility operator/manager based on the policies to encourage the use of PHEVs/BEVs.

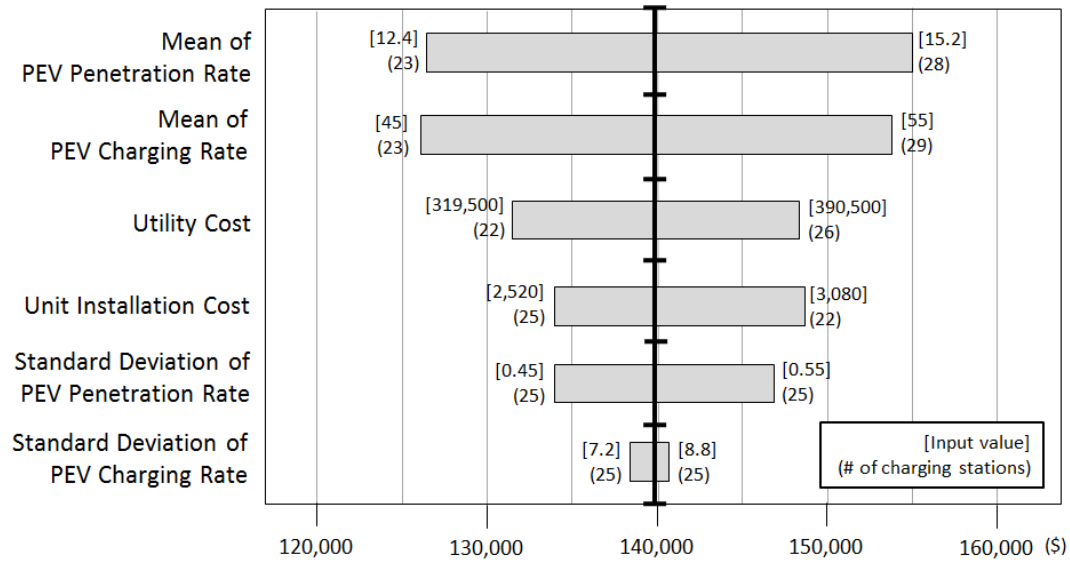


Figure 5.16 “Tornado” Diagram

5.4 Conclusions

This section presents a model to determine the optimal number of charging stations to be installed in a single parking garage and is applied to Northgate garage on Texas A&M University campus at College Station. The analysis shows the optimal number of charging stations and the upper and the lower bounds of the total cost. Sensitivity analysis shows that poor walkability, or low incentive parameters, will increase the influence of trip rates on parking. It is suggested that facility manager should be focused on determining utility cost.

This section presents a theoretical model to determine the optimal number of charging stations. In order to obtain more realistic results, the accuracy of parameters and the functions need to be improved. The following information is required to get better analysis result: actual parking capacity on the parking garages and lots, trip rates of PHEV/BEV entering to and exiting from all parking garages, installation cost for charging stations, and utility cost of facility manager. Sensitivity analysis shows that the mean value of PHEV/BEV penetration rate and charging rate are important factors in making decisions.

6. The Role of PHEVs and BEVs in Electricity Network

6.1 Introduction

This chapter presents the role of PHEVs and BEVs in the electricity network. Section 6.2 discusses the role of PHEVs and BEVs in an electricity market. Section 6.3 discusses the role of PHEVs and BEVs in a distribution system. The impact of PHEVs and BEVs concentrated charging/discharging on electricity networks is presented in section 6.4. Section 6.5 provides the conclusion.

6.2 The Role of PHEVs and BEVs in Electricity Markets

6.2.1 Overview

Vehicles that plug in to the power grid for some or all of their energy needs have the potential to make valuable contributions to the production, transmission, and distribution of electric power and to be a new resource to assist with grid operations. Specifically, the energy storage capacity of a plug-in vehicle can potentially be a storage resource for electricity markets and can provide ancillary services, given communications infrastructure and an aggregator. As noted earlier, two types of managed charging are feasible for PHEVs/BEVs. The first is simple on and off type of charging where charging occurs at the full charging rate when on and total PHEV/BEV demand changes in increments. An alternative charging control would modulate the charging rate over time, providing a smoother variation of load. With managed charging, PHEVs/BEVs could also provide various services to the electricity market as a managed load, providing for temporal shifts of load away from peak times to off-peak times, particularly using overnight charging at a home garage.

As battery wear due to bi-directional power cycling is not well understood, and could have a cost impact greater than the benefit produced [59], the global vehicle manufacturers perceive enough safety and durability risks with the first generation vehicles that they will avoid including two-way power flow capability (V2G) for the near term. Therefore, in this section the V2G capability is put aside and products and services are focused on demand response-type services only. This approach can also eliminate the interconnect issues around feeding power back to the grid.

A key issue regarding the provision of market services by PHEV/BEV loads is the charging to a target level (normally, fully charged) by a defined time. Thus, if a vehicle is providing services and reaches a time where it must charge at its maximum rate to achieve the targeted charge level at the target time, it can be expected to discontinue providing grid services unless it is compensated for the opportunity cost of not being fully charged. The charging control must be capable of anticipating that condition and not offering services on behalf of a PHEV/BEV for a given hour if the need to charge at the maximum rate is reasonably anticipated to occur during the hour ahead [35]. In the case of the PHEVs/BEVs, another solution is to continue providing services and then compensate the PHEV/BEV owner for not charging to the target level by an additional payment based on the fuel price, which would compensate the owner for the opportunity cost of not being fully charged by the target time.

The rest of this section is organized as follows. Section 6.2.2 will describe the potential PHEV/BEV products and services and section 6.2.3 will discuss the requirements and challenges.

6.2.2 Potential PHEV/BEV Products and Services

This section describes particulars of PHEV/BEV provision of various ancillary services and draws from various sources, including [34][35][59][60][61][62].

6.2.2.1 Regulation

Some studies [61][62] have identified regulation as the most valuable ancillary service that vehicles could provide. Regulation is a service that gives the grid operator the ability to directly control the output of a power plant up and down in real time. Regulation is used to fine-tune the match between generation, load, and interchange with other control areas and to contribute to overall grid frequency control.

Some ISOs (like CAISO and ERCOT) divide regulation into two parts: regulation up and regulation down. Regulation up represents increasing a power plant's output from a nominal level and regulation down represents decreasing a power plant's output from a nominal level. Power plants that provide regulation services will have a nominal scheduled power output level, often referred to as the preferred operating point, or POP, a regulation up limit, and a regulation down limit. The regulation up and regulation down limits are typically contracted by the hour; these values are fixed to specific levels for one hour at a time (the POP is sometimes varied at a finer time scale than an hour based on real-time market clearing conditions.) Figure 6.1 below shows an example of a power plant that is providing regulation up and regulation down, showing the POP (assumed fixed for an hour), up and down limits, and the actual dispatched power level. The capacity value of regulation is based on the up and down limits, not the actual dispatched power profile, although there is typically also compensation for any net energy provided to the grid by the regulation provider. The energy generated by the power plant on regulation is the area under the actual dispatched power curve.

The above description revolves around generation, which is the traditional resource used to provide regulation. However, the power fluctuations due to dispatch of regulation in the power profile shown in Figure 6.1 could equally well come from plug-in vehicles whose charger power levels are controlled by a utility, aggregator, or the grid operator. The only difference is the value of the POP. For a power plant, the POP is a positive value (i.e. a nominal generation level). For a plug in vehicle, the POP could be zero, or it could be negative. That is, the regulation service does not directly depend on the value of the POP; regulation is the capability to deviate up or down from a particular POP value. Hence the POP can just as easily be negative (a load) as positive (generation).

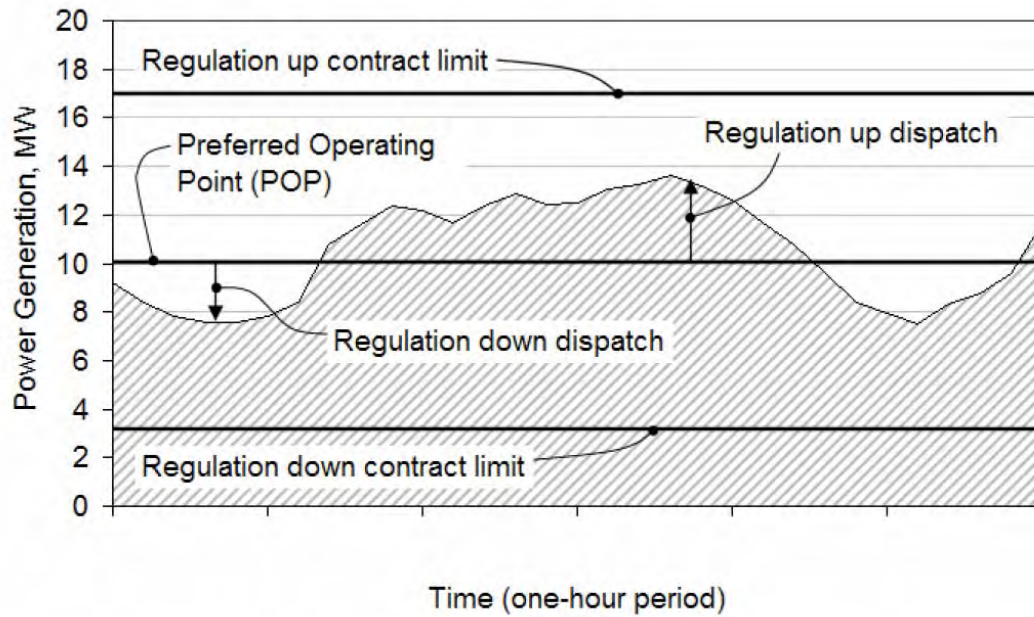


Figure 6.1 Example Power Profile for a Power Generator Providing Regulation Up and Regulation Down [59]
(The shaded area represents the energy generated over the one-hour period.)

Figure 6.2 shows an example of vehicle providing regulation. It illustrates a vehicle with a unidirectional 14kW charger providing regulation with a -7 kW (ie. 7 kW of load) POP value. The vehicle is drawing power from the grid a nominal POP rate of -7 kW and providing 7 kW of regulation up and 7 kW of regulation down. At the regulation up limit, the vehicle is placing no load on the grid and at the regulation down limit, the vehicle is placing a 14 kW load on the grid.

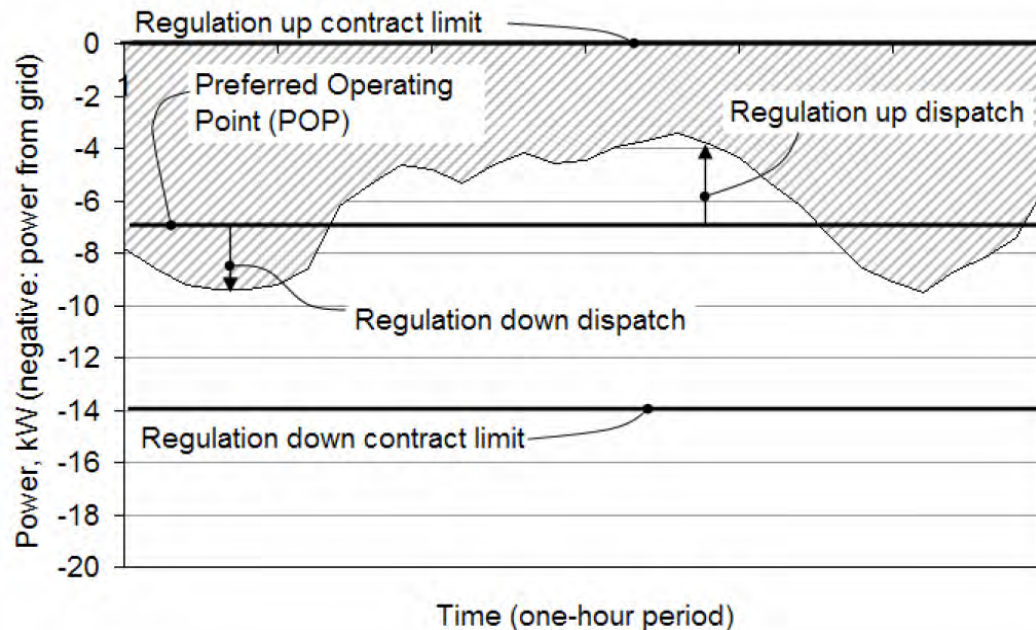


Figure 6.2 Example Power Profiles for a Plug-in Vehicle with a Unidirectional Charger Providing Regulation Up and Down Ancillary Service with a POP Value of -7kW [59] (The shaded area represents the energy delivered to the vehicle by the grid over the one-hour period)

The shaded area between the power profile and the axis at zero power represents the energy drawn from the grid for that period of time. The ratio of the energy drawn from the grid to the regulation capacity sold is an important metric. It represents the effective average charging rate as a fraction of the charger's maximum rated power. A low value of this ratio means that the average charging power is low, but the number of hours of regulation that can be sold is high.

Initial indications are that the ratio of energy to regulation capacity may be on the order of 20% for regulation down. Therefore, to have a total charge energy drawn from the grid of, for example 20 kWh with a 10 kW charger, the average charging power while performing regulation down would be only 2 kW and it would take 10 hours to charge the full 20 kWh. This low charging rate is not a disadvantage with nighttime charging; rather it is an advantage, allowing for 10 hours of 10kW regulation service to be provided with only 20 kWh of total energy throughput.

