New York State Energy Research and Development Authority

Transportation Electrification in New York State

Technical Update

June 2011

No. 11-07

nyserda
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Transportation Electrification in New York State

Technical Update

Prepared for the

New York State Energy Research and Development Authority

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NYSERDA Report 11-07

NYSERDA

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EXECUTIVE SUMMARY

The commercialization of plug-in hybrid and pure electric vehicles has created an urgent need for utilities to prepare for the installation of charging infrastructure in their service territories and manage the impact of these new loads on the electric distribution system. As part of an initiative with NYSERDA and Consolidated Edison, EPRI conducted a comprehensive study to assess the energy, economic, environmental and distribution impacts of Plug-in-Electric Vehicles (PEVs) in New York State. The purpose of this collaborative was to enable utilities to demonstrate regional leadership in planning for transportation electrification, to support customer adoption of plug-in vehicles, to support development of the charging infrastructure, and to understand and minimize the system impacts from vehicle charging. A particular interest in this study was to understand the impact to downstate New York due to the concentrated electric demand and vehicle population in those areas. This project lays the platform for model-based management of the smart distribution system to integrate Plug-in Electric Vehicles (PEV) within the planning and operation of the system. Key aspects covered as part of this study include:

- Identification of the 'base case' and realistic PEV penetration scenarios of transmission/distribution capacity assuming no PEV penetration,
- PEV distribution impacts on the largest secondary network in Manhattan and another radial circuit in New York,
- Understanding the economic impacts of PEV in New York State,
- Understanding the emission impact of PEV in New York State,
- Understanding the power quality impact of on-board charger systems to the grid, and
- Implications of PEV as a distributed resource for V2G applications or utility aggregated load control.

Base Case and PEV Scenarios for New York State

Base case scenario for the New York State electrical system and vehicle fleet was used as the reference to measure the effects of the introduction of PEVs in the PEV scenario. This scenario represents a relatively aggressive deployment of advanced grid technologies and advanced vehicles; in particular the grid scenario assumes the development of regulations to limit greenhouse gas (GHG) emissions and the vehicle scenario includes increases in vehicle efficiency and widespread deployment of PEVs. The electric grid was simulated for the timeframe from 2010 to 2050 in order to model GHG emissions using EPRI's National Electric System Simulator Integrated Evaluator (NESSIE) model. This analysis found that in the near term, until about 2020, the main trend was a shift from higher emitting conventional generation like oil and older coal towards renewable generation and combined cycle natural gas. After 2020, wind and biomass continue to expand and coal capacity transitions to Integrated Gasification Combined Cycle with Carbon Capture and Storage.

The transportation system changes over time as new vehicles are added and older vehicles are driven less and eventually retire. The scenario described in this study is derived from the 'Medium' scenario in EPRI reports 1015325 and 1015326, Environmental Assessment of Plug-In Hybrid Electric Vehicles Volumes 1 and 2 (called the EPRI-NRDC analysis). As in the base case, conventional vehicles, Hybrid Electric Vehicles (HEVs), and PEVs become more efficient, but in this case some HEVs are replaced with PEVs to achieve additional emissions decreases. This study assumes that the entry of PEVs into the vehicle fleet takes future market share from both conventional vehicles (CVs) and HEVs. Market penetration of CVs, HEVs, and PEVs from 2010 to 2050 was developed with HEVs representing approximately 15% of the market of new vehicle sales when PEVs are expected to enter the market in 2010. Based on the EPRI-NRDC Medium scenario, PEVs could reach a maximum of 10% new vehicle market share by 2015 timeframe and 36% by 2020. The increase in transportation electrification over the Base case decreases emissions, without any other changes to the vehicle mix or electricity policy assumptions. Total emissions decreased by 15% instead of 7%, despite significant increases in vehicle miles traveled and electricity usage.

PEV Scenarios & Distribution impacts Study for New York State

As with any load, PEV demand exhibits its own unique set of diversity characteristics. Given the particular spatial and temporal uncertainties associated with charger locations and usage, traditional methods of load forecasting and distribution system analysis methods only provided limited understanding of the true impacts of PEVs on the system. Also, system-wide assumptions do not address the potential impacts of coincident peak PEV charging at localized distribution levels where diversity benefits may be less than anticipated at system levels. Today, planning models are kept up to date based on GIS interfaces relatively infrequently and very few utilities have any kind of real time model to integrate and evaluate the impacts of electric vehicles into the distribution system. This effort was targeted to fill this void by evaluating the potential impacts due to PEV charging across the entire distribution feeder from the substation down to the individual customer.

Separate PEV scenarios were developed for 1) Con Edison's Yorkville secondary network circuit (Con Edison's largest network circuit) and 2) Don Bosco radial circuit. Both these circuits were within the Zones J and K, i.e. downstate, due to the concentrated electric demand and vehicle population in those areas. Although Yorkville was not best representative for expected near-term PEV vehicle adoption, ConEd recommended Yorkville circuit since it was the most heavily loaded network circuit in the City. In other words, by picking the Yorkville circuit as the worst case in terms of network circuit loading and overlaying the heaviest PEV loading, one would have created a worst case scenario. This would be useful in determining the likelihood of any problems occurring at all and, if potential problems are identified, what are the problems, what the magnitude is and what methods could be utilized to address them.

At an aggregate level, the overall energy and power demands of electric vehicles are modest—nearly 80% of vehicles are driven 40 miles per day or less. When factoring in average driving habits, average charging energy per vehicle is 5.1 kWh. The impact of PEV charging however is largely found at the distribution level. Preliminary market assessment indicates that PEV have a likelihood of 'clustering' and discrete locations, magnifying the impact of PEV charging on distribution transformers and other system components.

Distribution Impact Evaluation on Don Bosco circuit

To evaluate the potential distribution system impacts due to residential customer adoption of PEV, ConEd selected feeder Don Bosco circuit 17W55 (13.2KV) for the analysis. The circuit, served out of the Harrison substation, is a radial suburban circuit serving a total of 1,652 customers, 95% of which are residential.

An analysis methodology, developed by EPRI, was used to evaluate the circuit's response to PEV demand. Specifically, a three stage analysis identifies which assets are potentially at risk, the likelihood and severity of impacts, as well as any circuit characteristics which increase impact risk.

- **Asset Deterministic Analysis –** Examined the ability of each asset to safely supply the worst-case projected load base. Existing capacity and number of customers serviced is determined using the circuit model and compared with the projected PEV load derived from probabilistic evaluations of PEV projections.
- **System Level Deterministic Analysis –** This provides qualitative sensitivity information on system wide behaviour to worst-case charging conditions at various penetration levels. Additionally, the analysis provides a quick evaluation of the boundaries for potential impacts to the system.
- **Stochastic Analysis –** Evaluated both the system as well as PEV charging across not only the full calendar year but hundreds of different spatial and temporal variations. The results of this analysis provide insights into impact likelihood and severity as well as information concerning the conditions under which these particular impacts occurred.

Distribution system impacts evaluated in the study include thermal overloads, low voltage conditions, system losses, and voltage imbalance which were all found to be either be negligible or within satisfactory limits.

Based on the analysis, significant impacts are not expected to occur on Don Bosco circuit 17W55 for the near-term planning horizon. Nonetheless, any existing conditions not captured in the circuit model, such as low customer voltages or overloaded transformers, may be aggravated by the additional PEV load. However, these issues can arise for any per-capita load growth. While minor impacts cannot be completely ruled out, few impacts, if any, are expected to occur and will be limited to assets located closest to the customer. While feeder specific results were determined to be highly dependent on specific conditions, examination of the collaborative results permitted the qualitative identification of the universal factors or conditions when looking at the overall impacts. A few general but key takeaways from the collaborative effort include:

- Near-term horizon impacts are expected to be minimal for most utilities
- Initial impacts will be centered on undersized assets general located close to the customer
- PEV adoption will drive revaluation of system design practices such as component sizing in future years
- Controlled charging can defer projected impacts due to load growth to later years

Distribution Impact Evaluation on Yorkville

As part of this study, EPRI conducted a comprehensive evaluation of assessing plug-in electric vehicle (PEV) charging effects on a low-voltage secondary network in Manhattan. The geographic area is the Upper East Side, between Central Park and the East River from roughly 77th Street to 110th Street, plus Ward Island and Randall's Island. The network peak load (including losses) was about 300 MW in 2007. This neighborhood of Manhattan is called Yorkville.

The Yorkville network load and operation characteristics differ from those of a typical suburban radial feeder. There are very few single-family homes and relatively few driving commuters to or from Yorkville. The area is all served by subway, bus, and taxi. There are very few (if any) opportunities for on-street, driveway, or detached chargers owned by the resident. It was assumed that PEV chargers can be installed at existing public parking facilities, and those can be served from the Yorkville network as new loads. In addition, there may be commercial fleet (taxi) chargers not considered in this project. Service to fleet chargers would be planned and engineered by Con Edison like any other large spot load.

Additionally, Con Edison designs the secondary networks in Manhattan to be reliable under N-2 contingencies, which means that loads are served even with two primary feeders out of service. It is important to note that this criterion is not used on radial feeders, even those owned by Con Edison. Consequently, the analysis procedures in this project were customized to fit the N-2 planning process.

Con Edison uses software called PVL for network analysis, and the Yorkville model was converted from PVL to EPRI's OpenDSS software. The PVL and OpenDSS solutions do not match exactly, but they both show that Yorkville is already operating at its limit when the load is at the 2007 system peak. Both PVL and OpenDSS show the same two network transformers that already have significant overloads, even with no PEV load and no feeders out of service. Those base-case overloads were "fixed" in the model before evaluating PEV impacts.

Network transformer overload is the main limiting factor. At the system peak, approximately 2,800 chargers can be accommodated with 1% or fewer transformer upgrades. At 90% of the system peak, the limit increases to about 9,350 chargers. This means many more PEV can be accommodated if the charging times can be controlled to avoid system peaks, which only occur on a few days during summer, and during afternoon and evening hours.

These results, 2,800 vehicles at 100% load or 9,350 vehicles at 90% load, are representative of what should be expected in Yorkville. As the system and load evolved from 2007, and the PEV distribution may differ from that assumed in this study, the specific transformer overloads will change. But the total network capacity for PEV should be about the same.

Statewide Economic Impacts of PEV in New York State

This study analyzes the statewide economic impacts associated with large-scale use of plug-in electric vehicles (PEVs) in New York State. Specifically, the study examines the statewide economic impacts due to petroleum displacement, increased electricity demand, and annual fuel cost savings by consumers under a hypothetical scenario where PEVs achieve 40% market penetration in the state. The study applies regional input-output analysis to quantify Gross State Product (GSP) and employment effects under four different fuel price cases. In all cases, positive economic benefits were demonstrated, ranging from $4.45 to $10.73 billion/year and 19,800 to 59,800 jobs for GSP and employment impacts, respectively. These results imply that a transition to PEVs in New York could lead to large economic benefits for the state, and policies that promote the market adoption of PEVs may be warranted from a public benefit perspective.

There are certain limitations to these findings. The RIO method assumes static production functions, constant commodity prices, unconstrained labor markets, and production costs that are linear functions of production output [50]. The static nature of RIO analysis implies that future changes in the structure of the economy—such as the introduction of new industries—are not explicitly modeled. Thus, our results are applicable to future cases only inasmuch as the structure of a future economy reflects the structure of the present. However, even with these limitations, we believe our results provide useful insights into the macroeconomic impacts that fuel switching could have in New York State. As we have shown in this report, the potential statewide economic impacts from PEV use are substantial. In light of this report's findings, policies that encourage PEV use in New York State could have significant economic payback.

Future analyses might apply the analytical approach employed here to examine the net impact of PEV market penetration on a smaller scale. Given the scale of potential economic impacts seen here, gaining an understanding of expected economic impacts using near-term market penetration estimates could help to inform New York policy decision-making. Moreover, additional analyses might include evaluating the economic impact of PEV owners selling excess electricity to the grid, of inclusion of PEV incremental costs, or impacts of PEV emission reductions, such as health benefits. These types of analyses will provide a more comprehensive understanding of the anticipated economic impacts due to PEV market penetration in New York State.

Emission Impacts in New York State

Plug-in Electric Vehicles (PEVs) have the ability to use electricity as a transportation fuel, which can drastically reduce the amount of gasoline used by the vehicle. Petroleum reduction alone is a significant benefit, but this shift also enables a reduction in carbon dioxide (CO2) emissions and an improvement in air quality, since electricity generation for transportation usually has lower emissions than using gasoline as a transportation fuel. This report describes an analysis of the impact of a high penetration of PEVs in New York State by looking at the tradeoff between emissions from New York electricity generators used to charge electric vehicles and the reduction in gasoline use.

The air quality impacts of PEVs were analyzed by comparing the power plant emissions increases due to increased generation relative to the vehicle and fuel system fuel emissions reductions due to decreased gasoline use. These relative emissions were then simulated in an air quality model to determine resulting levels of ozone and fine particulate matter (PM2.5). The use of PEVs:

- Decreases ozone levels, and has a high impact on populated areas
- Leads to a reduction in PM2.5 across New York State and the surrounding areas, especially around New York City

Overall, the relative magnitude of changes is small even for large penetrations of PHEVs.

Investigation of On-Board Chargers Power Quality Impacts

As on-board chargers and PEVs continue to evolve and grow in popularity, adverse power quality issues could affect the grid. EPRI has conducted lab tests and collected data on onboard PEV charging systems with the purpose of determining the power quality impacts on the grid. Data collected focuses on charge cycle, distortion, harmonics, power consumption, and power factor. This data and future activities are discussed in depth in later sections. As indicated by the test results, the current distortion reaches noticeably higher values with the 120V system. With the tested 120V systems, there is a range of 4% to almost 30% Total Harmonic Current Distortion (ITHD%) vs 2% to 9.5% with the 208/240V systems. This tends to indicate that the 240V chargers tested created less distortion on the current waveform then the 120V chargers. The J2894 recommended practice that is being developed by Society of Automotive Engineers (SAE) recommends the ITHD% to be below 10%. Based on this criterion, three of the chargers evaluated would exceed this limit. The next power quality component looked at was the harmonic content of the various charging schemes. As noticed by the current distortion, it is expected that the 120V chargers will exhibit more harmonic content then the 240V systems. The third, fifth, seventh, and even the ninth harmonic show substantial presence on the 120V systems compared to the smaller values on the 208/240V system. In terms of both overall distortion and harmonic content, the 208/240V systems performed at a cleaner quality then the 120V systems.