At present, grid ancillary services are not typically provided by loads, but as illustrated above, loads appear to be capable of providing regulation just as effectively as power plants which currently supply this service. Potentially, plug in vehicles might even be able to do a better job than generators in providing ancillary services. For example, power plants have limitations on how fast they can change power levels whereas plug in vehicles can change power levels virtually instantaneously.

An aggregator providing regulation services from PHEVs/BEVs must be able to meet the requirements for regulation services (regulation up, regulation down, or symmetric up and down) as required by the individual ISO and as defined for conventional generators

or limited energy resources. It is expected that an aggregator would provide regulation services by combining the responses of a number of PHEVs/BEVs. It is the responsibility of the aggregator to have sufficient rate of change and total amount of change as embodied in aggregate PHEVs/BEVs charging load so as to meet its regulation commitments to the system operator.

In this scenario, the grid operator would continuously evaluate grid operations data as usual and would then determine an aggregate load dispatch command. The command is sent to the aggregator, and the aggregator then determines which connected vehicles to contact in order to comply with the load change represented by that particular command. With a large number of vehicles participating, it would be practical to control overall charging levels by simply turning charging on or off rather than trying to modulate the charging rate of each vehicle individually. With on-off control, only a small subset of the connected vehicles would need to be contacted at each step.

In order for the aggregators to be able to provide regulation services to an ISO, they will need to implement two-way communications with the PHEVs/BEVs and demonstrate they can meet the obligation to participate in the relevant ancillary services market, or otherwise demonstrate the real-time control and validation requirements of these services. Any penalties for non-commitment would be assessed by the ISO in the settlement process. Here, the ISO/RTO would validate provision of the regulation service. The ISO would also pay the aggregator, and the aggregator would pay the PHEV/BEV owner in turn.

6.2.2.2 Reserves

A PHEV/BEV providing reserves must be able to reduce its charging level on receipt of a control signal. As with regulation, the amount of reserves offered by the aggregation of PHEVs/BEVs' charging reduction is dependent on the charging infrastructure. A PHEV/BEV not capable of modulated charging or pulsed charging is nonetheless able to provide a component of the aggregate PHEV/BEV reserve by simply stopping charging, assuming that the vehicle would remain "off" for a sufficient period of time so as not to violate any vehicle pulse duty cycle restrictions. An aggregation of PHEVs/BEVs that responds to a reserve actuation signal must also remain "off" for a specific time or until the reserve signal is rescinded.

An aggregator that sells reserves from its PHEV/BEV base is responsible for having sufficient PHEV/BEV response available to reduce the overall PHEV/BEV load by the reserve amount offered, above and beyond any capacity offered for regulation services. In co-optimized markets, an aggregator could submit into both regulation and reserve markets and the ISO market could determine which one to schedule. For aggregators to provide reserve services in an ISO market, they will need two way communications with the PHEVs/BEVs and need to meet similar audit requirements to participate in the regulation market, or will have to otherwise demonstrate the real-time control and validation requirements of these services. Once the ISO/RTO validates the reserve has been provided, the settlement process is initiated. The ISO/RTO would pay the aggregator, and the aggregator would pay the PHEV/BEV owner in return.

6.2.2.3 Balancing Energy

An aggregator capable of altering PHEV/BEV charging on a real-time basis may offer changes in total PHEV/BEV charging load into the balancing energy/real-time dispatch market. The aggregator must be able to adjust PHEV/BEV aggregate charging load down (selling energy) or up (buying energy) in response to dispatch signals. The aggregator must be able to affect PHEV/BEV charging and respond in aggregate on time scales consistent with that of conventional generation.

6.2.2.4 Emergency Load Curtailment (ELC)

The aggregation of PHEVs/BEVs which are not providing reserve or regulation, but are scheduled to be charging, may be able to shed load in emergency situations, providing additional capacity when needed. Such an aggregation of PHEVs/BEVs must stop charging in response to a load shed signal from the grid operator or the utility. An aggregator providing load shed service to the grid operator must have scheduled charging available in excess of regulation and reserve so as to be able to reduce aggregate load by the load shed amount.

For this service, aggregators combine the quick response of individual PHEVs/BEVs to offer larger scale load curtailment resources for emergency events. Participation by PHEVs/BEVs owners might be voluntary. However, mandatory models are also feasible.

As with the other products, aggregators would register with the ISO or utility to offer a bundled package of demand capacity available for emergency alerts. Before scheduling resources with the utility or ISO, the aggregator must have an initial estimate of driver usage patterns to forecast the availability of demand as a resource. Initial driver scheduling estimates would facilitate this forecast. Another approach would be for the utility to implement a PHEV/BEV emergency load reduction program where PHEV/BEV owners get a break on their electric bills by signing up for this program. When the need arises for emergency load curtailment, the utility would shed PHEV/BEV load by sending a signal for the PHEV/BEV to not charge.

As it does now, the ISO would monitor system reliability and notify market participants of impending emergency events. In this model, aggregators would then monitor which resources are available for curtailment, possibly notifying drivers. With voluntary ELC, aggregators could confirm commitment from drivers. With mandatory ELC, the aggregators could simply prepare for automatic curtailment.

With aggregators as the primary interface between PHEV/BEV owners and the ISOs or utilities, settlements could be arranged with a single load-resource entity, the aggregator. As such, ISOs or utilities would directly reward aggregators, who could pass on earnings to PHEV/BEV owners through a variety of means (e.g., single up-front payment, subscription price reduction, follow-on payments). Such settlements could entail payments for service, or even a penalty for non-commitment.

6.2.3 Requirements and Challenges for Providing Ancillary Services

An aggregator should meet some requirements for participating in the market and providing some services to the grid through PHEVs/BEVs as controllable loads. One of these requirements for entering almost all markets is being able to provide at least a

minimum threshold capacity. Minimum capacity requirements vary amongst various products in some markets. While most markets have minimum capacity requirements, these requirements have a wide range. Demand response products have limits that range from 100 kW to 1 MW [35]. PHEV/BEV charging loads may be on the order of 10kW or less, and the available ancillary service capacity from each car would be somewhat smaller. Therefore, the aggregator would need to coordinate large numbers of PHEVs/BEVs to meet ISOs standards for minimum power.

There are also ISO performance requirements which should be satisfied. One of the requirements is telemetry measurements requirements. Based on the document released by ISO/RTO Council (IRC) which contains summary information for wholesale electricity demand response programs, products, and services administered by the ISOs and RTOs in North America [63], there are 2-10 seconds required telemetry reporting intervals for providing ancillary services in various ISO/RTOs. Therefore, the aggregator should have appropriate communication with both ISO and PHEV/EVSEs. For communicating with ISO, the standards for generator-to-ISO communication (ICCP or similar) can be used. However, there are many challenges for communicating with all PHEV/EVSEs due to the large number of them. Furthermore, communication methods that can be used for being in touch with PHEV/EVSEs that are parked in individual home garage are likely to be heterogeneous. It can be cell-phone, power line carrier, radio (FM, Zigbee, etc) or Internet (Cell-phone connection from car to internet or Wifi connection from car to home area network). Hence, any solution must cope with this heterogeneity.

There are also ISO standards for the periodicity of communication and the latency (delays tolerated) in the communication. For example Internet-based communication systems are acceptable for some ISOs like CAISO and ISO-NE, but some others, like ERCOT, are still skeptical about this kind of communication. In an experiment done at UT Austin for studying the security and reliability of Internet based communication systems, thousands of computers on campus were polled every second for 20 minutes. The greatest round-trip delay was less than 0.25 second, which suggests that Internet Protocol communications can satisfy the ISOs requirement and facilitate communication to large numbers of PHEVs/BEVs being charged at home.

Another challenge for controlling the PHEVs/BEVs and providing grid services is that an aggregator should have the information about the battery characteristics, state of charge and also targeted charge level and targeted time (deadline for charging to targeted charge level) of each PHEVs/BEVs. The J1772 standard does not currently support provision of the information regarding battery characteristics and state of charge from the car to the EVSE. Therefore, an aggregator needs to poll each car (or driver) for this information. This challenge is probably manageable for at-home charging, through information provided in the service agreement and by the driver about the car, but is possibly more difficult for parking lots where drivers are not likely to want to re-enter information about their car every time they charge.

ISOs also face some challenges. One of the most important one is the representation of PHEVs/BEVs, and in general the representation of dispatchable loads, in network models. For example in ERCOT, Loads can be categorized into three types – Firm Loads, Emergency Interruptible Load Resources and Load Resources (LR). Load Resources are eligible to participate in Ancillary Services. In the ERCOT zonal model, there was no

one-to-one correspondence between LR and physical loads in the network model. In many cases, an LR was represented as an entity not connected to any part of the network model, but rather as a group of physical Loads providing the committed MWs. Telemetry data for the Load Resource was obtained for a LR from its qualified scheduling entity (QSE). The problem caused by this approach in simulations and studies is when ancillary services are deployed by LR, the effect of such a deployment on the network model cannot be evaluated [64].

6.2.4 Case Study

In studying the cost and benefit of providing services by PHEVs/BEVs, there is a tradeoff between value of providing grid services and the communication/control complexity and the associated cost. Higher value services such as regulation have more stringent control and telemetering requirements, lower value services such as emergency load curtailment have more modest requirements. Therefore, the benefits of providing higher value services should be calculated carefully to determine if providing them is cost-effective or not. In the case of regulation, as an example, different ISOs have widely varying prices, and prices vary significantly from year to year. This variation in different ISOs can be seen in Figures 6.3-6.5 for ERCOT, PJM, and NYISO. These price variations indicate that the benefits of PHEV/BEV interaction will vary significantly over time, between different ancillary services, and from place to place.

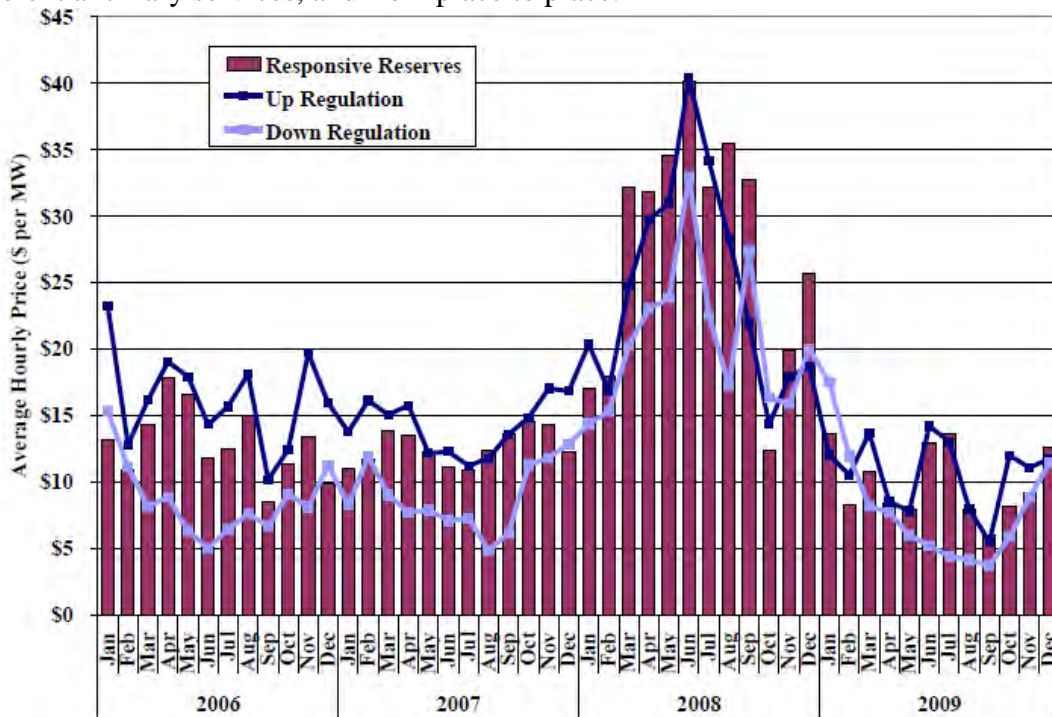


Figure 6.3 ERCOT Monthly Average Ancillary Service Prices 2006-2009 [65]

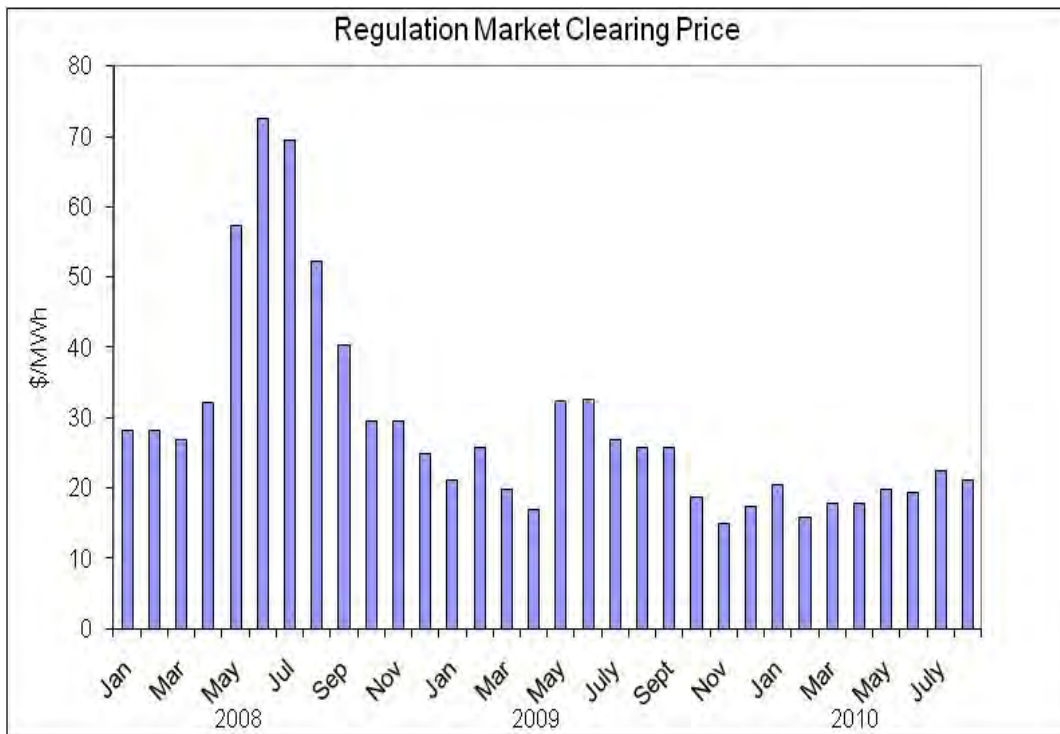


Figure 6.4 PJM Monthly Average Regulation Market Clearing Prices 2008-2010.

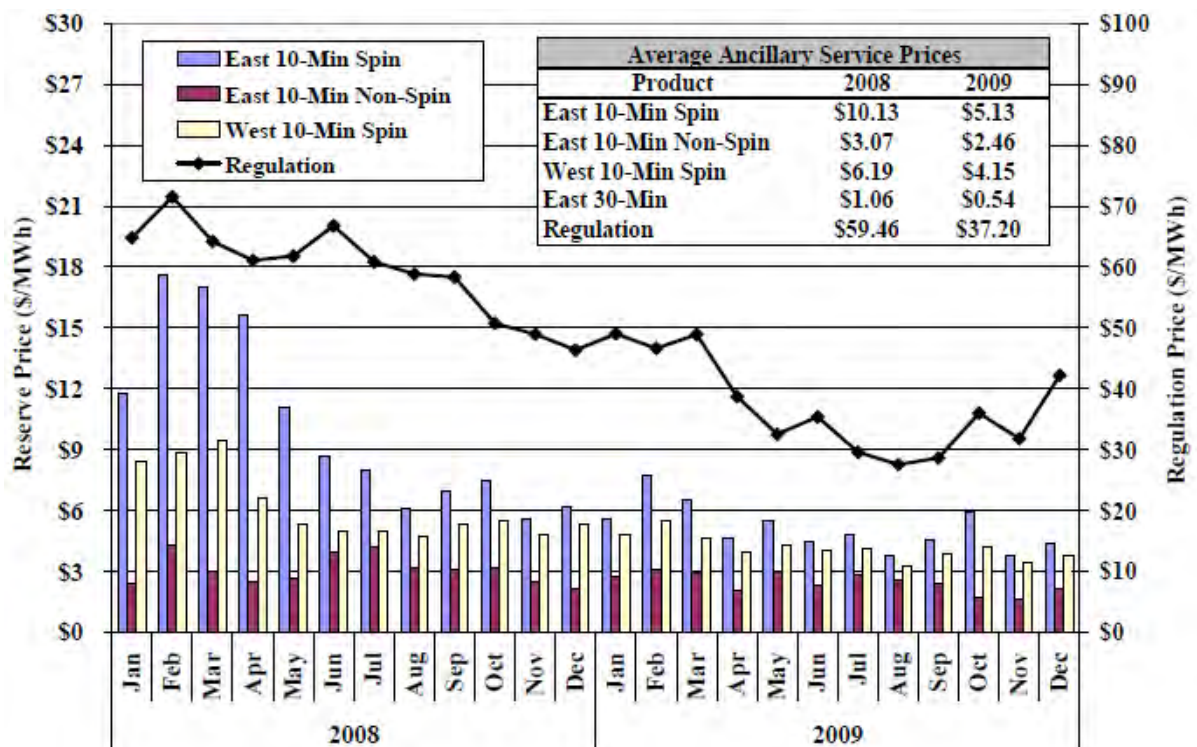


Figure 6.5 NY ISO Monthly Average Day Ahead Ancillary Service Prices 2008- 2009
[66]

The market prices in Figures 6.3-6.5 all show significant increases in 2008 compared to other times, reflecting high natural gas prices during this year. The advent of significant unconventional natural gas supplies in North America is likely to make future natural gas prices lower than encountered in 2008. Prices for ancillary services in ERCOT in 2006, 2007, and 2009 were around \$10 to \$20 per MW per hour. In PJM, the regulation prices were around \$15 to \$25 per MW per hour. In NYISO, for regulation the prices in 2009 were around \$40 per MW per hour, with the prices of other ancillary services much lower, around \$5 per MW per hour. As will be mentioned in section 7.3, however, the prevalence of large-scale demand side resources providing these ancillary services might affect the prices significantly.

To provide a perspective on this level of market prices for ancillary services, retail energy prices in these markets range around the \$100 to \$200 per MWh range. Consequently, providing ancillary services could constitute a non-trivial contribution to offsetting energy prices. As mentioned above, this benefit would come at the cost of the communication and telemetry needed to assure compliance with ISO requirements and the cost of setting up the aggregator function. To the extent that these communications and telemetry costs are fairly small, and to the extent that the effect of providing ancillary services on battery lifetime is negligible, the net benefits to the PHEV/BEV owner and the electricity system could be significant. These issues will be discussed further in section 7.3.

6.3 The Role of PHEVs and BEVs in Distribution System

6.3.1 Concept of V2B

From the discussion above, recent research on the feasibility of V2G is based on the assumption of large-scale penetration of PHEVs/BEVs, which is envisioned on a 15-30 year time horizon in the most optimistic scenarios. As a more near-term application of V2G, Vehicle-to-building (V2B) operation is proposed in this report. V2B is defined as the option of exporting electrical power from a vehicle battery into a building connected to the distribution system to support loads. Due to early adopters, the availability of electrical vehicles in major cities may create a critical mass of vehicles for aggregated use to be available 5-10 years from now. With the introduction of smart garage, which represents an interface between the transportation network and electric power system, the vehicle charging/discharging infrastructure and control system can be available widely making the proposed V2B idea viable and economically attractive.

V2B considers batteries in PHEVs/BEVs as a generation resource for the buildings via bidirectional power transfer through energy exchange stations (chargers/dischargers) at certain periods of time, which could increase the flexibility of the electrical distribution system operation. V2B operation could 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. Figure 6.6 shows the frameworks of V2B implemented in distribution system.

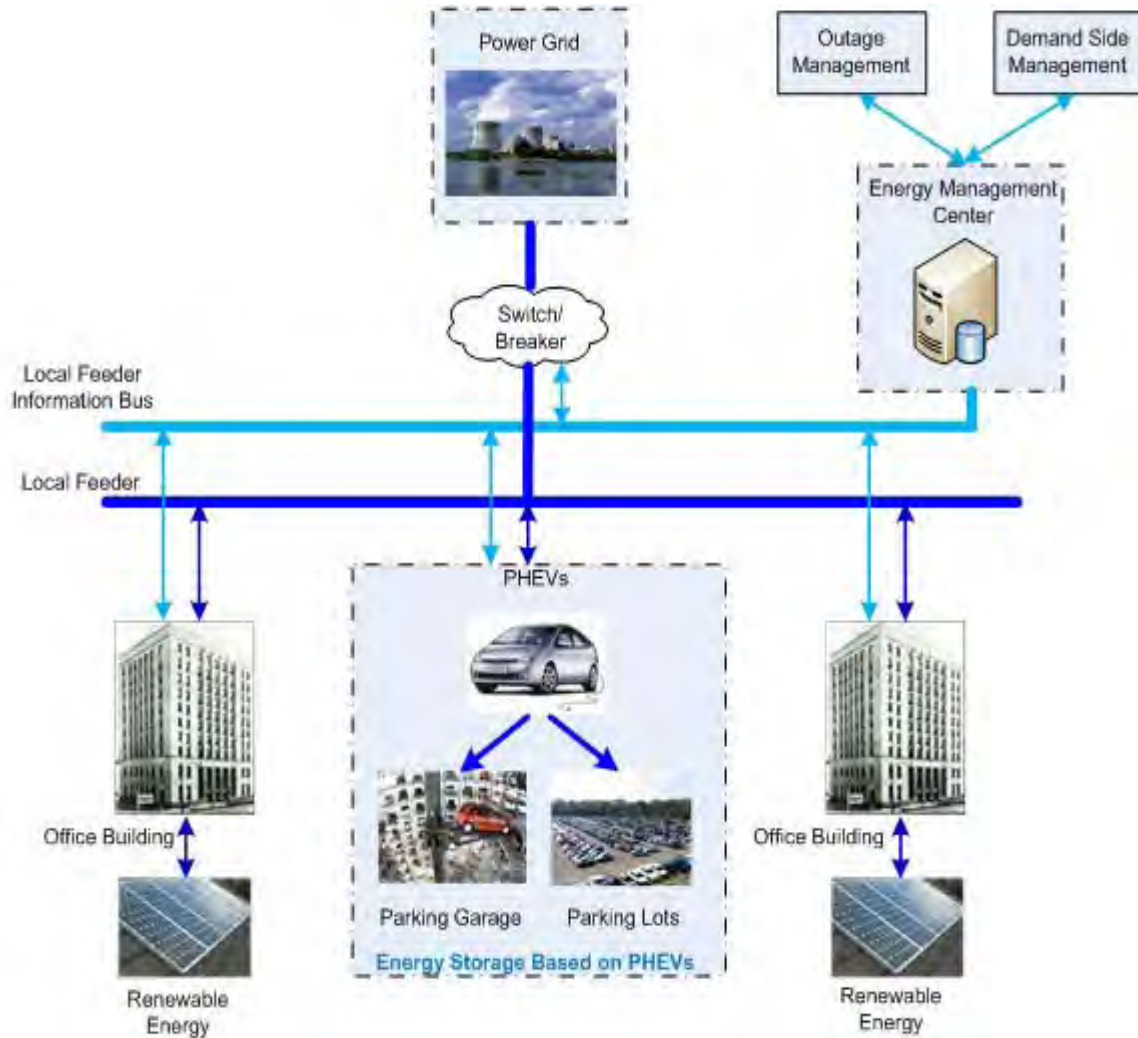


Figure 6.6 Frameworks of V2B in Distribution System

6.3.2 Outage Management

6.3.2.1 Overview

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 with a minimal interruption of service to the customer. Outage management must be performed very quickly to reduce outage time. A recently completed project proposes an optimal fault location scheme which will help the operator to find the faulted section very quickly [67]. In this section we will focus mainly on the restoration strategy under an outage for a commercial facility or building. One application of V2B is using the battery energy storage in PHEVs/BEVs as an emergency back-up power for the commercial facility/building, which increases the reliability of the power supply for that load.

The following types of outages and studies about the impact of PHEVs/BEVs adoption are considered:

Outage beyond the distribution system:

These may be caused by generator failure, fault on transmission line or substation busbar. Usually spinning reserves are kept for these circumstances. From the previous study [5], it is concluded that PHEVs/BEVs based energy storage system can be a candidate solution for replacement of spinning reserves (as the traditional fast-acting spinning reserve generators are highly costly while PHEV/BEV, when aggregated, may qualify for fast response with lesser cost). One may consider using a real-time security constrained optimal power flow under the contingencies to calculate amount of power generation from PHEV/BEV battery required for a certain location at a specific instance.

Outage in distribution system:

These may be caused by a fault occurring on the distribution system and can be mitigated by precise spatial adjustment of energy generation from PHEV/BEV battery that may offer local generation support during and shortly after the outage.

To propose the restoration strategy where PHEVs/BEVs are 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:

- Detect a fault;
- Estimate the location of the fault;
- Analyze the amount of generation required to support the building and the availability of PHEV/BEV that can provide an alternative generation until the faulted section is repaired. This will also consider the generation connection time requirement (i.e. time to repair the faulted section).
- Implement V2B by scheduling the aggregated energy generation from PHEVs/BEVs batteries optimally. The technique of V2G converters has been proved to be feasible in PJM [68]. This is a multi-objective optimization problem which can be formulated as: minimize operating cost, real power loss, time of outage under system operation and security constraints. For simplicity we have used cost minimization objective in this report but the optimization problem can be easily expanded to a multi-objective problem considering all of the objectives.

6.3.2.2 Problem Formulation and Solution Approach

A security constrained optimal power flow to schedule energy generation from PHEV/BEV battery was proposed and tested using an IEEE test systems before [4], which tries to minimize the operating cost under normal system operation. In this section we will discuss a restoration strategy by scheduling PHEVs/BEVs optimally under outage condition. This will basically provide a generation support (by using PHEVs/BEVs) to a building experiencing power outage.