Implications OF PEV As A Distributed Resource

This report also summarizes studies and demonstrations of the use of demand-side resources, in particular plug-in vehicles (PEVs), to provide services to the grid and smooth the output of renewable generation such as solar photovoltaic (PV). PEVs include plug-in-hybrid (PHEV) and battery electric vehicle (EV) technologies. The vehicles represent a controllable load whose charging may be curtailed, and in addition the vehicle may provide energy back to the grid to act as a source of mobile energy storage. This is commonly called vehicle-to-grid (V2G), and would require the capability for bi-directional power flow when the vehicle plugs into the grid. The economic value and the value of the PEV as a source of energy depend on the storage capacity of the battery system, the capacity of electrical supply where the vehicle is plugged in, and the service the vehicle is providing.

Several studies have assessed possible economic benefits from PEVs providing grid services such as frequency regulation. The results of these studies suggest that the storage on board PEVs may be used for a variety of services in the power grid and merit further research as vehicles are introduced into the mass market. Depending on the local market conditions and other infrastructure development such as advanced metering infrastructure (AMI) or increased penetration of renewables it may be worthwhile to explore the topics herein in further detail.

As an example, the V2G program at the University of Delaware (UD) has assessed the economic potential for advanced vehicle technologies providing ancillary services in various independent system operator/regional transmission operator (ISO/RTO) markets [1- 3]. The annual net revenue for a single vehicle was assessed considering PEV, EV and fuel cell vehicles and ranged from $290 to $2,554 depending on the type of vehicle and the service being provided. Another report found that the net revenue achievable for a vehicle providing frequency regulation is three to four times as much as providing spinning reserve depending on the market [2]. Fleet applications have also been considered with a resulting $200 to $800 per vehicle in some applications [3].

The objective of this work was to determine the state of distributed storage and V2G research and demonstration. The material will interest energy providers who are considering the impacts of PEVs in their service territories. In addition the examples of valuation of the economic benefits of providing grid services will be of interest to vehicle owners when considering participation in enhanced demand response and V2G programs in the future.

The results and applications discussed in this study may be extended to any form of modular energy storage which may be used to improve bulk grid reliability or in combination with distributed intermittent renewable generation sources. As smart grid infrastructure including two-way communications associated with AMI become more widespread and as ISO/RTO markets evolve to better accommodate participation of smaller capacity resources the topics discussed will become more relevant. In addition current vehicles being released in the near-term will not be equipped for bi-directional energy supply associated with V2G, therefore substantial work in the area of hardware, software, and control technologies will be needed for large-scale application of these ideas.

The work being done at EPRI with vehicle and power system modeling will aid in the assessment of which forms of vehicle supply will be feasible and what their impacts will be on grid operations. EPRI is actively involved in standards development of automated demand response, smart grid, AMI and PEV technologies and therefore is in touch with the needs of stakeholders throughout the V2G value chain. The needs of power grid, grid operators, and vehicle owners must all be considered when exploring the use of PEV as distributed energy storage.

The results presented herein will allow users to identify possible benefits associated with increasing penetration of PEV and provides examples of the value streams that vehicle owners might realize by allowing their vehicles to be used for V2G applications. The material was gathered through a thorough review of current academic and industry literature.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

1
INTRODUCTION

A new era of Plug-In Electric Vehicles (PEVs) is about to begin. Nissan and General Motors have announced plug-in vehicles for delivery by the end of 2010. They are followed by Ford, Mitsubishi and Toyota, all of whom have announced the introduction of plug-in vehicles to the U.S. market by 2011 or 2012. The rapidly approaching commercialization of plug-in hybrid and electric vehicles has created an urgent need for utilities to support adoption of electric vehicles by their customers, prepare for the installation of residential, commercial, and private infrastructure in their service territories, and manage the impact of these new loads on the electric distribution system.

There are several strong indicators that the State of New York is one of the leading early markets for plug-in vehicles. While the implications of increased penetration of PEVs is being studied generally on a national level and in several more localized regions as part of the multi-utility distribution impact work, the specific impact to New York State has not yet been fully understood.

At an aggregate level, the overall energy and power demands of electric vehicles are modest—nearly 80% of vehicles are driven 40 miles per day or less. When factoring in average driving habits, per vehicle charging energy per vehicle is 5.1 kWh. The impact of PEV charging, however, is largely found at the distribution level. Preliminary market assessment indicates that PEV have a likelihood of 'clustering' and discrete locations, magnifying the impact of PEV charging on distribution transformers and other system components.

As part of an initiative with NYSERDA and Consolidated Edison, EPRI conducted a comprehensive study to assess the energy, environmental and distribution impacts of PEVs in New York State. The purpose is to outline a number of potential roles for electric utilities to consider when developing electric transportation readiness plans. These roles have been formulated with the objective of enabling utilities to demonstrate regional leadership in planning for transportation electrification, to support customer adoption of plug-in vehicles and supporting charging infrastructure, and to understand and minimize the system impacts from vehicle charging.

Scope of This Report

A particular interest in this study was to understand the impact to downstate New York due to the concentrated electric demand and vehicle population in those areas. Key aspects of this study include:

- Identification of the 'base case' scenario of transmission/distribution capacity assuming no PEV penetration,
- Identification of several realistic PEV penetration scenarios, including vehicle characteristics and required load support,
- Understanding the economic impacts of PEV in New York State,

- Understanding the emission impact of PEV in New York State,
- PEV Distribution impacts on the largest secondary network in Manhattan and another radial circuit in NY,
- Understanding the Power Quality impact of on-board charger systems to the grid, and
- Implications of PEV as a distributed resource for V2G applications or utility aggregated load control.

2 BASE CASE SCENARIOS FOR NEW YORK STATE

Executive Summary

This chapter describes the Base case scenario for the New York State electrical system and vehicle fleet. This scenario is used as the reference to measure the effects of the introduction of Plug-in Electric Vehicles (PEVs) in the PEV scenario. This scenario represents a relatively aggressive deployment of advanced grid technologies and advanced vehicles; in particular the grid scenario assumes the development of regulations to limit greenhouse gas (GHG) emissions and the vehicle scenario includes increases in vehicle efficiency and widespread deployment of Plug-in Electric Vehicles (PEVs).

The electric grid was simulated for the timeframe from 2010 to 2050 in order to model GHG emissions using EPRI's National Electric System Simulator Integrated Evaluator (NESSIE) model. This analysis found that in the near term, until about 2020, the main trend was a shift from higher emitting conventional generation like oil and older coal toward renewable generation and combined cycle natural gas. After 2020, wind and biomass continue to expand and coal capacity transitions to Integrated Gasification Combined Cycle with Carbon Capture and Storage.

Overview

This chapter describes the Base case scenario for the New York State electrical system and vehicle fleet. This scenario is used as the reference to measure the effects of the introduction of Plug-in Electric Vehicles (PEVs) in the PEV scenario. This scenario represents a relatively aggressive deployment of advanced grid technologies and advanced vehicles; in particular the grid scenario assumes the development of regulations to limit greenhouse gas (GHG) emissions and the vehicle scenario includes increases in vehicle efficiency and widespread deployment of Hybrid Electric Vehicles (HEVs).

The scenario described here is substantially derived from the 'Medium' scenario in EPRI reports 1015325 and 1015326, Environmental Assessment of Plug-In Hybrid Electric Vehicles Volumes 1 and 2 (called the EPRI-NRDC analysis below). These chapters describe the detailed assumptions that lead to the results described in this summary.

Electricity System Evolution

The electric grid was simulated for the time frame from 2010 to 2050 in order to model GHG emissions using EPRI's National Electric System Simulator Integrated Evaluator (NESSIE) model. This modeling assumes a growth in load based on historical rates of increase (about 1.45% per year for the base case scenarios shown in Figure 2-1 through Figure 2-3 without the inclusion of PEVs), then simulates the evolution of the generation system to meet this load. This evolution includes the retirement of plants that are no longer economically competitive and the construction of new plants based on a variety of detailed assumptions concerning the costs and limitations of new generation.

Figure 2-1 shows the simulated load in the base case for New York State. The load grows by about 100 TWh over the study timeframe, even in the absence of additional load from PEVs.

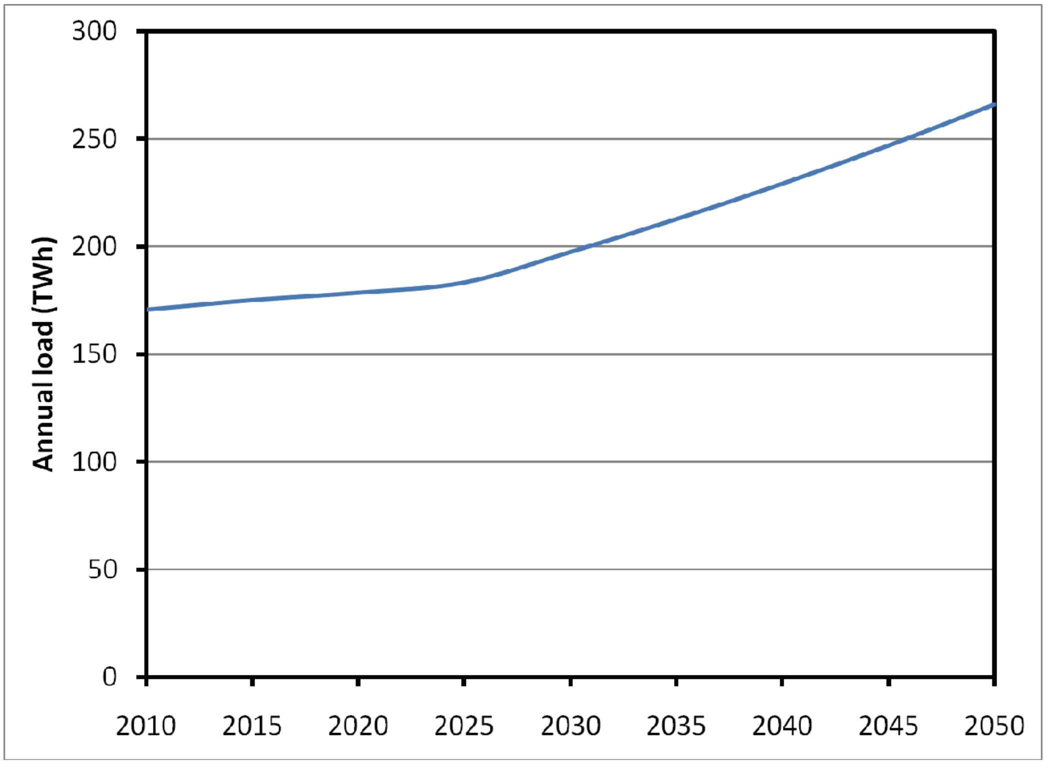

Figure 2-1
Load for New York State

Figure 2-2 shows the simulated capacity evolution for the Base case. Before 2020, the main notable trend is the reduction in oil generation, which is replaced by renewable generation and combined cycle natural gas. After this, wind and biomass are the most significant sources of new generation. Advanced nuclear expands, but mainly replaces retired nuclear. Coal plants using Integrated Gasification Combined Cycle (IGCC) generation combined with Carbon Capture and Storage (CCS) are an important source of new generation once the technology becomes available, in about 2025.

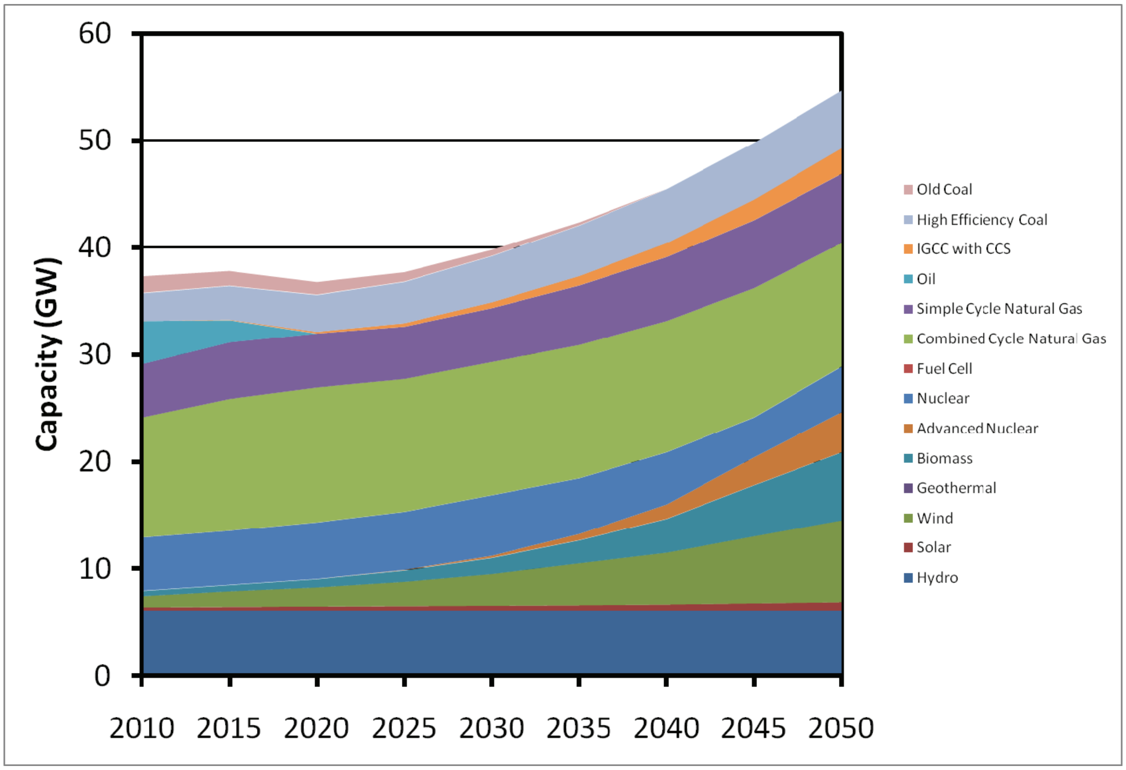

Figure 2-2
Capacity Evolution in Base Case

Figure 2-3 shows the generation sources in the Base case. In the near term, the most important sources of generation are combined cycle natural gas and nuclear, with substantial contributions from hydro and coal. As the grid evolves, biomass becomes an important source of generation, and wind and IGCC with CCS provide important contributions. Advanced nuclear expands, but mainly replaces existing nuclear.

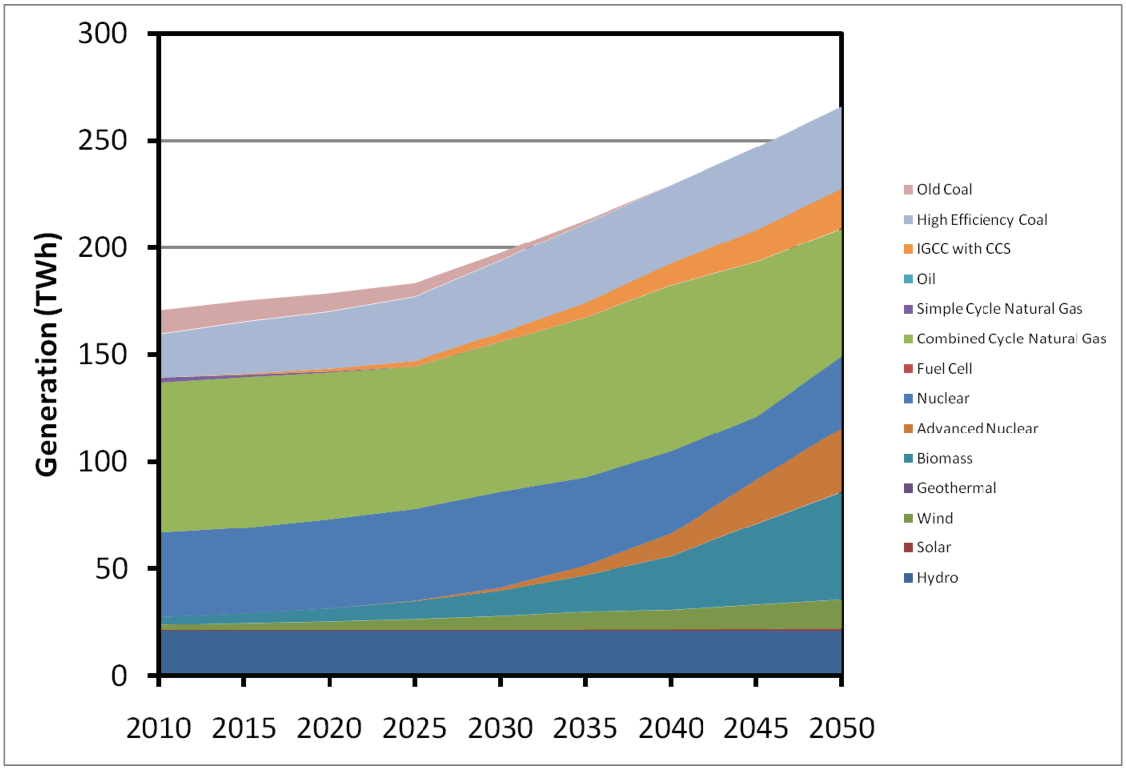

Figure 2-3
Generation in Base Case

3
PLUG-IN ELECTRIC VEHICLE SCENARIOS FOR NEW YORK STATE

Executive Summary

This chapter describes the PEV scenario for the New York State electrical system and vehicle fleet. This scenario is used to measure the effects of the introduction of Plug-in Electric Vehicles (PEVs) in the PEV scenario. This scenario represents a relatively aggressive deployment of advanced grid technologies and advanced vehicles; in particular the grid scenario assumes the development of regulations to limit greenhouse gas (GHG) emissions and the vehicle scenario includes increases in vehicle efficiency and widespread deployment of Plug-in Electric Vehicles (PEVs).

The transportation system changes over time as new vehicles are added and older vehicles are driven less and eventually retire. As in the base case, conventional vehicles, Hybrid Electric Vehicles (HEVs), and PEVs become more efficient, but in this case some HEVs are replaced with PEVs to achieve additional emissions decreases.

The increase in transportation electrification over the Base case decreases emissions further, without any other changes to the vehicle mix or electricity policy assumptions. Total emissions are now decreased by 15% instead of 7%, despite significant increases in vehicle miles traveled and electricity usage.

Transportation System Evolution

The transportation system changes over time as new vehicles are added and older vehicles are driven less and eventually retire. The PEV case models a rapid and substantial shift to vehicle electrification, presumably due to an intense societal focus on petroleum and emissions reductions.

Figure 3-1 shows the simulated real-world fuel economy for new conventional vehicles, for each vehicle class. Fuel economy increases at a high rate relative to historical trends, but the rate of increase is achievable. Figure 3-2 shows the simulated fuel economy for new HEVs. The fuel economy for hybrids starts considerably higher than for conventional vehicles, and increases at the same rate. Plug-in hybrid electric vehicles have the same performance as HEVs when operating on gasoline. When operating on electricity, PEVs have the electricity consumption shown in Figure 3-3.

Figure 3-4 shows the simulated new vehicle sales for conventional vehicles, HEVs, and PEVs for the study time horizon. Figure 3-5 shows the fleet mix that results from the combination of these sales and retirements. This is an aggressive scenario; PEVs rapidly increase in market share and penetrate the fleet in fractions that are high relative to the penetration of HEVs and other advanced technologies. This represents an assumption that there will be a societal focus on petroleum and emissions reductions, which will be reflected in incentives early in the market development and high consumer demand once the market develops.