The restoration strategy based on scheduling PHEVs/BEVs by optimizing a multiple-objective problem is proposed here. The problem can be stated as:

$$\text{Min } f_i(\underline{x}, \underline{u}, \underline{p}) \quad (6.1)$$

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

$$h_i(\underline{x}, \underline{u}, \underline{p}) \leq 0 \quad i = 1, 2, \dots, n$$

Where

$f_1(\underline{x}, \underline{u}, \underline{p})$ and $f_2(\underline{x}, \underline{u}, \underline{p})$: The functions to be minimized;

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

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

\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). Cost minimization is the traditional economic load dispatch approach, which is done for minimizing generation cost (PHEVs/BEVs here) while maintaining set of equality and inequality constraints. Loss minimization is typically performed by minimizing total transmission loss of the system. This is done by controlling voltages of the generating units while keeping controllable generator real power outputs constant except for changing output of one generating unit only (called slack bus or swing bus). Thus when the loss is minimized the slack bus generation is also decreased as this is dependent upon the total loss. Thus the total cost is further decreased after the loss minimization. Though outage time is dependent on several other factors (time to locate fault, time to repair etc.), the effective outage time (i.e. from time of fault to start of backup by vehicles) can be reduced by having more vehicles in the vicinity and choosing vehicles having lesser time to discharge.

Presently due to lack of available data, we are considering only the cost minimization objective. The objective function can be formulated as:

$$f(\underline{x}, \underline{u}, \underline{p}) = \sum_{i=1}^{N_G} \beta_G[i] \cdot P_G[i] \quad (6.2)$$

Where

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

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

The equality constraints are the power flow equations. The inequality constraints are the PHEV/BEV battery generation limits, bus voltage limits, and line overload limits.

The restoration strategy is 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 aggregated batteries in garages, the 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.

6.3.3 Demand-side Management

6.3.3.1 Overview

For electric utility, Demand-side management (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 [69]. 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 [70]. The utility and customer cooperatively participating in DSM will provide the benefits to the customer, utility, and society as a whole, which is summarized in Table 6.1 [71].

Table 6.1 DSM Benefits to Customer, Utility and Society [71]

<i>Customer benefits</i>	<i>Societal benefits</i>	<i>Utility benefits</i>
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	Reduce capital needs

In the V2B operation, 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/discharger 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 demand of V2B supported building is lower than its peak load and discharge the batteries to partially supply the building to reduce the peak demand during a high demand. There could be a collateral load profile impact due to outage. An example is an extensive outage in the evening where a large number of residentially based PHEVs/BEVs cannot get their full charge at home. Those PHEVs/BEVs may be plugged in next day at work, which could cause a large sympathetic and unexpected load increase at a different location. The objective of DSM is to minimize the impact of the unplanned event, improve reliability of power supply and create revenue.

6.3.3.2 Problem Formulation and Solution Approach

Power system utilities in North America offer a variety of load control and demand side load management programs to their clients. These programs can provide enhanced power system security and many benefits to their participants. For example, Southern California Edison (SCE) has introduced a number of demand response programs, such as Demand Bidding Program (DBP) and Critical Peak Pricing (CPP) [72]. Considering the electricity rate is lower when the vehicle batteries are charged than when the batteries are discharged, the battery storage may be used to offset high cost during the peak demand. The formulas for calculating revenue depend on the program that the V2B power resource is participated in. In this report, a typical business customer is considered as demonstration scenario. There are three basic charges for business rate schedule: customer charge, energy charge, and demand charge. Consequently, the monthly total revenue for PHEVs/BEVs based V2B operation is calculated as:

$$r = E_{ec} (r_{rc_onpeak} - r_{rc_midpeak}) \times t + r_{tdc} (P_{\max} - P_{dsm_max}) \quad (6.3)$$

where

E_{ec} : the energy shifted from On-peak time to Midpeak time (kWh);

r_{rc_onpeak} : the On-peak time energy charge rate (\$/kWh);

$r_{rc_midpeak}$: the Mid-peak time energy charge rate (\$/kWh);

t : number of days in a month

r_{tdc} : the time-related demand charge (\$/kW);

P_{\max} : the maximum On-peak power demand (kW);

P_{dsm_max} : the maximum On-peak power demand after demand-side management (kW).

In practical application, for the given electric vehicle, the actual maximum power from V2B is calculated as:

$$P_{vehicle} = P_{ideal} \times \eta_{charger} \times \eta_{inv} \times \eta_{other} \quad (6.4)$$

where

$P_{vehicle}$: the actual maximum power for V2B (kW);

P_{ideal} : the ideal maximum power from V2B, usually it is the maximum power of charging station (kW);

$\eta_{charger}$: the efficiency of charger;

η_{inv} : the electrical conversion efficiency of the DC to AC inverter;

η_{other} : other factors, such as power loss, battery self-discharge, etc.

As an example, the studied case is presented in next section with the detailed rate structure of SCE

6.3.4 Case Study

6.3.4.1 Implementation Considerations

In this section, we will discuss the implementation considerations for V2B.

Vehicle Assumptions

Rechargeable batteries are one of the most important components of the PHEVs/BEVs. Many researchers have conducted several studies on design and requirements, cost-effectiveness assessment, and performance of PHEV/BEV battery, which included the nickel-metal hydride (NiMH) [73] and lithium-ion (Li-Ion) [74] technologies. The study results have shown that the advanced battery technology is good enough to support most of the available PHEV/BEV vehicle models. Battery capacity for PHEVs/BEVs depends on the electric range and the vehicle electric drive efficiency. The uncertainty about what the most economical size and configuration of marketable PHEVs/BEVs when comparing the battery pack size, electric motor size, and internal; combustion (IC) engine size should be is still high.

Denholm, et al. provided the estimations of the potential miles displaced by electricity for a variety of PHEV ranges [75]. Their results show the range from 0.25 kWh/mile for compact vehicles to 0.42 kWh/mile for large SUVs. Thus, for a compact PHEV-20 (referring to a vehicle that may be driven 20 miles before the state of charge (SOC) hits the acceptable lower limits), 5.0 kWh is required for the usable battery capacity over this range of vehicles. For a large SUV PHEV-40, 14.4 kWh is required. An average usable battery capacity of 10.2 kWh is assumed [75]. The Electric Power Research Institute (EPRI) reports that 50% of American automobiles travel less than 26 miles/day, which is shown in Figure 6.7 [76]. Thus, PHEVs that could operate 26 miles on battery power alone would have the potential to meet half of America's daily automotive transportation needs. Hence PHEV-40 or similar BEV is chosen as the typical electric vehicles in this report. Two popular electric vehicles are selected for demonstration of V2B operational mode: Chevy Volt and Nissan Leaf. Table 3.1 summarizes the fundamental specifications of two vehicles [44][45]. Particularly, Level 3 chargers may supply very high voltages (for example, 300-500VDC) at very high currents (over 100 amperes). It is possible that Nissan Leaf can draw 24 kWh in 30 minutes.

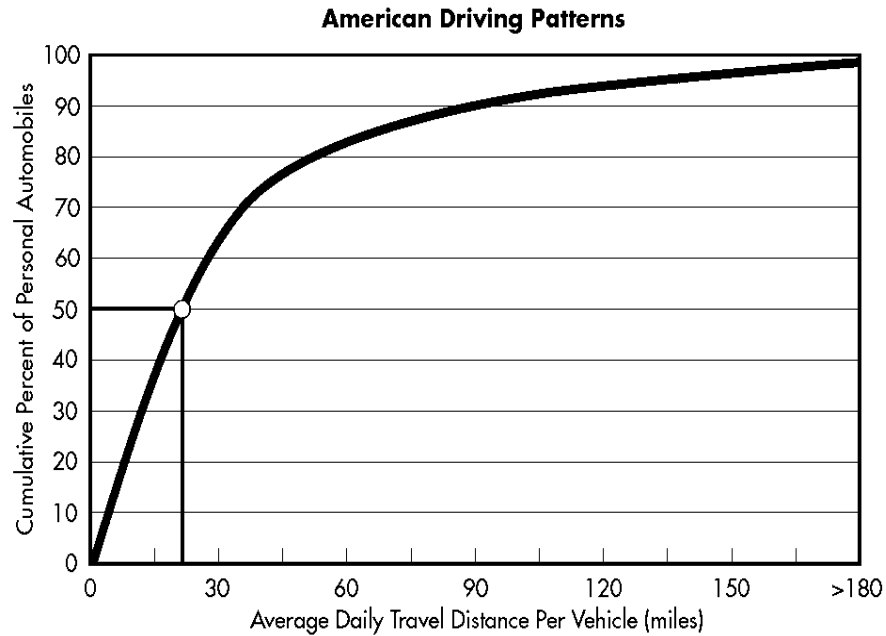


Figure 6.7 American Daily Vehicle Travel [76]

Table 6.2 Electric Vehicles Battery Specifications

<i>Auto Model</i>	<i>Battery Type</i>	<i>Capacity (minimum)</i>	<i>Range</i>	<i>Charging Time</i>
Chevy Volt	Lithium Ion	16 kWh	40 miles	6-6.5 hours (240V)
Nissan Leaf	Lithium Ion	24 kWh	73 miles	7 hours (240V) 30 minutes (quick charger)

Data Requirements

Data availability is an important factor for the implementation. Different types of data from various sources are needed to implement the proposed algorithms. The typical data are summarized as below:

- Power system static data;
- Real time topology information & load data;
- Event data;
- Location of the fault ;
- Location of the building which is out of electricity due to the fault;
- Possible location of PHEV/EBV battery generation;

- Availability and possible amount of generation (that will depend on the number of vehicles, state of charge and owner's choice);
- Status and performances of charging stations;
- Price of charge/discharge;
- Time to charge/discharge.

6.3.4.2 Outage Management Case Study

The proposed restoration scheme was tested on a small distribution system (IEEE 37 node radial test feeder [77]). Figure 6.8 shows the test feeder with smart garages at some nodes.

This is an actual feeder located in California, which consists of several unbalanced spot loads. The nominal voltage is 4.8kV. The hourly load distribution data throughout the year as a percentage of peak load (product of weekly peak, daily peak and hourly peak) is obtained from literature [78]. We have considered a winter morning (Thursday of 40th week at 11 a.m.) and a summer morning (Thursday of 20th week at 11 a.m.) and considered outage time of 30 minutes.

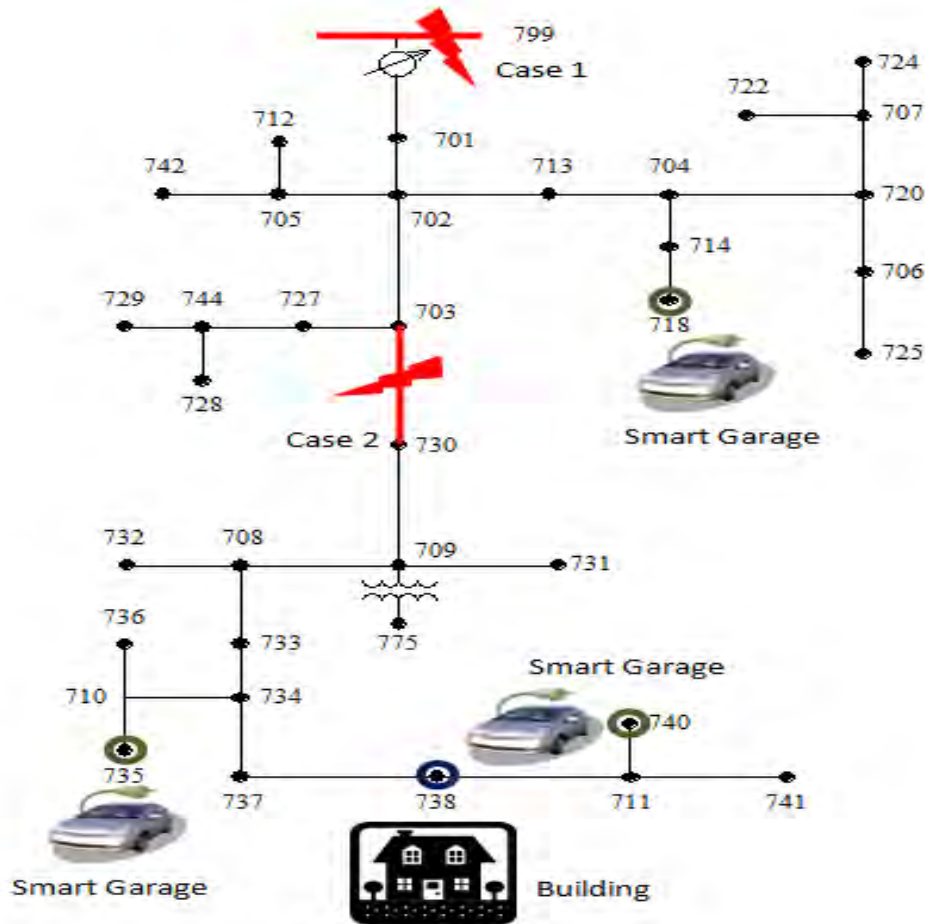


Figure 6.8 Diagram of Test Feeder with Smart Garages

The following assumptions are taken:

- Three nodes are specified as smart garages (nodes 718, 735 and 740);
- The total number of cars in garage at node 718 is 65, at node 735 is 55, and node 740 is 70;
- Maximum capacity of each vehicle is 15 kWh (10kWh is available to use for OM);
- Discharge vehicles with state of charge (soc)>70%;
- PHEV/BEV tariff for charging is 5c/kWh and for discharging is (15-40) c/kWh (depending on different garages). Discharging tariff for node 718 is 40c/kWh, for node 735 is 30c/kWh, for node 740 is 25c/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:

- Case 1: Fault on or beyond node 799: In this case, there is no external generator supply in the distribution system we considered. Battery generation of PHEVs/BEVs at nodes 718,735 and 740 were scheduled to satisfy all the loads on the feeder. Table 6.3 shows the case results.
- Case 2: Fault on line segment 703-730: In this case, part of the distributed system is supplied by external sources (Node 799 will supply all the loads between node 799 and the line segment 703-730) and the segment after node 730 has no external supply and therefore should be backed up by battery generation. Battery generation of PHEVs/BEVs at nodes735 and 740 will be scheduled to satisfy the island created by a fault on line 703-730. Table 6.4 shows the case results.