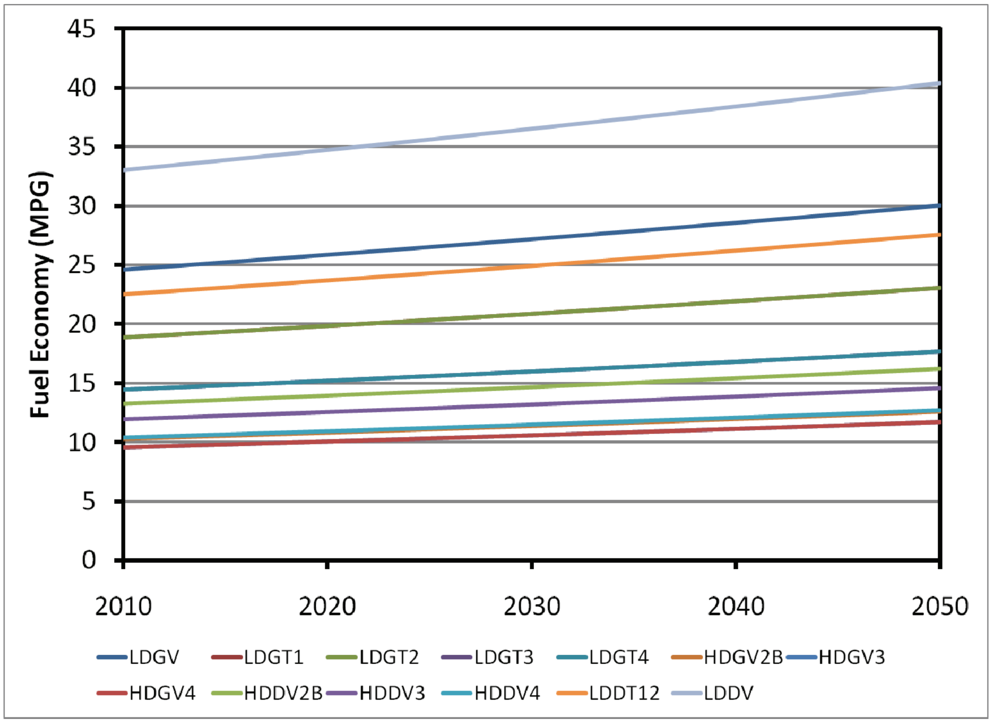

Figure 3-1
Fuel Economy for New Conventional Vehicles

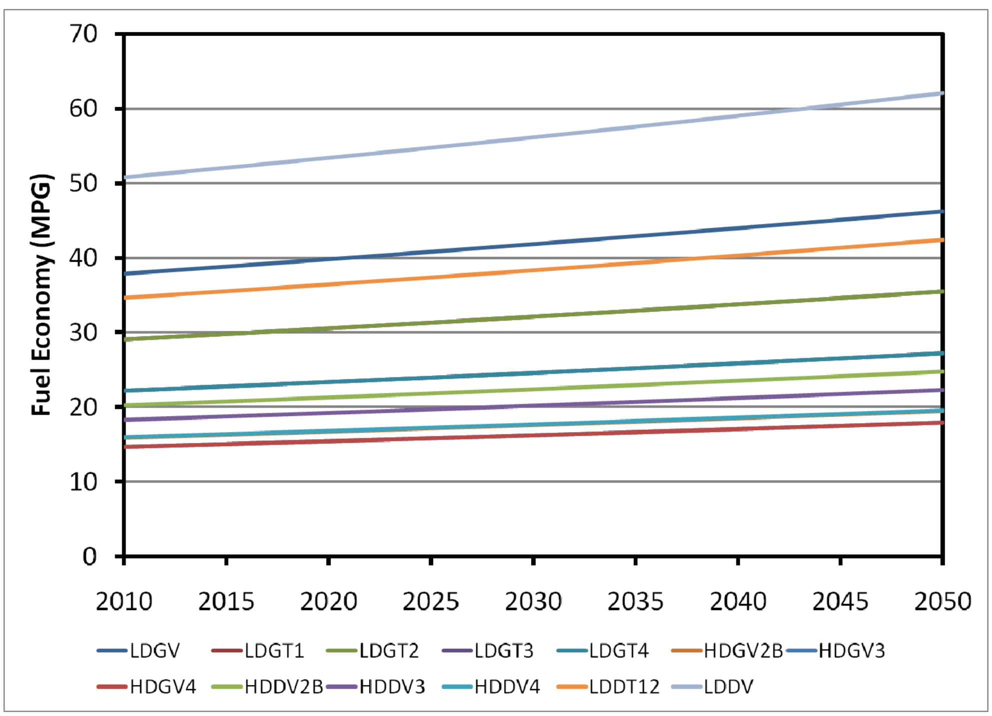

Figure 3-2
Fuel Economy for New Hybrid Electric Vehicles

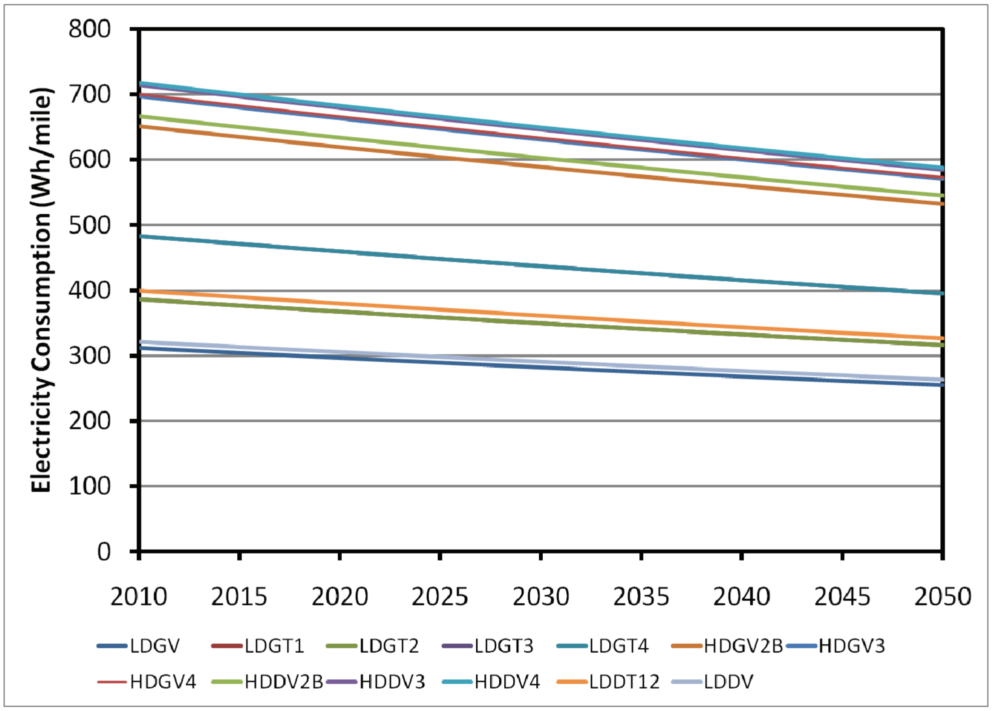

Figure 3-3
Electricity Consumption for PEVs

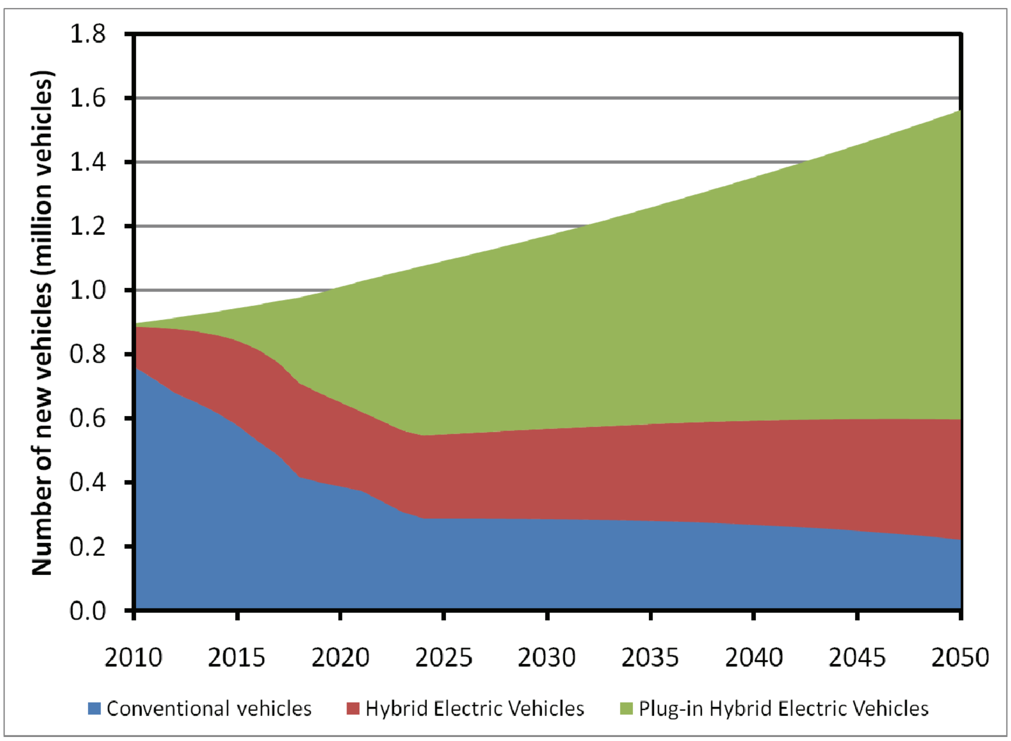

Figure 3-4
New Vehicle Sales in PEV Case

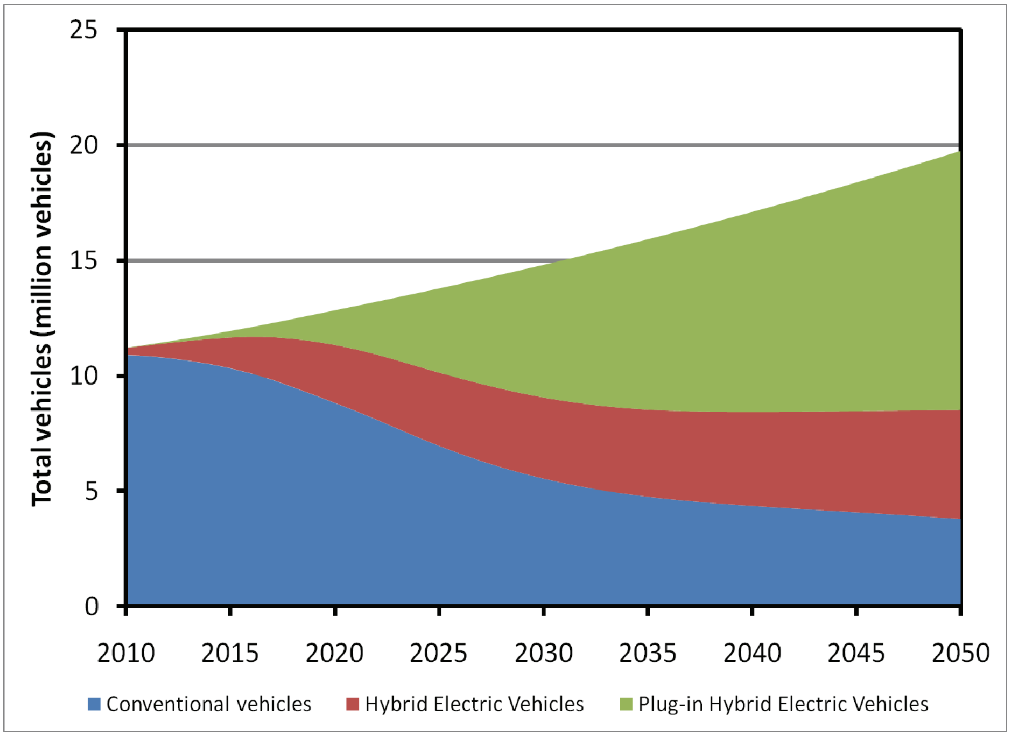

Figure 3-5
Vehicle Fleet in PEV Case

Bisector Emissions

In the PEV case, emissions from the transportation sector decrease despite increases in vehicle miles traveled due to increases in vehicle emissions and displacement of gasoline by lower-emission electricity. Figure 3-6 shows this trend over the study period. Natural gas and conventional biofuels were not considered in this analysis, but have roughly similar life-cycle emissions to gasoline and diesel. Low-carbon bio-fuels such as imported sugarcane ethanol or future cellulosic ethanol would decrease the non-electricity transportation emissions (EPRI report 1017680). It should be noted that emissions are increasing at the end of the study period due to continued increases in vehicle miles traveled, but at a low rate and from a much lower base than would have otherwise existed. The relative emissions from electricity usage are less than may be expected from Figure 3-6 since PEVs only travel about 50% of their miles on electricity, electric energy use is significantly lower than gasoline energy use for equivalent miles traveled, and emissions intensity per unit energy is significantly lower for electricity than for gasoline. The cumulative effect of these changes significantly decreases the relative emissions of electricity compared to the relative makeup of the vehicle fleet.

Figure 3-7 shows the combined emissions from the electricity and transportation sectors. Total emissions decline by about 15%, despite significant increases in vehicle miles traveled and electricity usage. Compared with the Base case, the PEV case has approximately doubled the emissions decrease. Note that this study uses a ‘medium’ regulatory environment for the electricity sector, so it represents a likely case that could be improved upon with more aggressive assumptions.

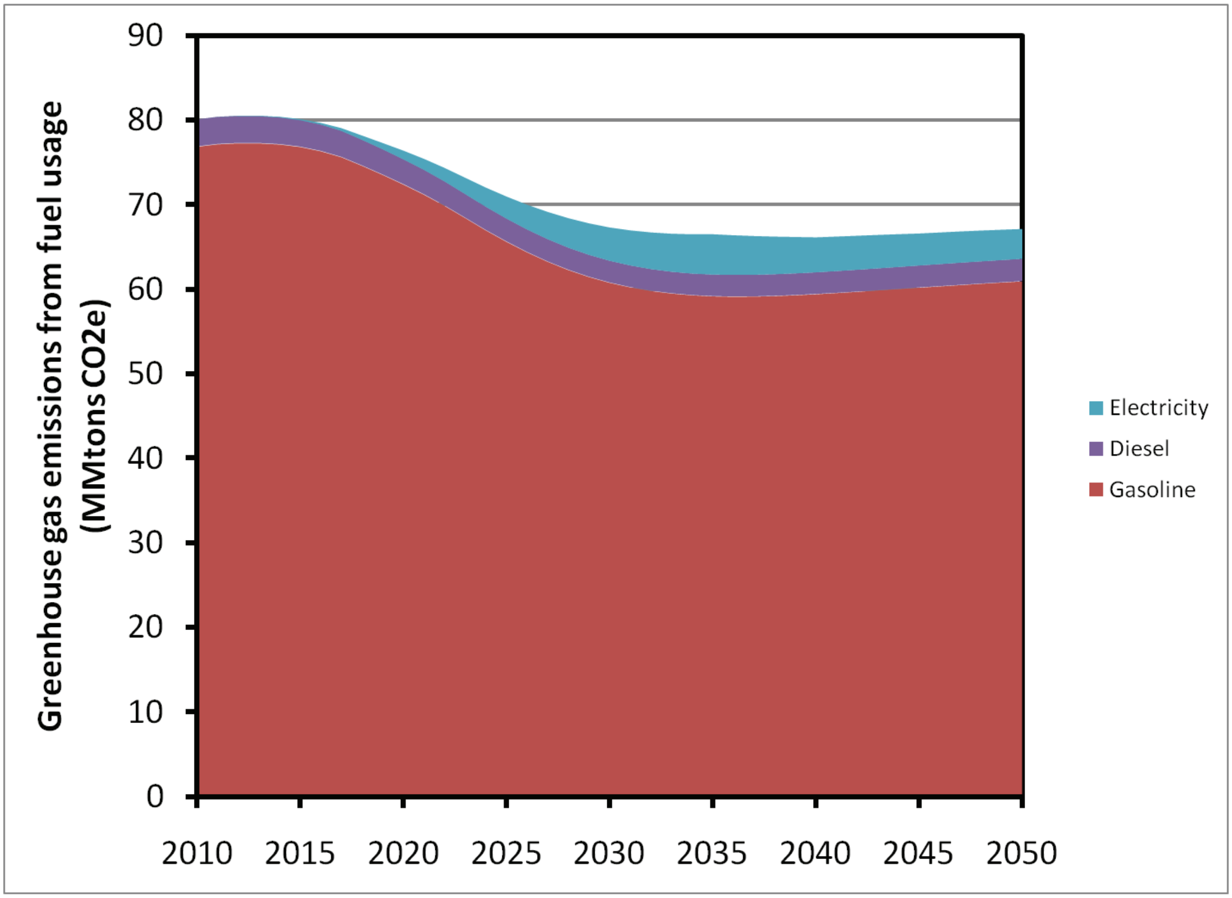

Figure 3-6
Transportation Emissions in Base Case

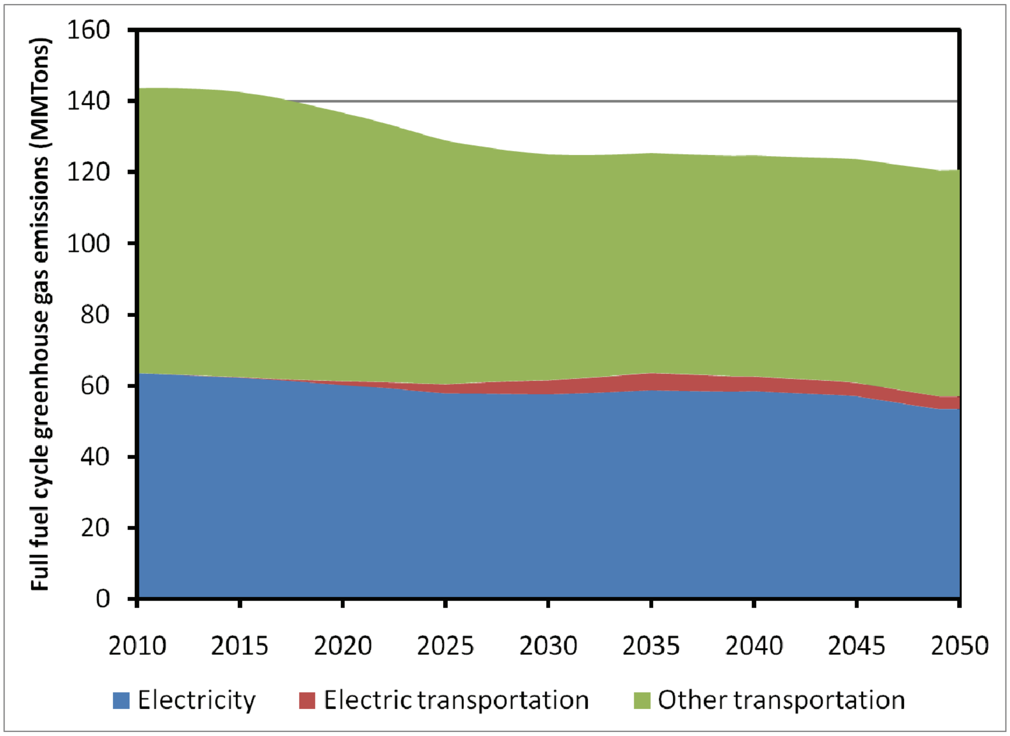

Figure 3-7
Greenhouse Gas Emissions for the Electricity and Transportation Sectors

4
PEV SCENARIOS USED IN ANALYSIS OF CON EDISON CIRCUIT IMPACTS

This chapter describes the PEV scenarios that were used for the two circuits that were analyzed as part of the distribution impact work. Separate scenarios were developed for 1) Con Edison's Yorkville secondary network circuit (Con Edison's largest network circuit) and 2) Don Bosco radial circuit. Both these circuits were within the Zones J and K, i.e. downstate, due to the concentrated electric demand and vehicle population in those areas.

Although Yorkville was not the best representative for expected near-term PEV vehicle adoption, ConEd recommended Yorkville circuit since it was the most heavily loaded network circuit in the city. In other words, by picking the Yorkville circuit as the worst case in terms of network circuit loading and overlaying the heaviest PEV loading, one would have created a worst case scenario. This would be useful in determining the likelihood of any problems occurring at all and, if potential problems are identified, what are the problems, what is the magnitude and what methods could be used to address them. Concepts of PEV Clustering are also discussed in this chapter. Also, included here is the projection of aggregate loading at the substation and the concepts of different diversity factors (such as system load profiles, PEV charge behaviors, as well as temporal and spatial variations in PEV spatial variations) when accounting for aggregate loading at the substation. Implications of different charging patterns including uncontrolled charging, controlled charging, and set-time charging are also discussed.

Evaluations of Plug-In Electric Vehicle Distribution System Impacts

With plug-in electric vehicles poised to enter the automotive market this year, a remaining concern for electrical distribution utilities is how to account for these loads in their planning process. Seamless integration of PEVs to the grid is a critical step to encourage utility support for PEV commercialization. While technological barriers concerning PEVs continue to fall, the expected influence of PEVs on the electrical system has not been completely evaluated. Understanding the causes and relationships between this new load type and the distribution system will provide the ability for utilities to augment the planning process to account for any additional stresses to their systems.

From a distribution planning perspective, the spatial and temporal variations of plug-in electric vehicles in terms of feeder loading, asset overloads, and aging across a distribution system are unknown. In order to accurately assess potential distribution systems impacts, these characteristic variations must be accounted for when performing system analyses.

Initial studies [1-3] mainly focused on the adequacy of generation to supply the increased load levels associated with increasing customer adoption of PEV. Additionally, many of these studies have assumed the additional initial PEV load could be contained within the system off-peaks without affecting the peak demand. Such system-wide assumptions do not address the potential impacts of coincident peak PEV charging at localized distribution levels where diversity benefits may be less than anticipated at system levels.

The overall ability of distribution networks to reliably supply this additional load was typically not considered nor was the influence of localized PEV concentrations, or clusters, on the system. Furthermore, these studies also concluded that the initial PEV demand could be contained within off-peak evening hours. However as system wide controls will be unavailable for the first generation of PEV, the actual demand will most likely be driven by customer behavior and therefore unlikely to be contained within off-peak evening hours.

As part of an initiative with NYSERDA and ConEd, EPRI conducted a comprehensive study to assess the energy, environmental and distribution impacts of PEVs in New York State. The purpose of the project is to identify, define, and calculate the impact of PEV on specific utility distribution systems. The basic premise of this project is to conduct a comprehensive evaluation of PEVs' influence on distribution systems operations using real distribution circuits and measured data. Based on these few studies, some initial quantitative and qualitative findings are drawn in papers [4-6]. In particular, dominant factors influencing PEV electrical characteristics as well as likely negative impact indicators are discussed.

In papers [4-6], initial findings concerning total additional feeder loading, asset overloads, and services transformer insulation aging is addressed in terms of PEV characteristics and circuit configuration. Assuming a radial configuration, typical for most North American distribution circuits, the level of PEV load diversity experienced by each feeder asset will vary based on the number of customers served off that asset. For instance, substation equipment which serves large numbers of PEVs will benefit the most from diversity in the load characteristics while those assets closest to the point of PEV interconnection will experience the least diversity.

Plug-In Electric Vehicle Technologies

Plug-in electric vehicles are a family of electric-drive vehicles[1] with the capability to recharge using grid electricity. PEVs generally include battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). A BEV's sole source of energy is the electricity contained in the battery system and must be recharged when depleted. A PHEV adds a combustion engine to allow extended driving even with a fully depleted battery.

Charging Infrastructure Technologies

There are a number of different ways to recharge PEVs at power levels ranging from less than one kilowatt (kW) to as much as 250 kW at charging times of less than 30 minutes to more than 24 hours. Most residential and public charging will occur at power levels ranging from less than 1 kW to as much as 19.2 kW and full charge times of 3 – 8 hours. Charging is grouped into two classifications based on whether the electricity delivered to the charge port on the vehicle is alternating current (AC) or direct current (DC). With AC charging, an onboard charger (an AC-

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[1] The term electric-drive vehicle can be used describe any vehicle where the propulsion system contains one or more electric motors that contribute, partly or entirely, toward providing the motive force to drive the vehicle. The family of electric drive vehicles includes hybrid electric vehicles, plug-in hybrid electric vehicles, battery electric vehicles, and fuel cell electric vehicles.

DC converter) transforms the supply into DC electricity for storage in the battery. In all cases the vehicle has ultimate control over the charging process.

AC charging is governed by SAE Recommended Practice J1772 (SAE J1772). Level 1 charging uses 120 volts AC (VAC) and the equipment generally consists of a self-contained cordset that terminates in a standard NEMA 5-15R plug compatible with any 120 volt outlet. Level 2 charging delivers 208 – 240 VAC and requires a dedicated charging appliance called an Electric Vehicle Supply Equipment (EVSE) featuring a hardwired cordset and connector. The EVSE is hard-mounted, either to a wall or a pedestal and a dedicated circuit. Both Level 1 and Level 2 charging use the same connector design at the vehicle and most vehicles can charge at either voltage through the same charge port. Level 1 AC charging is generally limited to 1.44 kW while Level 2 can reach 19.2 kW.

DC charging, often referred to as 'fast charging,' uses an offboard charging station to convert AC electricity to DC and directly charge the vehicle battery without the need for an onboard charger. Its primary purpose is to enable the rapid recharge of battery electric vehicles. The maximum charging power for a vehicle depends on the battery chemistry and system design. BEVs have already been designed and tested for DC charging at rates of 50 – 60 kW.

PEV Scenarios Used for Distribution Impact Study

To better understand distribution impacts and load growth of electric vehicles on the distribution grid, PEV scenarios were developed for radial systems as well as networked urban systems. The scenarios are detailed in the subsequent sections.

PEVs combine operational aspects of both battery electric vehicles (BEVs) and power-assist hybrid electric vehicles (HEVs). Similar to a BEV, a PHEV can store significant energy within an onboard battery for use during daily driving and recharge the battery from the electric grid. PHEVs, however, also have internal combustion engines that are used for propulsion when the battery is depleted, which will increase the near-term marketability of PHEVs relative to BEVs. From the perspective of the grid, BEVs will be the same as PHEVs, but will have larger batteries and will therefore charge for longer periods. While another potential use for PEVs is as distributed electrical sources, this functionality is not expected in the first generation of PEVs. Hence, the distribution impact analyses only consider loading characteristics of PHEVs.

To ensure that utilities can meet these new demands, utilities must undertake distribution feeder-level analyses to:

- Understand how the charging of increasing numbers of PEVs can influence the electrical network
- Accurately capture PEV loads across the distribution system
- Develop a consistent methodology to assess the "true impact" of adding PEV fleets on a utility's distribution system, and
- Ascertain what levels of penetration and charging behaviors will result in excess demand requiring remediation.

The developed framework considers the following principle factors that define PEV loading on distribution systems:

- Different PEV charge spectrums (battery type, charger efficiency) and profiles
- PEV market penetration levels per utility customer class (residential, commercial)
- Time profiles and likely customer charging habits
- Battery state of charge based on miles driven

Urban System PEV Scenarios

To model an urban system, electric vehicle charging profiles are developed for the New York urban area and compared with averaged urban profiles for all of the United States. Development of such urban profiles is a multi-step process and depends on several variables that include the location of charging (home, work, shopping, etc), time of charging, battery size, charging power, and the depth of discharge of the plug-in electric vehicle. This section describes the process of creation of charge profiles for urban centers and presents some results derived from the analysis.

Data Used and Modeling Approach

In 2001, the US Department of Transportation conducted the National Household Travel Survey (NHTS) to collect data on both long-distance and local travel by the American public. The joint survey gathered trip-related data such as mode of transportation, duration, distance, and purpose of trip. It also gathered demographic, geographic, and economic data for analysis purposes.

As a first step toward developing an electric vehicle charge profile, the data on purpose of trip, miles driven, start time of trip, end time of trip, and type of vehicle were extracted from the NHTS 2001 survey. In order to get a better picture of what is happening to the grid, a more accurate model is needed. This section aims to address this issue by developing a charger power profile that:

- Assumes that charging can take place multiple times per day and at any location (home, shopping, work, school, and so on)
- Assumes a mix of actual OEM PEVs/BEVs (Nissan Leaf, Chevrolet Volt, and Ford Escape), more realistically allocated as per the NHTS 2001 data
- Can segregate data based on urban versus rural location
- Can develop region (down to the state level) specific charger power profiles representative of local driving habits specific to the region

The NHTS classifies all data as either rural or urban. Urbanized area is further classified into four sub-categories: in an urban cluster; in an urban area; in an area surrounded by urban areas; and not in urban area. Urban areas in the United States are defined by the U.S. Census Bureau as contiguous census block groups with a population density of at least 1,000 inhabitants per square mile (386.1 /km^2) with any census block groups around this core having a density of at least 500 inhabitants per square mile (193.1 /km^2). Urban areas are delineated without regard to political boundaries. The census has two distinct categories of urban areas. *Urbanized Areas* have populations of greater than 50,000, while *Urban Clusters* have populations of less than 50,000. An urbanized area serves as the core of a metropolitan statistical area, while an urban cluster serves as the core of a metropolitan statistical area[2]. For the purpose of the modeling, it is assumed that the New York area could be considered a mix of all the first three urban classifications above. Hence, the NHTS data was filtered to extract data for urban cluster, urban area, and the area surrounded by urban areas.

The data is then further filtered into the following categories for creating individual charging profiles based on the location of charging. This is done by sorting the NHTS category "purpose of trip".

- **Home** (consisting of NHTS sub categories: Home (01))
- **Work** (consisting of NHTS sub categories: Go to work (11), Return to work (12), Attending business meeting/trip (13), Other work related(14))
- **Shopping** (consisting of NHTS sub categories: Shopping/errands (40), Buy goods: groceries/clothing/hardware store (41), Buy services: video rentals/dry cleaner/post office/car service/bank (42), Buy gas (43), Use personal services: grooming/haircut/nails (63), Meals (80), Get/eat meal (82), Coffee/ice cream/snacks (83))
- **School and church** (consisting of NHTS sub categories: School/religious activity (20), Go to school as student (21), Go to religious activity (22), Go to library: school related (23))
- **Transporting** (consisting of NHTS sub categories: Transport someone (70), Pick up someone (71), Take and wait (72), Drop someone off (73))
- **Other** (consisting of all remaining categories)

All the NHTS data is comprised of gasoline vehicles. Based on the "vehicle type", an equivalent plug-in electric vehicle (PEV) is then modeled. Table 4-1 shows the modeling assumptions made. *Further, all gasoline vehicles are assumed to be distributed as 60% GM Volt and 40% Nissan Leaf. All larger vehicles are assumed to be replaced by the Ford Escape PEV*. This allocation is made randomly assuming a uniform distribution function.

Table 4-1
Equivalent PEV assumption per NHTS vehicle category

Vehicle classification	NHTS classification	Assumed PEV equivalent	Adjusted DC consumption (KWhr/mile)	Max Charge Power (KW) @ 240Vac	Usable battery energy capacity
LDGV	Car	GM Volt	0.2	3.3	8
		Nissan Leaf	0.2	6.6	20
LDGVT1	Van, SUV, pickup truck	Ford Escape	0.16	1.44*	5
LDGVT3	**Other truck**	**Ford Escape**	**0.16**	**1.44***	**5**

*@120Vac

[2] United States urban area, http://en.wikipedia.org/wiki/United_States_urban_area

The charging efficiency is assumed to be 90%. It is also assumed that each vehicle starts its trip day with 100% state-of-charge. Each vehicle trip may comprise of multiple stops. This may, for example, include drops at work place, shopping, and back home in the evening. The charging may take place at any of these locations. The actual time for charging is calculated based on the batteries remaining SOC and charging power. The sequence of calculations is briefly described as follows:

1. Initialize SOC = 100%: Trip starts with full battery
2. The **electricity consumed per trip segment** is calculated to be the minimum of either (Miles driven * energy consumption) or (battery capacity*SOC). Battery capacity and maximum charge power depend on type of PEV assumed (Table 1)
3. **New SOC** = Absolute (Previous SOC – electricity consumed/battery capacity)
4. Identify **location of charging** from NHTS data. Under this category allocate the charging profile developed in the following steps
5. Identify **trip start time** (in minutes; all charging profiles will be developed to one minute resolution)
6. **Energy required for charging** = ((100-New SOC)/100)*battery capacity
7. **Time required for charging** = 60*required energy/(maximum charge power*charging efficiency)
8. **Charge end time** = (start time + time required for charging) or depends on when the next trip segment begins (this is to account for the fact that the PEV may be unplugged before full battery charge is complete)
9. Compute **energy used for recharging** = maximum charge power * charger efficiency * (charge end time – charge start time)
10. Update **New SOC** = minimum (100% or most recent SOC + recharged energy/battery capacity)
11. Create charge profile for this case; start time to end time = maximum charge power; zero elsewhere
12. Add above charge profile to previous charge profile created. This step sums up all charge profiles for a given charge location or any other selected criteria
13. Go to step 4 and keep repeating until all trips and all trip segments are analyzed
14. Create **average charging profile (<u>by location of charging</u>)** by dividing the summed up charge profiles obtained so far by the total number of vehicles

The above sequence of calculations can be applied to individual states or all of US. Figure 4-1 and Figure 4-2 show the average charging profiles per vehicle charging location (using 60/40 split on Volt/Leaf and all trucks replaced by Ford Escape) for all of US and the New York urban region, respectively. It can be seen that the charge profile in Figure 4-2 is coarser than Figure 4-1. This is attributed to the reduced sample size in the NHTS 2001 data when only considering the New York subset.