Table 6.3 Case study 1: Results for PHEV/BEV Battery Generation Scheduling

<i>Date & Time</i>	<i>Node 718</i>			<i>Node 735</i>			<i>Node 740</i>			<i>Cost of scheduling (\$)</i>
	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)	
Thursday of 40 th week at 11 a.m.	0	0	68	320	320	320	165	106	340	450.6
Thursday of 20 th week at 11 a.m.	0	0	224	320	320	300	269	198	340	572.2

Table 6.4 Case study 2: Results for PHEV/BEV Battery Generation Scheduling

<i>Date & Time</i>	<i>Node 718</i>			<i>Node 735</i>			<i>Node 740</i>			<i>Cost of scheduling (\$)</i>
	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)	
Thursday of 40 th week at 11 a.m.	0	0	68	320	320	320	165	106	340	450.6
Thursday of 20 th week at 11 a.m.	0	0	224	320	320	300	269	198	340	572.2

6.3.4.3 Demand-side Management Case Study

Demand-side Management during Peak Power Demand

Data availability is an important factor for the implementation. Different types of data from various sources are needed.

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 different commercial sectors, including large office building [79]. 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 [79].

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 [79]. The following assumptions are taken:

- The studied building is 450,000 sq ft;
- There are up to eighty PHEVs/BEVs that arrive at 8 AM and are available at building's parking facility for the entire day;
- Maximum capacity of each vehicle is 15 kWh;
- The batteries in PHEVs/BEVs are drained on average by 4.0 kWh one way during the driving cycle used;
- The charging levels assumed are AC Level 2: 208-240 VAC

The 450,000 sq ft building is the typical size of commercial building in metropolitan area. The typical garage will have the ability to provide the charging service for hundreds of vehicles. Thus availability of 80 electric vehicles is a reasonable assumption. All the PHEVs/BEVs owners will charge their vehicles till full during the night at lower rate. Level 2 charging is ideal for commercial use at lower cost with good performance.

When PHEVs/BEVs are on site, the building can charge the batteries during the morning hours (lower electricity price) and drain the batteries during afternoon hours (higher electricity price). Certainly, the necessary amount of battery energy will be assured to let the owner of PHEV/BEV have sufficient SOC in their battery storage to meet the driving cycle on return home. This lower boundary is set as 6.0 kWh considering the charging/discharging SOC patterns. With the available AC Level 2 charging stations, PHEV/BEV batteries can be charged to full capacity in less than 1 hour. Faster charging stations (AC Level 3 or DC charging) can finish the charging process in 30 minutes. Figure 6.9 shows the impacts of charging PHEVs/BEVs by AC Level 2 (4 kW power level) charging stations. The load demand profiles of the building with and without PHEVs/BEVs load are presented in this figure. From Figure 6.9, charging electric vehicles will elevate the peak demand of the office building to 1.94 MW since the charging method causes a large load in a short period. This is not recommended for either utilities or customers.

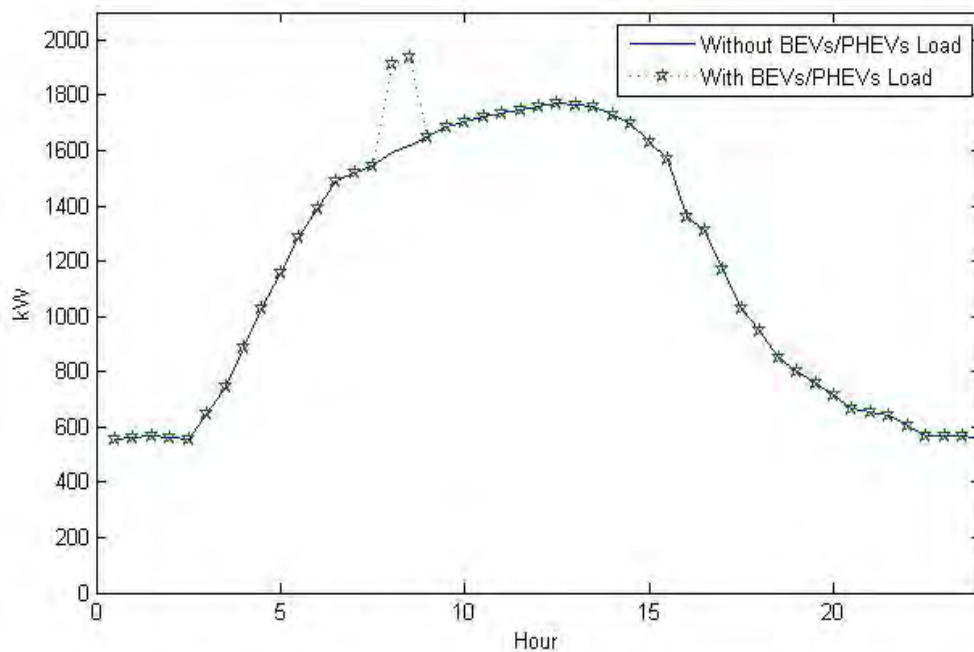


Figure 6.9 Impacts of Faster Charging PHEVs/BEVs on Load Demand

Figure 6.10 shows the change in the load shape for the typical summer day by using PHEVs/BEVs based V2B operation mode. The load curve is changed by shifting the afternoon peak load to the morning off-peak load when charging and discharging the PHEVs/BEVs. The electric vehicle discharging covers a larger area than the charging. The extra energy is coming from night time charging at home with reduced cost.

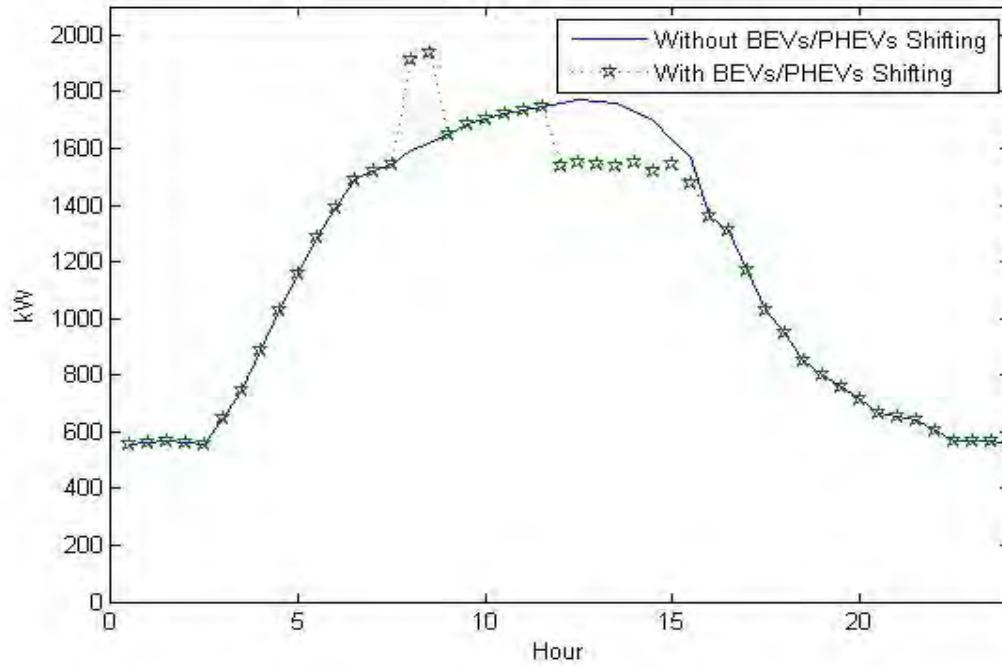


Figure 6.10 Peak Load Shifting with PHEVs/BEVs for a Typical Summer Daily Load

Monthly Revenue of V2B based DSM

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. Let us use the example of Southern California Edison (SCE) utility company. For business rate plans, SCE provides the plan of Time-of-Use-General Service-Large (TOU-8), which is a flexible, customized rate schedule to help SCE and its business customer save money [72].

For most business customers, utility will customize their rate schedule by using four day types—weekday, weekend, hot day (weekday), cold day (weekday) and for four seasons (winter, spring, summer, fall). In our case, TOU-8 energy rates are divided into three time-of-use periods: on-peak, mid-peak, and off-peak. In summer season (June 1 to Oct. 1), mid-peak time is defined as 8 a.m. – noon weekdays except holidays; on-peak time is defined as noon – 6 a.m. weekdays except holidays. The rest are off-peak times. Table 6.5 summarized the SCE rate schedule of TOU-8 Primary Voltage (from 2 kV to 50 kV) in the summer season [72].

In the example of peak load shifting with PHEVs/BEVs, 720-kWh power demand will be shifted from on-peak to mid-peak. At the same time, with the shifting load, the maximum on-peak energy demand reduces from 1.7743 MW to 1.5493 MW. Hence, according to equation (1), the ideal monthly revenue (20 weekdays) for V2B based DSM operation will be \$3769.56. The detailed calculation is presented in Appendix 3. By considering the charging efficiency, the conversion efficiency, power loss, battery self-discharge, etc. the monthly revenue will be reduced to \$2839.61. We do not consider the battery capital

cost. Since each battery will be only charged and discharged once as its regular routine, the charging cycles for these batteries do not increase.

Table 6.5 SEC Rate Schedule for TOU-8 Primary Voltage (Summer Season)
[72]

<i>Customer Charger</i>	<i>Demand Charge (per kW)</i>	<i>Energy Charge (per kWh)</i>
\$275.69 Per month per meter	Facilities-related: \$10.18 per monthly maximum kW per meter	On-peak: \$0.11086 Mid-peak: \$0.09096 Off-peak: \$0.06483
	Time-related: \$15.48 per maximum On-peak kW in the summer season only	

6.4 Impact of PHEVs and BEVs Concentrated Charging/Discharging on Electricity Network

This section investigates the impact of PHEVs/BEVs on traffic flow and micro-level power system configuration, such as nodal area, from parking garage developer's perspective. In the future, the parking garage servicing parked connected PHEVs/BEVs (referred as 'smart garage') would be an important place to exchange an electric power. Parking garage developers could have an opportunity to gain revenue not only from the parking fees and charging service, but also acting as aggregator or contracting with one to act in electricity markets. Therefore, in order to maximize the total revenue, optimal location and incentive structure (i.e. parking fee) of parking garage would be an important decision factor. The scope of the study is limited to project planning stage.

The next section will present an overview of the problem and the key assumptions. Section 6.4.2 presents model formulations. A simple numerical example for impact of PHEVs/BEVs and total revenue model is provided in Section 6.4.3

6.4.1 Overview

For this study, we consider a directed transportation network $G(N, A)$, a set N of nodes and a set A of links. Further, a set A consists of two subsets of links - driving and walking, A_d and A_w , respectively. The network includes k origin-destination pairs (r_i, s_i) , $r_i, s_i \in N$, $i = 1, \dots, k$. On the other hands, we consider a power system network with $M+1$ buses and L branches, $P(M, B)$. The set of buses are denoted by $M \in \{0, 1, 2, \dots, M\}$, with the slack bus at bus 0, and the set of branches connected between buses are denoted by $B \in \{b_1, b_2, b_3, \dots, b_L\}$.

Generally, a bus in power network is the smallest unit where power transaction is conducted in nodal market, and nodes in transportation network represent junctions, a starting point and an end-point. A bus could be associated with one node or more nodes placed within operating area. Figure 6.11 shows a schematic representation of the power and transportation network with smart garage (SG) context. While node 1 is within the operating area of bus 1, node 2 and node 3 are within the operating area of bus 2.