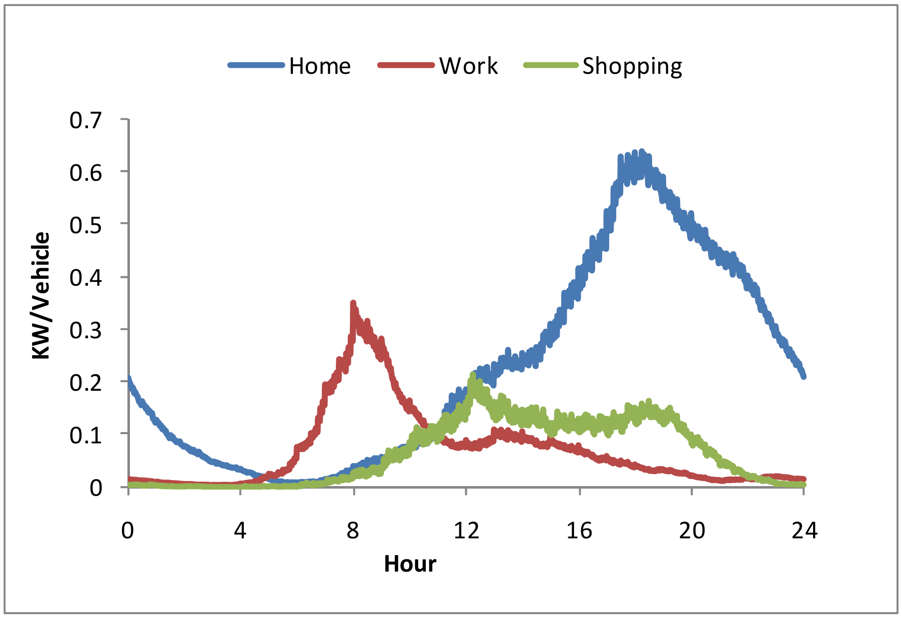

Figure 4-1
Averaged Urban Charge Profile for all of US for Charging Locations

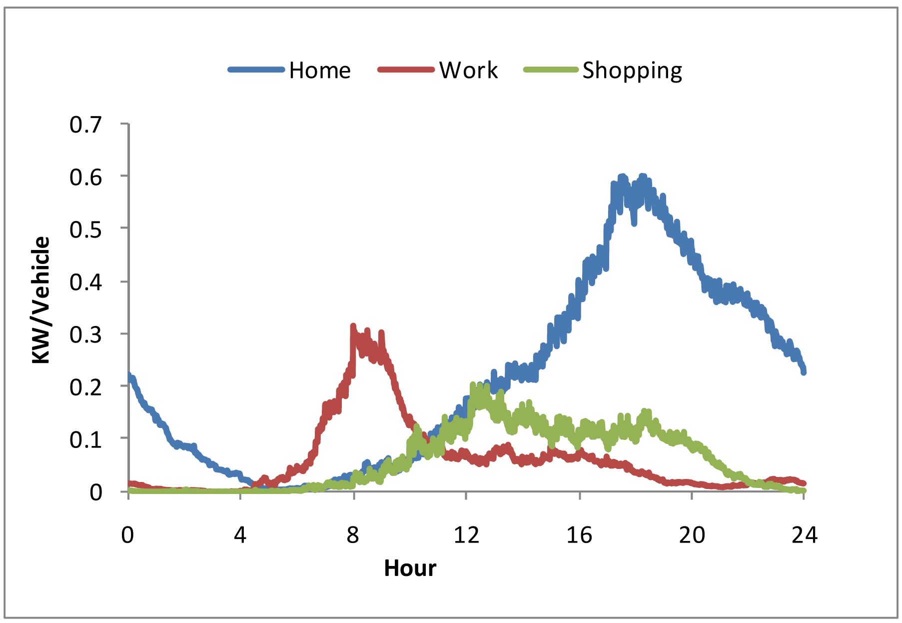

Figure 4-2
Averaged Urban Charge Profile for New York for Charging Locations

Cumulative Urban Charging Profile

Figure 4-1 and Figure 4-2 show the urban charging profiles by location or vehicle usage. Still, a cumulative urban profile would be comprised of charging at all locations (home, work, and shopping). To obtain a cumulative urban charge profile, a weighted average of the individual charge profiles is computed. The weights are chosen based on the distribution of home, work, and shopping charging in an urban area. As an example, for the purpose of this study a combination of 70% home charging, 20% work charging, and 10% charging during shopping is assumed. Figure 4-3 and Figure 4-4 show the cumulative urban charging profile computed using 0.7, 0.2, and 0.1 as weights for home, work, and shopping charging locations. These weights can be altered depending on social patterns and demographics of the geographic location under analysis.

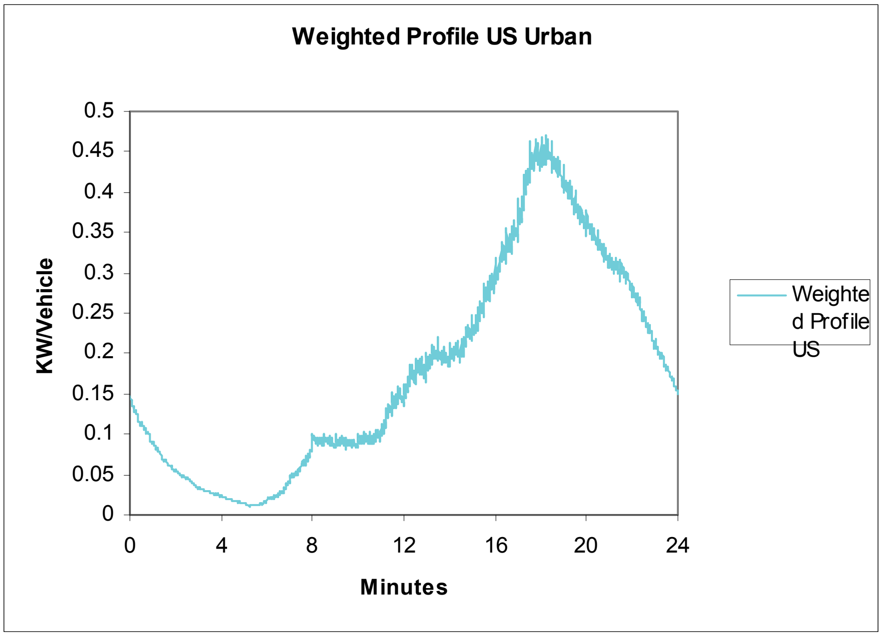

Figure 4-3
Cumulative Urban Charge Profile for all of US for 70% home, 20% work, and 10% shopping charging locations

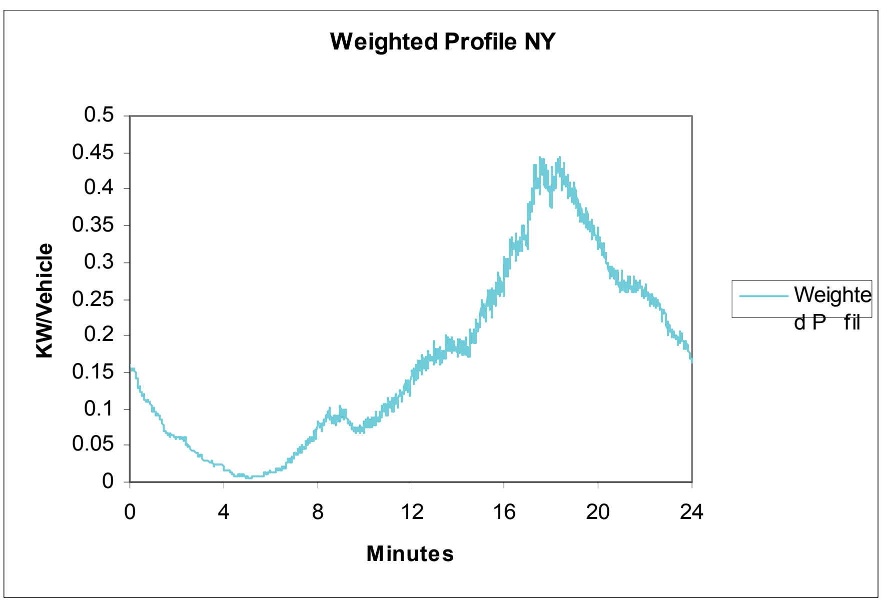

Figure 4-4
Cumulative Urban Charge Profile for New York for 70% home, 20% work, and 10% shopping charging locations

Conclusions – Urban Scenario

The prior sections outline the modeling approach and assumptions used to create urban charging profiles. The case of NY urban center is illustrated here and compared with all of US. The urban charging profile developed in this report uses a 60/40% distribution of the GM Volt and the Nissan Leaf among light duty gasoline vehicles. All SUVs, pickups, and other similar vehicles are assumed to be replaced by a Ford Escape PEV. The model takes into account the battery capacity, maximum charging power, and the range of each vehicle to develop the charging profile. Driving patterns and other demographic data are obtained from the 2001 NHTS survey.

Radial Configured System PEV Scenarios

PEV Type / Charge Profiles

PEVs are similar to existing hybrid electric vehicles (HEV) with the primary difference being the incorporation of an "energy" battery that allows the PHEV to directly store grid electricity for propulsion. Thus, PHEVs require a method of charging the battery on a regular basis. As proposed in SAE J1772, conductive charging is a method for connecting the electric power supply network to the EV for the purpose of transferring energy to charge the battery. The conductive system architecture is suitable for use with electrical ratings as specified in Table 4-2. While PHEV systems are still in development, likely electrical charge characteristics are being identified. SAE J1772 identifies three levels of charging based on voltage and power levels, as presented in Table 4-3.

Table 4-2
Electrical Ratings (North America)

Charge Method	Nominal Voltage (Volts)	Max Current (Amps-continuous)	Circuit Breaker Rating (Amps)
AC Level 1	120V, 1phase	12A/16A	15A/20A
AC Level 2	208-240V, 1phase	32A/80A	40A/100A

Table 4-3
PEV Charging Model Characteristics

Type	Rated Current	Power Level
AC Level 1: 120 VAC	12A or 16A	1.2 – 1.92 kW
AC Level 2: 208-240 VAC	<=80A	<=19.2 kW
AC Level 3: 208-240 VAC	TBD	>20KW
DC Level 1 Charging: 200-450VDC	<=80A	<=19.2 kW
DC Level 2 Charging: 200-450VDC	<=200A	<=90 kW
DC Level 3 Charging: 200-600VDC	<=400A	<=240 kW

The PEV charge profile influences how the distribution system is impacted as it partially defines daily and annual PEV load shapes. One aspect of the study is to determine the extent to which the network is influenced by various charge profiles. The electrical demand over time, or charge profile, is defined by the battery size, charger efficiency, miles driven, and charge type.

The type of PEV purchased will determine the electrical characteristics as viewed at the meter given associated battery size, converter efficiency, connection voltage, and rated current. Example charge profiles for an 8 kWh battery with 90% efficiency rating are provided in Figure 4-5. The charge profiles shown are for a fully discharged battery; the actual duration of the charge profiles will vary depending upon battery depletion when plugged in to recharge.

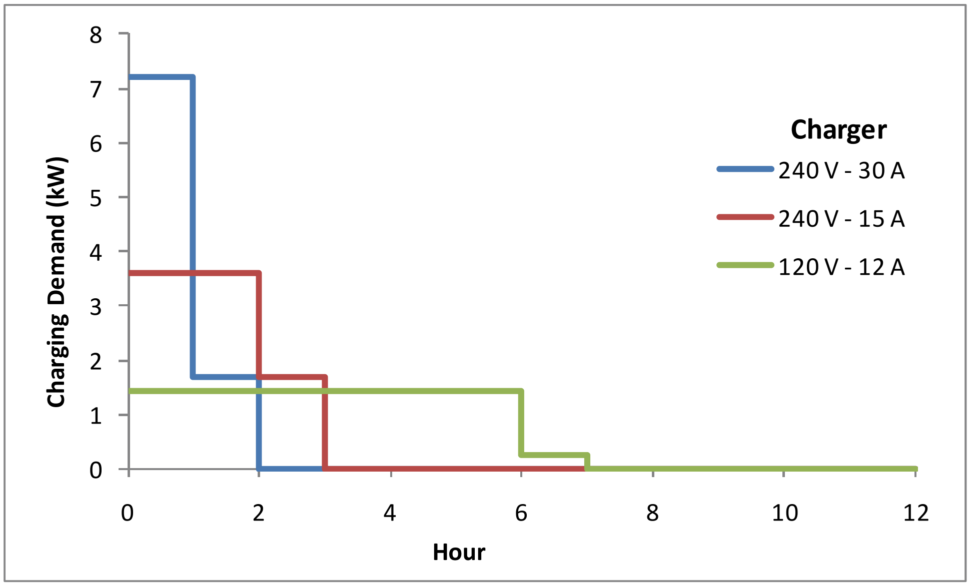

Figure 4-5
Battery Charge Profiles (8 kWh)

In the study, PEV charge profiles are composed of 4kWh, 8kWh and 24kWh batteries charged by either a 120V 12A, 240V 15A, or a 240V 30A connection. These charge profiles are representative of many of the PEV models being proposed in the industry including the GM's Chevy Volt, GM's Saturn Vue, Ford Escape, Toyota Prius, etc. Each charge profile is weighted in the stochastic analysis as documented in the associated PEV battery type probability distribution shown in Table 4-4.

Table 4-4
PEV Battery Type PDF Used for Stochastic Analysis

PEV Type Probability			
120V 12A 4kWh	240V 15A 8kWh	240V 30A 8kWh	240V 30A 24kWh
0.1	0.4	0.4	0.1

Customer Charging Habits

The modeled PEV demand is based on likely customer behavior. Likely customer charging behavior is derived from U.S. driving pattern data from the 2001 National Household Travel

Survey (NHTS 2001)[3]. Assuming customers with no incentive to do otherwise will likely plug-in the vehicle when arriving at their residences, residential customer home arrival time data is used to generate PEV interconnection time probabilities. The resulting customer PEV charge time probability distribution used for the stochastic analysis is shown in Figure 4-6. Features of the dataset include:

- Analysis looks at a simple case; charging once per day at home, as soon as the driver arrives home
- This is the arrival time for the longest dwell time, and does not take into account arriving at home multiple times per day
- At any given time, a maximum of 12% of people are arriving home and will begin charging (the peak time is between 5:00 and 6:00 PM)
- People arrive at home throughout the day, although the highest rates of home arrival unsurprisingly occur during the peak hours for electricity use
- By 8:00 PM, 70% of drivers have arrived home
- Early morning arrival times coupled with long miles are unlikely
- Overall driving patterns - 74% of trips are less than 40 miles a day
- 14% probability that the vehicle is not driven that day is taken into account by the cumulative probability not reaching 100%.

[3] NHTS 2001 Unweighted Travel Day Data: Summary by Home Type, Purpose, End Time of the Last Trip, and Miles per Vehicle

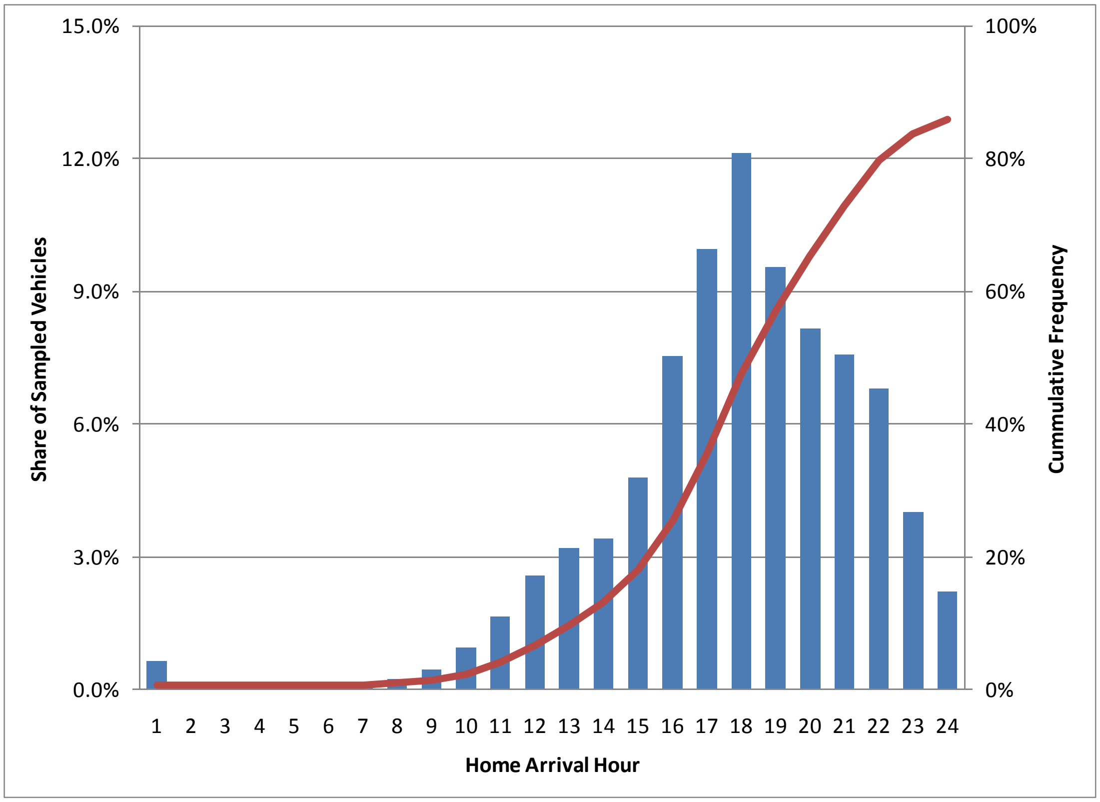

Figure 4-6
Customer Home Arrival Times

Battery State of Charge

Typical daily driving distances are also obtained from the National Household Travel Survey. For each possible home arrival time, a conditional probability is derived for the associated miles driven that day. Assuming a fixed depletion rate and battery size, the amount of energy required to recharge the battery is tied to the associated miles driven. Relationships between projected home arrival times and miles driven are represented in the study by the probability distribution shown in Figure 4-7.

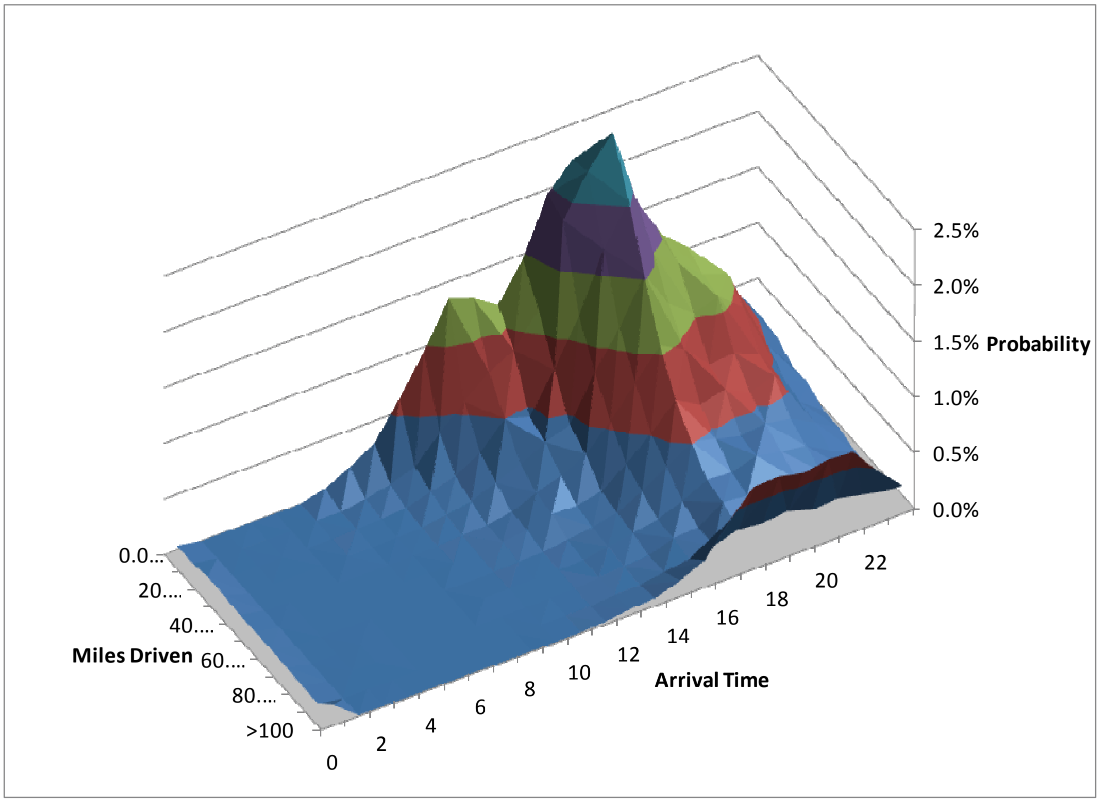

Figure 4-7
Conditional Probability Relationship between Arrival Time and Miles Driven

PEV Characteristics and Clustering

EPRI's study targets distribution system loading impacts based on near-term projections (1-5 years) of PEV market penetration. The study does not consider PEV technologies that will not be available for the first generation of electric vehicles. In particular, PEVs acting as distributed generation and two-way communication controls are not evaluated. Hence, each modeled PEV is treated solely as a load whose behavior is determined solely by projected customer behaviors rather than external control settings.

Assessing PEV impacts on the distribution systems requires an accurate projection of the nature of the PEV loads. Fully representing these loads not only necessitates accounting for the electrical characteristics of the loads but the customer behavior that inherently dictates the PEV charging demand. A detailed explanation of the various PEV characteristics considered in this study is discussed in [[4]].

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[4] J. Taylor, A. Maitra, M. Alexander, D. Brooks, M. Duvall, Evaluation of the impact of PEV Loading on Distribution system operations, IEEE Power Engineering Society, Calgary, July, 2009
A. Maitra, K. Kook, J. Taylor, A. Giumento, Evaluation of PEV Loading on Hydro-Quebec's Distribution System Operations, EVS24, Stavanger, Norway May 13-16, 2009

In general the projected market penetrations considered in this study of PEV penetration levels were varied from 2-25%. Given the 1-5 year projection of the study, this range is expected to provide impacts for low to extremely high levels of projected market penetration. Still, even the "low" scenario is higher than that experienced with today's hybrid electric vehicles (HEV). While in some cases a high as steep as 25% penetration level is considered, 8% penetration rates are actually considered a more viable high estimation, given near-term projections.

It's important to note that even for low overall customer PEV adoption rates, PEV clusters can still occur. Based on system configuration and the assumed customer adoption probabilities, clusters will occur randomly throughout the system for each case. For example, PEV clusters are visible in the daisy plot shown in Figure 4-8. Each PEV is represented by the circle, and as PEVs are introduced at the same location they are spaced in a similar fashion as petals on a flower. Higher penetration rates, of course, increase the potential for larger cluster sizes and more frequent occurrences. While PEV clustering may indicate an increased risk higher than average loading levels, PEV clustering alone does not signify the likelihood of negative impact occurrence as the other PEV load characteristics, and must also be taken into account.

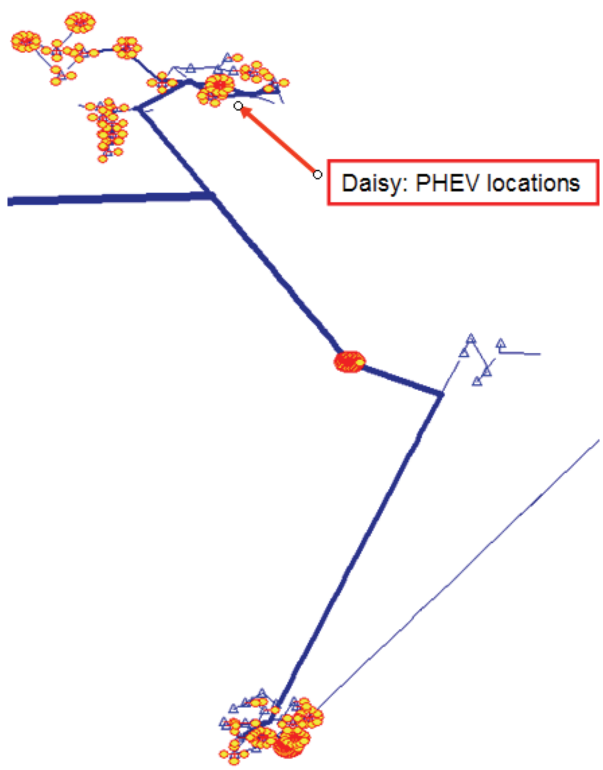

Figure 4-8
Example Daisy Plots Illustrating Clustering at 8% Penetration Levels

Given the radial configuration of most distribution circuits, the closer a circuit component is located to the loads the more likely it is to serve a PEV cluster. This relationship is illustrated in Figure 4-9, which shows the maximum occurring clusters sizes experienced during the analyses for 8% adoption of PEV. In this case, cluster sizes are expressed in terms of the ratio of PEVs per customer served. Higher ratios indicate higher percentages of PEVs per customer served off that device. As shown, components serving fewer customers experienced higher relative cluster sizes. Nevertheless, for assets serving large number of customer (primary lines, single phase laterals, two phase laterals) this PEV/customer ratio converges toward the original customer adoption rate in response to increased diversity in PEV spatial variations.

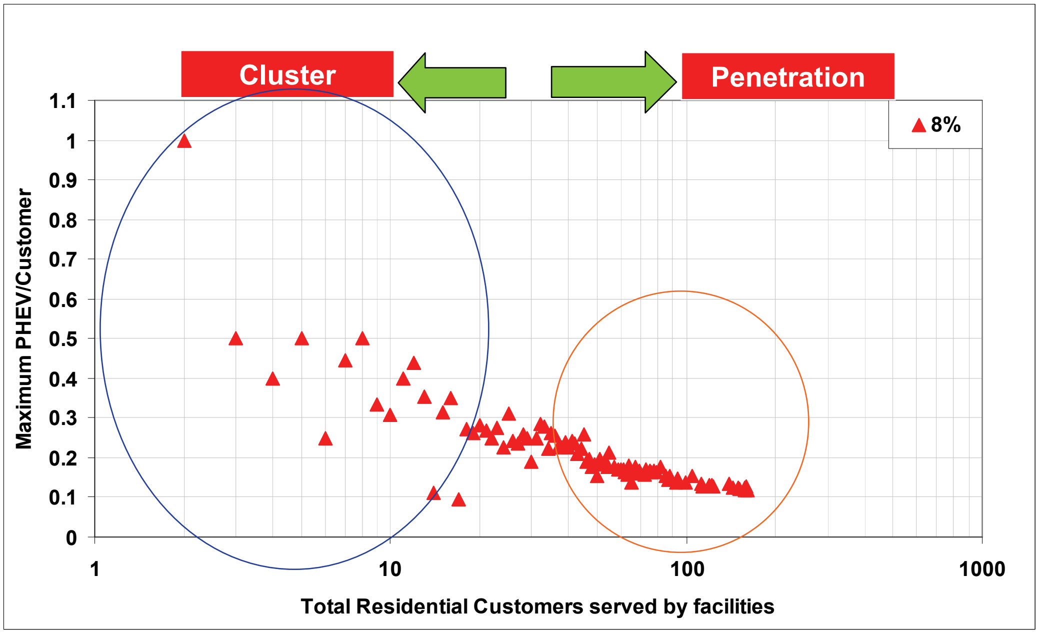

Figure 4-9
Relationship between Cluster Size and Customers Served

Aggregate Feeder Loading Analysis

Characterizing PEV load diversity's influence on the system is examined through the total additional loading expected to occur at the head of the feeder for each circuit. In analyzing the potential distribution impacts of electric vehicle charging a 'worst case' scenario will be needed to bind the potential negative effects; however, it is important for this worst case to be plausible. There are uncertainties in the expected makeup of PEVs, different charging patterns served off each feeder, and customer habits, but these uncertainties can be reasonably bounded at the aggregate level as seen by the substation transformer.

At this level, charging patterns correlate more closely with statistical driving patterns. Driving pattern data from the National Household Transportation Survey (NHTS)[5] is used to represent likely charge times short of smart-charging incentives. For instance, potential interconnection hours were derived from the likely residential customer home arrival times shown in Figure 4-6. Vehicle home arrival is correlated with peak load, so it is often assumed that vehicle charging could create a large coincident peak. Still, vehicles will not all be connected at the exact same time. Even during the peak hour of 5:00 to 6:00 PM, only about 12% of drivers arrive home during the hour. It is also important to note that people do not necessarily drive far enough to completely discharge their cars.

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[5] Vyas, A, Wang, M., Santini, D., and Elgowainy, A., Analysis of the 2001 National Household Transportation Survey in support of the PHEV project to evaluate impacts on electricity generation and GHG emissions, unpublished information, 2009.