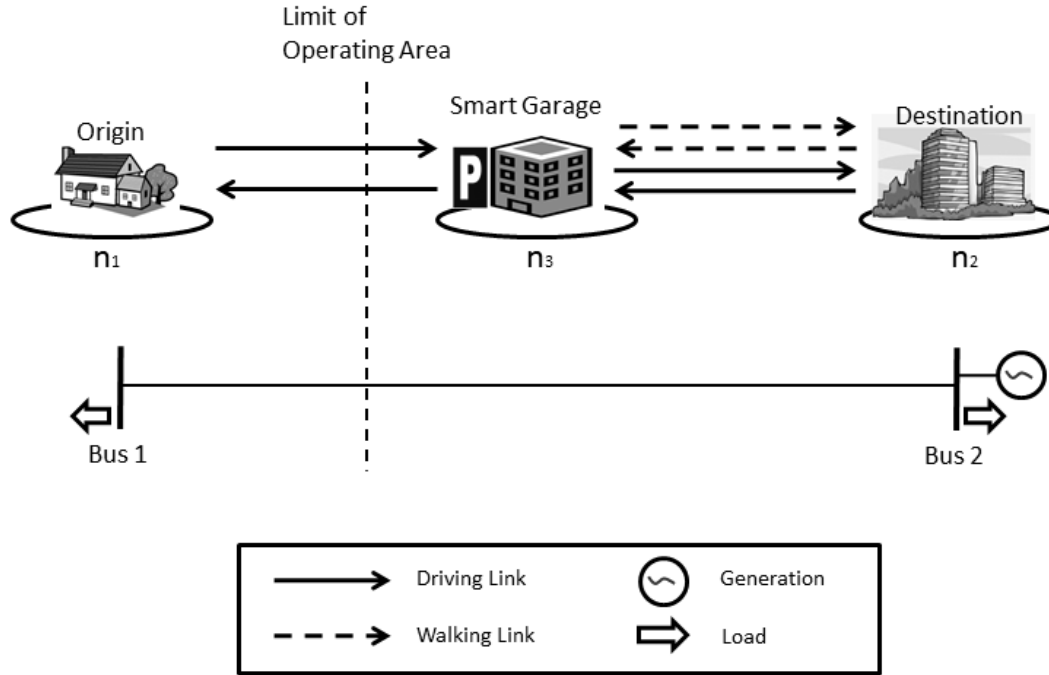


Figure 6.11 Schematic Representation of the Networks with Smart Garage

In the transportation network, both node 1 (n_1) and node 2 (n_2) have conventional parking garages where both internal combustion engine (ICE) vehicles and PHEVs/BEVs can be parked. Node 3 (n_3) indicates the smart garage where PHEVs/BEVs can be charged or discharged. PHEVs/BEVs drivers would choose a parking garage between on node 2 and on node 3 based on a parking fare and walking distance. On node 3, batteries in PHEVs/BEVs could be charged from or discharged to a power grid. That is, SG on node 3 could be a load or generator within operating area of bus 2. Given this schematic representation, the developer of SG needs to make an optimal location and parking fare decisions that would maximize the total revenue.

In this section, the key assumptions are defined for clarity of the model presentation. In transportation network problem, three assumptions defined in Section 5.2.1 are also used in this Section 6.4. On the other hand, in electric power network problem, following three assumptions are defined for the model:

- Minimum MW contract size is not considered,
- Power load is the sum of the total power consumption within an operating area, and

- Movement of people between each other operating area is accomplished only through vehicles.

6.4.2 Model Formulation

This section shows the formulation for network design problem and power system operating conditions. First, the formulation for network design problem explains how developer's decision of location and incentive affects drivers' travel choice and a demand of SG. Second, the formulation of power system operating conditions account for the relationship between power system operating conditions and traffic flow of PHEVs/BEVs.

6.4.2.1 Network Design Problem

Network design problems (NDP) have often been modeled as bi-level program (BLP). Basically, the formulation of an NDP as a BLP consists of two levels: an upper-level managerial problem, and a lower-level follower problem that explains drivers' behavior. The objective functions of network design problem for smart garage is formulated as below and constraints can be referred from Section 5.2.2.

$$\max_{l,i} r_{Total}(l,i) = r_{PF}(l,i) + r_{RS}(l,i) + r_{PH}(l,i) \quad (6.5)$$

$$\max_{l,i} r_{Total}(l,i) = r_{PF}(l,i) + r_{CH}(l,i) \quad (6.6)$$

A developer of SG seeks to maximize profit by constructing a parking garage at the optimal location with parking fare policy. Developer's decision on location (l^*) and incentive (i^*) affects the demand of SGB and the power system conditions, which changes the developer's revenue. This study proposes two business models for the smart garage building; for V2G mode and for G2V mode. The total revenue for V2G mode is defined as a sum of parking fee (disincentive), regulation service fee, and peak demand service fee as in Equation (6.5), while total revenue for G2V mode as the sum of parking fee and charging service fee as in Equation (6.6). Three revenue components, including parking fee, regulation service fee, and peak demand service fee, are already defined at Section 5.2.2.2. Here, the other revenue component, charging service fee, is defined as follows:

$$r_{CH}(l,i) = \sum_{h=1}^{24} \left((P_{D,SG})_h \cdot f_c - (P_{D,SG})_h \cdot \hat{Z}_h \right) \quad (6.7)$$

where $P_{D,SG}$ is a power load from SG. f_c is a charging fee for PHEVs/BEVs.

6.4.2.2 Power System Operating Conditions

Locational marginal price (LMP) is the cost of providing the next increment of demand at a specific node. Different LMP between buses are generally caused by power system operating conditions, such as transmission system, generation, and load. As mentioned in

assumptions, traffic flow of PHEVs and BEVs and movement of people could change power system operating conditions, which results in changing LMP on the buses.

Power Generation and Load of SG

The amount of power generation and load of SG is determined by the number of parked PHEVs/BEVs (or demand of smart garage building $[d_h]$). Demand of SG varies depending on the amount of traffic flow. Generally, the demand of garage building during a day time is higher than during a night time as shown Figure 5.4. Based on the demand of SG, power generation and load from SG are evaluated.

In V2G mode, SG provides ‘regulation service’ and ‘peak demand service’. Regulation service corrects unintended fluctuations of power generation in order to meet a load demand. The service could be called 400 times per a day as regulation up or regulation down, and regulation reserve equal to around 1.5 percent of peak demand on regional area. Due to these properties, in this study, it is assumed that regulation service from SG does not affect the volume of generation and the load in regional area. On the other hands, as a peak hour service, the operator of SG can make a contract with the independent system operator (ISO) to sell a power for a specific period. If developer of SG extracts the power stored in PHEVs/BEVs up to d^{***} for peak demand service, batteries in PHEVs/BEVs would be drained. Therefore, it is essential to define a proper power extraction ratio (λ).

Power generation and load from SG, $P_{G,SG}$ and $P_{D,SG}$, is derived from available PHEVs/BEVs and discharging and charging rate.

$$(P_{G,SG})_h = d_h^{**}(l,i) \times P \quad (6.8)$$

$$(P_{D,SG})_h = d_h(l,i) \times C \quad (6.9)$$

where $d_h^{**}(l,i) = \lambda(d_h^{***}(l,i) - d_h^*(l,i))$. $d_h^{***}(l,i)$ is the most number of PHEVs/BEVs between 8 a.m. and 8 p.m. $d_h^*(l,i)$ is the least number of PHEVs/BEVs for 24 hours. C is a charging rate.

Power Load on Buses

Population at origin and destination nodes, pop_r and pop_s , can be expressed based on trip rates.

$$(pop_r)_h = (pop_r)_{Total} - \eta \times \left[(q_j^{rs})_h + (q_k^{rs})_h - (q_w^{sr})_h - (q_y^{sr})_h \right] \forall r, s \quad (6.10)$$

$$\begin{aligned}
(pop_s)_h &= (pop_s)_{Total} \\
&+ \eta \times \left[(q_j^{rs})_h + (q_k^{rs})_h - (q_w^{sr})_h - (q_y^{sr})_h \right] \forall r, s
\end{aligned} \tag{6.11}$$

where $(pop_r)_{Total}$ is total population in an origin node and $(pop_s)_{Total}$ is total population in a destination node. η is the average number of passengers. Details for trip rate can be referred in section 5.2.2.1.

Based on the current population, power load in node i , $P_{D,i}$, can be expressed as follows:

$$(P_{D,i})_h = \kappa_h \times P_{ave} \times (pop)_h \tag{6.12}$$

where P_{ave} is the daily average power consumption per a person and κ_h is the ratio of power consumption on time h to power consumption for one day.

6.4.3 Numerical Example

Figure 6.12 shows (a) transportation network with four nodes and twelve links and (b) power network with three buses and three branches. For transportation network, it is assumed that node 1 is origin in residential area and node 2 and node 3 are final destination in central business district (CBD). Node 2 and node 3 have a conventional parking garage and smart parking garage is constructed on node 4 where is distance l^* from node 2. For power network, each bus has unique power source and load. Bus 2 and bus 3 have their own operating area and the operating area is divided by the limit of operating area where is distance l_p from bus 2.

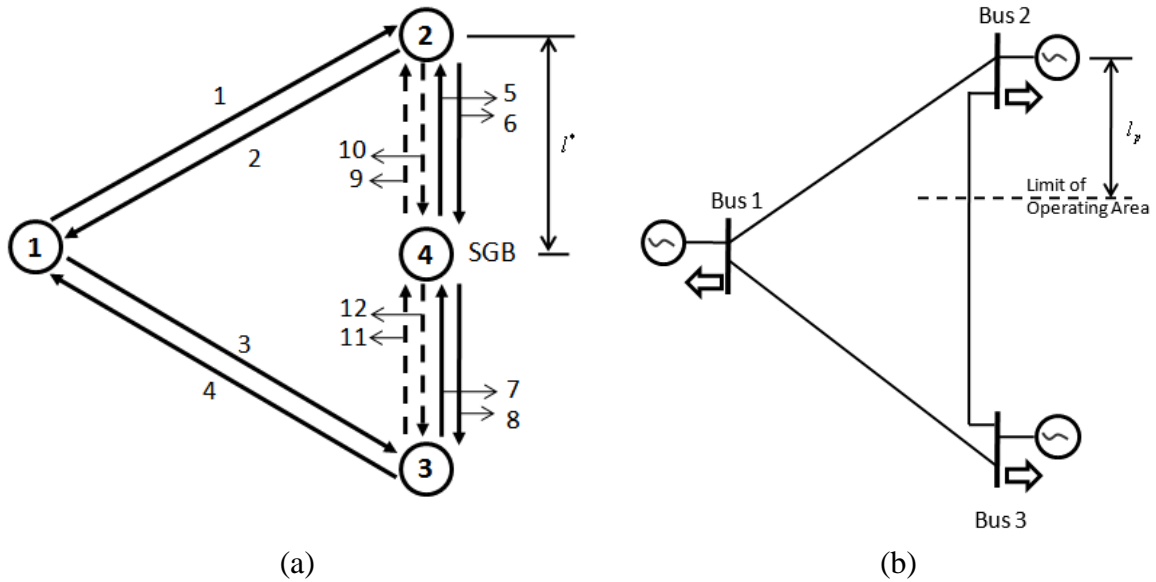


Figure 6.12 Example Networks

For transportation network, each link has own parameters for length and capacity. Details for the parameters can be referred in Section 5.2.3.

For power network, it is assumed that three buses and three branches have equal reactances of 0.10 p.u. and the real power flow on branch 2-3 is limited to 0.05 MW. The power network has three generators.

Table 6.6 shows the properties of each generator. The generator offers are assumed as in the form of linear function. For simplicity, voltage loss and limit are not considered.

Table 6.6 Generation Data for Example Network

Generation Bus	Generation Cost (\$/MW)	Max. of Generation (MW)	Min. of Generation (MW)
1	20	20	0
2	25	5	0
3	30	5	0

In additional, limit of operating area (l_p) is assumed as 1 km from bus 2. Charging and discharging rate for PHEVs and BEVs are assumed as 1.4 kW and 20 kW, respectively. Initial population on residential area (node 1) is assumed as 15,000 and initial populations on CBD (node 2 and 3) are assumed as 1,500, and 2,000. Optimal power flow problem and locational marginal prices are computed using MatPower 3.2.

6.4.3.1 Results for Impact of V2G and G2V

Impact of V2G

Electric power stored in PHEVs/BEVs is used for peak hour service in V2G mode. Therefore, electric power extracted from smart garage building would reduce power load during 8 a.m. to 8 p.m. Figure 6.13 shows load and generation on each bus. Load on bus 1 is not changed at all, because smart garage building is not located within operating area of bus 1. Depending on developer's decision, smart garage building is located within operating area of bus 2 or 3. If l_p is 1.5 km, smart garage building provides peak hour service to operating area of bus 3 and power load at bus 3 would be reduced. Here, the best top lines in load figures indicate base power load without peak hour service. Figure 6.13 shows various load patterns depending on locations and incentives of SG. As electric power load at bus 2 or 3 is decreased by SG, dependency on power generation at bus 1 is reduced during 8 a.m. to 8 p.m. Figure 6.13 shows decreased generation at bus 1 and increased generation at bus 2 and 3. Based on the power system operating conditions, locational marginal prices are calculated at in Figure 6.13. LMP at bus 1 are constant at 20 \$/MW, but LMP at bus 2 and 3 are fluctuated due to insufficient capacity of transmission line.

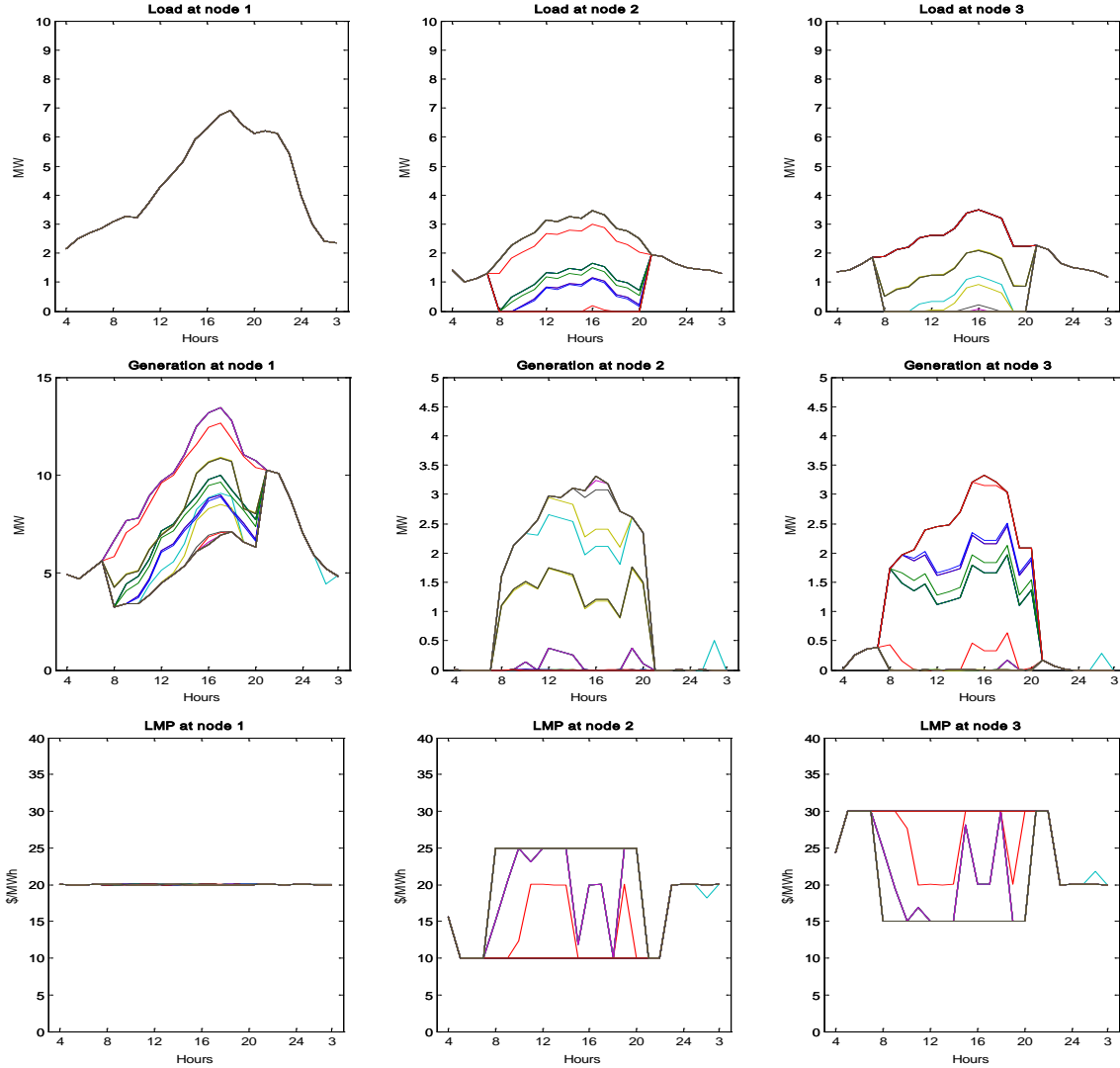


Figure 6.13 Power Load, Generation, and LMP in V2G

(First row shows power load for each node; second row shows power generation for each node; third row shows LMP for each node; first column indicates node 1; second column indicates node 2; third column indicates node 3).

Impact of G2V

Charging service at smart garage increases an electric power load. Figure 6.14 shows increased electric power loads at bus 2 and 3 and increased power generation at bus 1. In G2V mode, electric power generations at bus 2 and 3 are less than the generations in V2G mode, because of absence of power generation from SG. The result shows that fluctuation in LMP in G2V is bigger than that in V2G.

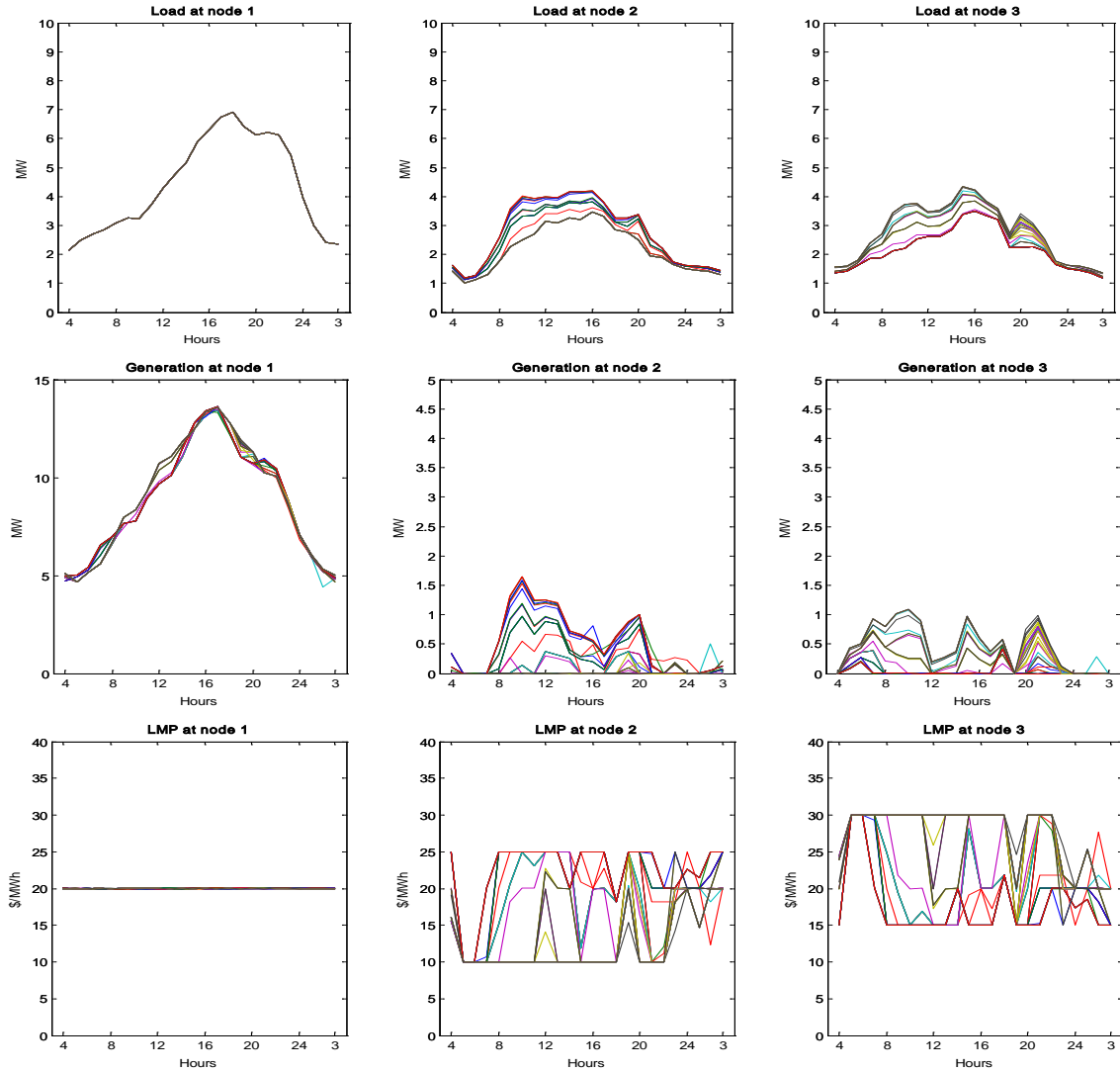


Figure 6.14 Power Load, Generation, and LMP in G2V.

6.4.3.2 Results for Impact of Total Revenue

Figure 6.15 shows the contour graphs for total revenue. Comparing to graph for V2G with uniform price, graphs for V2G with LMP and G2V with LMP present the bumpy line at location of 1.0 km, which results from the impact of SG on bus 2 and 3. The business model in V2G mode with LMP makes more profit than the business model in G2V mode with LMP. Overall, optimal location and incentive of smart garage building are determined at similar points in all cases, but amount of total revenues are all different.

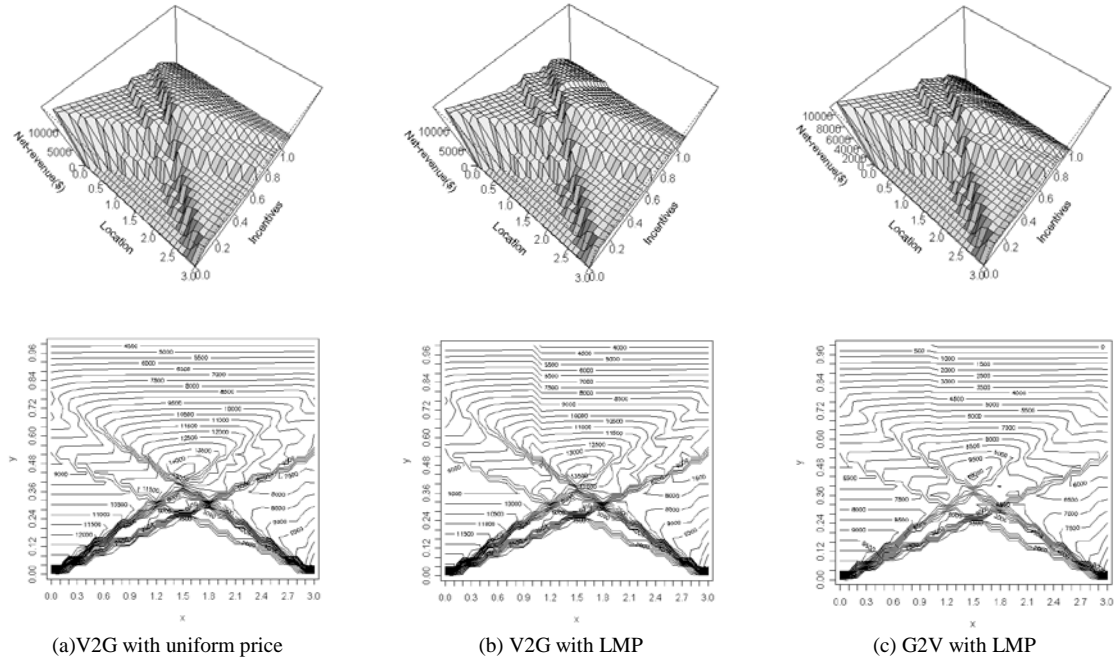


Figure 6.15 Surface and Contour Graphs for Total Revenues

6.5 Conclusions

This section discussed the role of PHEVs and BEVs in electricity network. PHEBs/BEVs based energy storage system can change the load demand curve and provide ancillary services in electricity markets. The demand-side management and outage management based on V2B present the typical future applications in distribution system. PHEVs/BEVs concentrated charging/discharging options have impacts on electricity network. The penetration of significant number of PHEV/BEV could affect power system operating conditions and LMP. More accurate estimation of market penetration rate of PHEVs/BEVs would be quite beneficial. A model to account for the impact of a smart garage on power system and the total revenue of SG developer are discussed in detail. Smart garage represents an interface station point between the transportation networks and electric power networks. Hence, parking garage developer's decision on location and incentive affects the traffic flow on transportation network and electric power flow on an electric power network. The models proposed in this report for the dispersed energy storage system and smart garage can be improved to account for uncertainty, modification of the model parameters from the survey results, and addition of other potential revenue and cost components.

7. Synergy between Electricity and Transportation Networks

7.1 Introduction

The impacts PHEVs/BEVs will have on transportation systems and power systems are very complex. This chapter will discuss the synergy between electricity and transportation networks. Section 7.2 discusses the spatial and temporal characteristics of PHEVs/BEVs. Energy exchange for ancillary services is discussed in section 7.3. Section 7.4 discusses smart garage representing load as a resource. Conclusion is given in section 7.5.

7.2 Spatial and Temporal Characteristics

As discussed above, PHEVs/BEVs can provide promising solution acting as dynamically configurable dispersed energy storage. The widespread adoption of PHEVs/BEVs will place human vehicle operators (PHEV/BEV driver) at the intersection of transportation and power systems. Driver decision making in the context of PHEV/BEV usage and how behavior can be shaped by incentive structures and training interventions are extremely critical. Thus the spatial and temporal characteristics of PHEVs/BEVs based dispersed energy storage system are very unique comparing with other traditional energy storage systems.

Figure 7.1 illustrates the spatial and temporal coupling of the power and transportation systems through showing an example of a PHEV/BEV driver's route, highlighting destinations where the driver could potentially engage in G2V and V2G activity. The spatial and temporal nature of the interactions of power and transportation systems can improve the efficiency of the transportation and energy system.

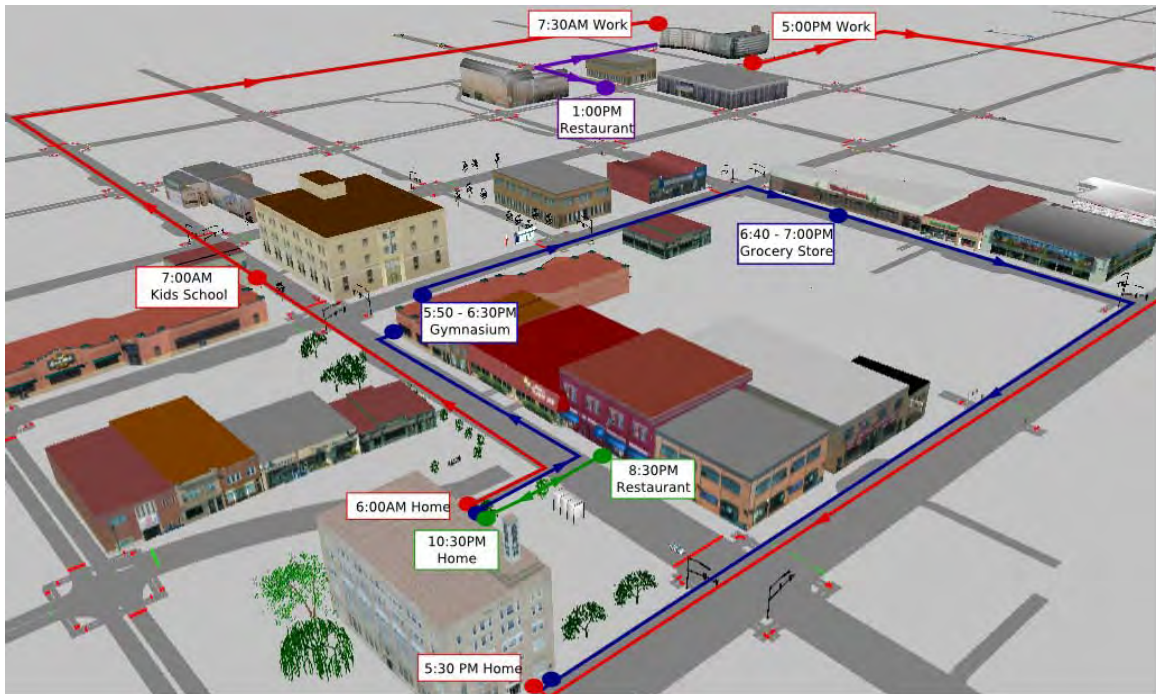


Figure 7.1 Temporal and Spatial Dimensions of Plug-in Opportunities

7.3 Energy Exchange for Ancillary Services

As discussed in previous sections, ancillary services are important aspects of the operation of electricity markets. Traditionally provided by generation resources, there is great potential for these services to also be provided by demand-side resources such as PHEVs/BEVs. For the most part, when generators provide ancillary services, the capacity needed must be dedicated to the provision of the ancillary service. That is, the cost of providing ancillary services by generators is tied to the opportunity cost of reserving the generation capacity and not providing energy. This means that costs of ancillary services will typically track energy prices. This is evident in Figures 6.3-6.5 as discussed in section 6.2.4.

In contrast, the provision of up regulation and reserves by PHEVs/BEVs does not “subtract” from capacity in the same way, since provision of these ancillary services by demand-side resources simply reflects a commitment to reduce consumption. This means that if there is large scale provision of ancillary services by demand-side resources then the market price will be less directly related to the price of energy. While this may make returns to PHEV/BEV owners less attractive than otherwise, particularly in the context of competitive markets, it means that capacity of generation resources can be more fully dedicated to provision of energy. To summarize, the provision of ancillary services by PHEVs/BEVs and other demand-side resources will provide an important synergy with the electricity grid by freeing up generation resources from the provision of ancillary services.

7.4 Smart Garages Representing Load as a Resource

The key feature of PHEVs/BEVs is an outlet connecting plug. PHEVs/BEVs can charge and store electricity from a power grid—referred to as grid-to-vehicle (G2V) operation—or discharge and generate it to a power grid during the parking hours—referred to as vehicle-to-grid (V2G) operation. As such, PHEVs/BEVs provide a link between transportation and electric power systems, acting as a means of transportation in a roadway network and then a mobile load or distributed generator during parking hours.

If smart garage is operated in V2G mode, the smart garage can perform the role of a distributed generator. Distributed generator provides some advantages on an electricity power network. Therefore, it is expected that smart garage gives same advantages as a distributed generator: improving efficiency of power generation, making power grids more stable, and reducing the losses from transmission and distribution systems. In fact, the average vehicle is operated for approximately one hour and parked for the remainder of the day. Hence, during parking hours, PHEVs/BEVs can be utilized as a distributed generator to support a building or a distribution feeder.

In the case that smart garage is operated in G2V mode, the smart garage with G2V will show an important potential synergetic role with other renewable energies helping with the difficulty in managing such energy sources. For example, G2V technology of smart garage, as a solution for managing supply of the wind energy, can provide operating reserves and storage to control the volatility of wind energy.

The impact of V2G and G2V technologies on a power system operating conditions and the locational marginal prices is investigated in Section 6.4. The analysis results present

that, by the types of service, smart garage can be an electricity power generator or a load in a regional area. Both of V2G and G2V technologies influence the power system operating conditions on an electricity power network, and G2V technology, which indicates charging service at smart garage, shows more variation in locational marginal prices.

7.5 Conclusions

Synergy between electricity and transportation network make PHEVs/BEVs based energy storage system own a unique characteristics: the spatial and temporal nature. Energy exchange for ancillary services can be implemented based on smart garage. Smart garage represents an interface station point between the transportation networks and electric power networks. V2G and G2V technology applied to smart garage will bring some synergetic advantages in the form of a distributed generator and an operating reserve. As a distributed generator, smart garage supports integrity of electricity power networks. On the other hand, as an operating reserve, smart garage solves the difficulty in managing volatility of the generation using renewable resources.

8. Conclusions

This final report describes the different aspects of the G2V and V2G services related to the use of PHEVs/BEVs based dynamically configurable dispersed energy storage and related impacts. With introducing the charging characteristics of PHEVs/BEVs and the control/communication capabilities of PHEV-EVSE, the strategies for development of smart garage is studied. PHEVs/BEVs based energy storage system will have strong impact to both transportation and power systems with the aggregating mode of operation. This distributed storage system, aggregated under a service provider, can participate in the electricity market by changing the load demand curves and providing ancillary services. The following are the conclusions of this report:

- This report described the battery system and the battery charging profile for PHEVs and BEVs. Different charge methods and charging system architectures were described based on the SAE J1772 standard. The battery system and charging infrastructures are assumed to be capable of providing charging and discharging functions for the applications of PHEVs/BEVs in power and transportations systems.
- From the discussed techniques for PHEV and BEV use, it can be concluded that different plug-in vehicles generations will have different capabilities for interaction with the grid based on their charging/discharging technologies. Also, grid capabilities and infrastructure can affect the interactions.
- Comparing to existing infrastructures, parking facility for PHEV/BEV represents an interface between the transportation network and electricity power systems. Therefore, when parking facility for PHEV/BEV is constructed, two different networks, electricity and transportation, need to be considered simultaneously.
- From this perspective, smart garage location problem discussed in this report includes user equilibrium problem for traffic flow and electricity power price for contracting with aggregators, and presents the optimal decision for a parking garage developer. It is shown that the developer will be able to make a maximum profit based on the smart garage location problem. Also, the model provides important managerial implications for developers.
- Charging station installation problem discussed in this report shows the optimal number of charging stations to be installed can be determined based on a study proposed in this report. The model includes the uncertainties of PHEV/BEV penetration rate and charging rate. Using the model, parking garage operator is able to decide the optimal number of charging stations and estimate the minimum total cost under the future uncertainties. The sensitivity analysis suggests operators should be careful when determining utility cost.
- There are different services to the grid which can be provided by PHEVs/BEVs like regulation, reserves, and emergency load curtailment. It was noted that these services have some requirements and challenges, which were addressed in this report.

- As a more near-term application of V2G, V2B is defined as the option of exporting electrical power from a vehicle battery into a building connected to the distribution system to support loads. Based on the battery charging/discharging characteristics of electric vehicles, PHEVs/BEVs could play a major role in the distribution system by serving in V2B mode if aggregated.
- For demand-side management, the peak load shifting strategy using PHEVs/BEVs can reduce on-peak load demand and energy consumption, which in turn will reduce the electricity purchase cost for the customer and vehicle owner. For outage management, the outage restoration stage using PHEVs/BEVs to generate power is envisioned by solving a multi-objective optimization problem of merit-order scheduling of PHEVs/BEVs under operating constraints
- The impact of smart garage on power system operating conditions, locational marginal prices, and the optimal decisions in V2G and G2V mode are discussed in this report. Results of the proposed model shows developer's decision of location and incentive affects electricity power flow and their own revenue. Also, the model shows that business model of using V2G to affect LMP makes the most profit for a parking garage developer.

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Appendix 1: Notations of parameters, variables, and sets used in SGDP model

Sets

A_D	=	the set of driving links in O-D trip
A_W	=	the set of walking links in O-D trip
J	=	the set of path of ICE vehicles
K	=	the set of path of PHEVs/BEVs
N	=	the set of nodes
W	=	the set of path of smart garage non-users
Y	=	the set of path of smart garage users

Parameters

c_a	=	the capacity of driving link
c_b	=	the capacity of walking link
E_{dis}	=	the total energy dispatched over the contract period
f	=	the parking fee at conventional parking garage
f'	=	the parking fee at smart garage building
I	=	the upper limit of incentive (i)
L	=	the upper limit of distance (l)
P	=	the power limited by a vehicle's stored energy
p_{cap}	=	the capacity price
P_{con}	=	the contracted capacity (MW)
R_{d-c}	=	the dispatch-to-contract ratio
s_a	=	the average speed of cars
s_b	=	the average speed of pedestrians
t_{con}	=	the duration of the contract
U	=	the upper limit of parking hours (u)
\hat{Z}_h	=	the forecast power price
γ	=	the incentive parameter
$\delta_{a,j}^{rs}$	=	the indicator variable —1 if link a is on path j of ICE vehicles connecting O-D pair $r-s$, 0 otherwise
λ	=	the power extraction ratio
τ	=	the ratio of PHEVs/BEVs to all vehicles

Variables

$d_h(\cdot)$	=	the demand of smart garage
$(f_j^{rs})_h$	=	the flow on path j of ICE vehicles connecting O-D pair $r-s$ on time h
i	=	the incentive provided by smart garage

- l = the distance between smart garage and destination
- $(q_j^{rs})_h$ = the trip rate of ICE vehicles connecting O-D pair $r-s$ on time h
- $r_{PF}(\cdot)$ = the revenue from the parking fee
- $r_{PH}(\cdot)$ = the revenue from the peak hour service
- $r_{RS}(\cdot)$ = the revenue from the regulation service
- $r_{Total}(\cdot)$ = the total revenue
- $t_a(\cdot)$ = the driving link cost function
- $t_b(\cdot)$ = the walking link cost function
- $(x_a)_h$ = the link flows on A_D at time h
- $(x_b)_h^u$ = the link flows on A_W at time h and with u parking hours

Appendix 2: Notations of parameters, variables, and sets used in two-stage stochastic model

Sets

N_p = the set of parking nodes

Parameters

N = the maximum number of charging stations to be installed

$(q_{in}^s)_h$ = the trip rate to node s on time h

$(q_{out}^s)_h$ = the trip rate from node s on time h

Variables

d = average PHEV/BEV demand of parking garage

d_h = PHEV/BEV demand of parking garage on time h

$f(\cdot)$ = the installation cost

l^s = the minimum distance from node s to parking garage

n = the number of charging stations

$Q_j(\cdot)$ = the developer's utility cost

$W(\cdot)$ = the attraction rate by walking distance

$(x_c)_h$ = the sum of trip rates of PHEV/BEV entering to parking garage

$(x_d)_h$ = the sum of trip rates of PHEV/BEV exiting from parking garage

Random Variables

$\tilde{\xi}_1$ = PHEV/BEV penetration rate

$\tilde{\xi}_2$ = PHEV/BEV charging rate

ξ_1^ω = realization of $\tilde{\xi}_1$

ξ_2^ω = realization of $\tilde{\xi}_2$

$P^{\omega_1} = P(\tilde{\xi}_1 = \xi_1^\omega)$

$P^{\omega_2} = P(\tilde{\xi}_2 = \xi_2^\omega)$

Appendix 3: Monthly revenue of V2B based DSM operation

In the following, the monthly revenue of V2B based DSM operation described in section 6.3 is calculated. The monthly revenue depends on the amount of V2B energy shifted from mid-peak time to on-peak time, and the incentives provided by the demand side load management program of local utilities. In this paper, Southern California Edison (SCE) is considered as the case study. The monthly revenue is calculated according to Equation 6.3. It is assumed all the shifted energy from on-peak time will be charged in mid-peak time. Certainly, it will bring more revenue if the shifted energy is charged in off-peak time. Table A. 3. 1 shows the calculation of the ideal revenue from electrical vehicles participating DSM program.

Table A.3.1 SEC rate schedule for TOU-8 Primary Voltage (summer season)

<i>Revenue Parameters</i>	<i>Values</i>	<i>Comments</i>
E_{ec} (kWh)	720	Assume: 80 EVs with 9 kWh available energy to use for each battery (15 kWh-capacity battery with 6.0 kWh reserved considering SOC pattern)
r_{rc_onpeak} (\$/kWh)	0.11086	On-peak energy charge rate in SCE TOU-8 in summer season
$r_{rc_midpeak}$ (\$/kWh)	0.09096	Mid-peak energy charge rate in SCE TOU-8 in summer season
t (day)	20	Assume: 20 workdays per month
r_{tdc} (\$/kW)	15.48	Time-related demand charge for maximum on-peak power in SCE TOU-8 in summer season
P_{max} (kW)	1774.3	The maximum on-peak power demand of the study building
P_{dsm_max} (kW)	1549.3	The maximum on-peak power demand after DSM

The total monthly revenue of DSM in this case will be:

$$r = E_{ec} (r_{rc_onpeak} - r_{rc_midpeak}) \times t + r_{tdc} (P_{max} - P_{dsm_max}) = 3769.56 (\$)$$

The actual revenue will be reduced with considering the charging efficiency, the conversion efficiency, power loss, battery self-discharge, etc. Assume the efficiency of charger $\eta_{charger} = 0.9$, the conversion efficiency $\eta_{inv} = 0.93$, and $\eta_{other} = 0.9$, the actual revenue will be:

$$r_{actual} = \eta_{charger} \eta_{inv} \eta_{other} \times r = 2839.61 (\$)$$