By coupling these statistics with different customer daily driving distances patterns, known PEV types, electrical chargers characteristics, different profiles that can be used to control charging, the aggregate hourly demand as seen by the substation transformer, the aggregate hourly demand as seen by the substation transformer can be estimated.

Even without smart charging the load of vehicle charging is relatively well distributed. For example, Figure 4-10 shows a plausible high case for vehicle charging, which assumes that the fleet is made up of 30% Extended-Range Electric Vehicles (E-REVs), 50% blended PEVs, and 20% BEVs, all with 7.68 kW chargers which begin charging at full power immediately upon arriving at home. Since home arrival is coincident with other activities the load occurs on-peak, but vehicle charging has a maximum of about 0.7 kW per vehicle, and is relatively evenly distributed over about six hours. Other vehicle mixes, which include more PEVs or lower power chargers, will decrease the vehicle charging peak and shift it later. Similarly, EVs with higher power chargers will increase the vehicle charging peak, but the charging will finish sooner. Based on the study it was observed that for different vehicle mixes the aggregate on-peak load for a PEV will vary between 500-1100W per vehicle.

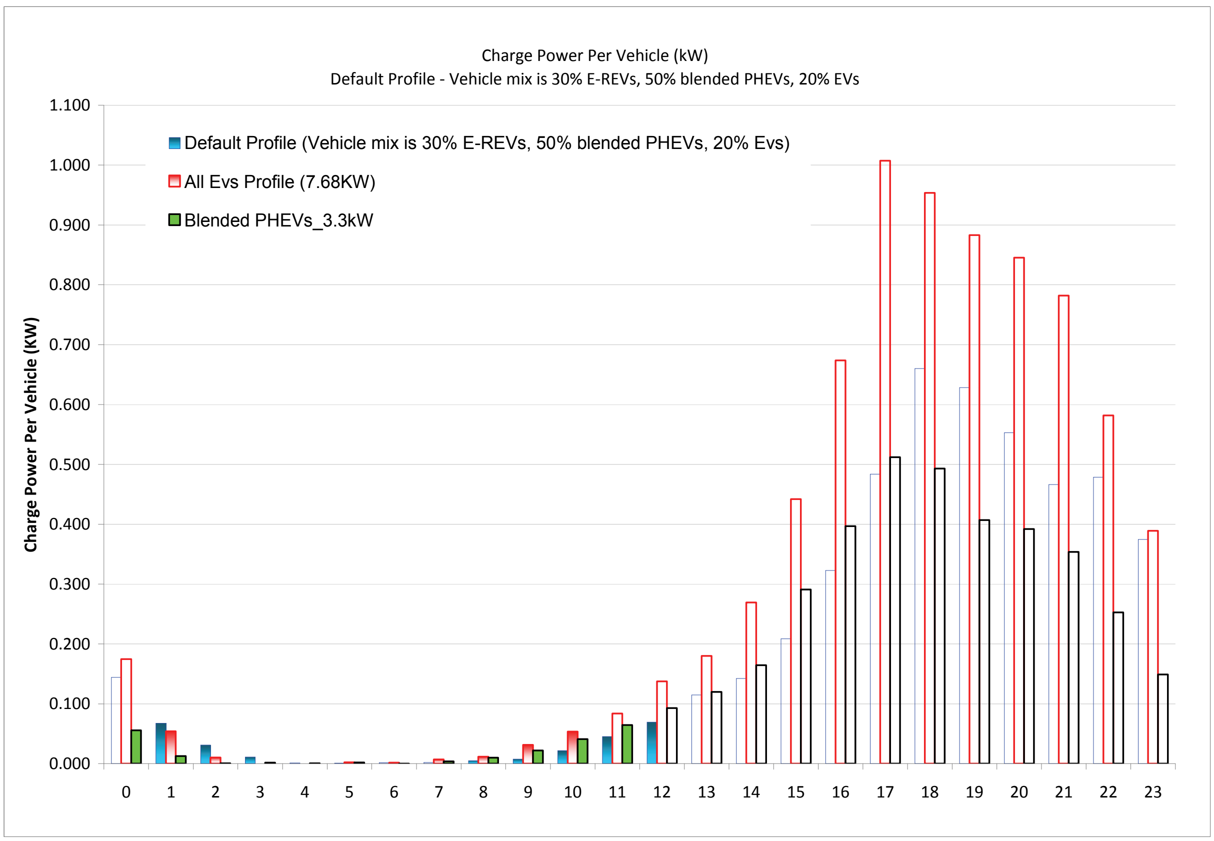

Figure 4-10
Aggregate Power Demand for Uncontrolled Vehicle Charging

Controlled charging can significantly resolve projected impacts of PEV to assets. It is possible to achieve any load shape with sophisticated control; various parties have proposed ‘valley filling’ strategies, ‘renewable matching’ strategies, and others. Figure 4-11 shows a simple control strategy (using the same PEV mix discussed in the previous section) that shifts the charge load to nighttime, but spreads it out relatively evenly over six hours. This can be accomplished by staging vehicles to start charging during one of seven hours from 9:00 PM to 3:00 AM. The charge remains at about 0.7kW per vehicle, but is now during a time which is more favorable for the generation system. Controlled this way, vehicle charging would not require additional generation capacity and would have a relatively small system impact. More sophisticated control strategies could optimize this even further.

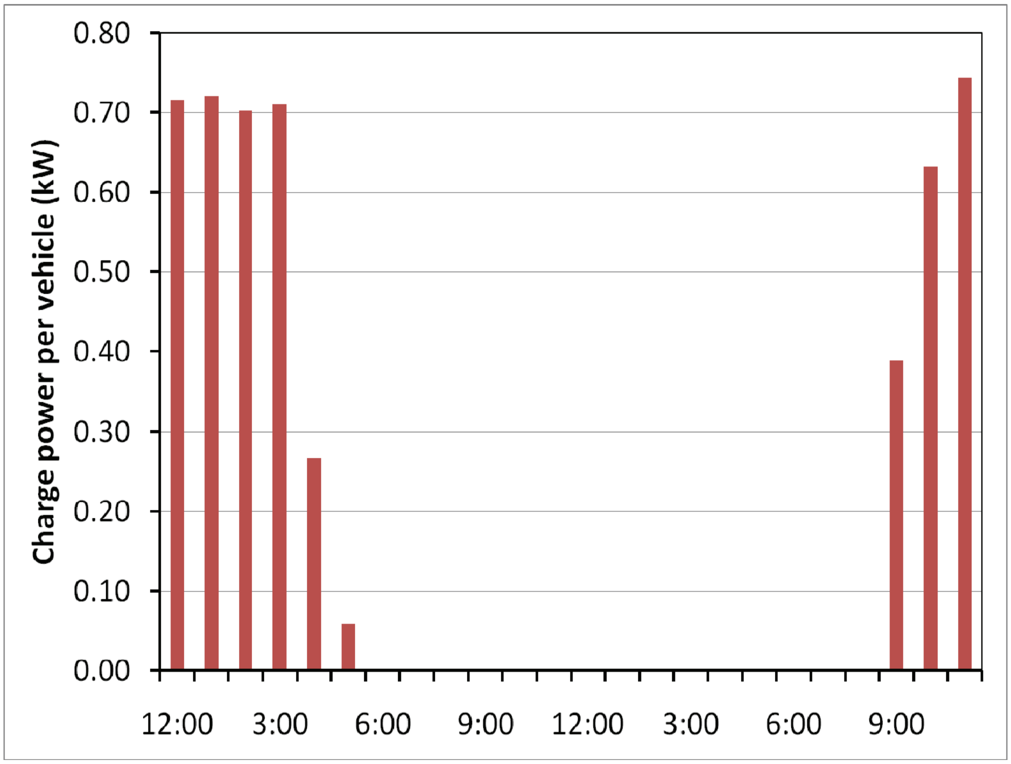

Figure 4-11
Average PEV Loading for Customer Behavior with simple charge control

One important characteristic of PEVs, relative to other loads, is that the charging can be deferred. There is a potential for negative impacts caused by incorrect control. If the default setting (wait until a specific time, then start charging" presumably with the assumption that this would move the load off of the peak) is for all of the vehicles to start at one time, such as 8:00 PM (after the main peak), this could be a potential problem due to the creation of high levels of coincident load since about 73% of vehicles (shown in Figure 4-5) would be available to charge.

Figure 4-12 shows the charge power profile in this case. The 3.1x difference between the 0.7kW 'uncontrolled' case and the 2.2kW 'incorrectly controlled' case illustrates the need to diversify the charging time and stresses the importance of achieving some level of communication and control. Utilities with simple Time-of Use (TOU) customers can potentially experience the same phenomenon, given the nature of these loads.

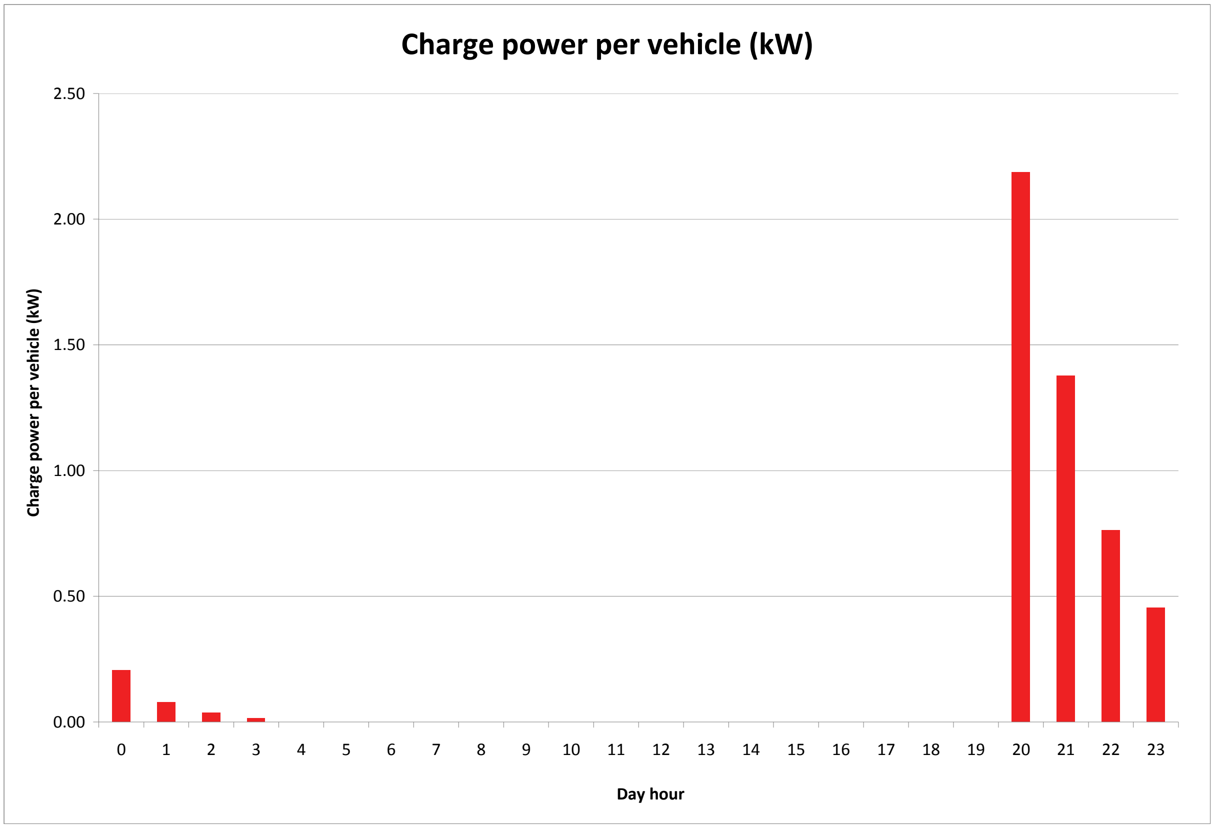

Figure 4-12
Average PEV Loading for Incorrectly controlled electric vehicle charging load

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[1] M. K. Meyers, K. Schneider, R. Pratt, "Impacts Assessment of Plug-in Hybrid Vehicles on Electric Utilities and Regional US Power Grids Part 1: Technical Analysis," Pacific Northwest National Laboratory, Nov 2007.

[2] M. J. Scott, M. K. Meyers, D. B. Elliott, W. M. Warwick, "Impacts Assessment of Plug-in Hybrid Vehicles on Electric Utilities and Regional US Power Grids Part 2: Economic Assessment," Pacific Northwest National Laboratory, Nov 2007.

[3] S. W. Hadley, A. Tsvetkova, "Potential Impacts of Plug-in Hybrid Electric Vehicles on Regional Power Generation," ORNL/TM-2007/150, Jan 2008.

[4] J. Taylor, A. Maitra, M. Alexander, D. Brooks, M. Duvall, Evaluation of the impact of PEV Loading on Distribution system operations, IEEE Power Engineering Society, Calgary, July, 2009

[5] A. Maitra, K. Kook, J. Taylor, A. Giumento, Evaluation of PEV Loading on Hydro-Quebec's Distribution System Operations, EVS24, Stavanger, Norway May 13-16, 2009

[6] J. Taylor, A. Maitra, M. Alexander, D. Brooks, M. Duvall, Grid Impacts of Plug-in Electric Vehicles on Hydro Quebec Distribution System, IEEE PES T&D March 2010

5 IMPACT EVALUATION OF PLUG-IN ELECTRIC VEHICLES ON DON BOSCO CIRCUIT 17W55

Executive Summary

To evaluate the potential distribution system impacts due to residential customer adoption of PEV, ConEd selected feeder Don Bosco circuit 17W55 (13.2KV) for the analysis. The circuit, served out of the Harrison substation, is a radial suburban circuit serving a total of 1,652 customers, 95% of which are residential.

An analysis methodology, developed by EPRI, was used to evaluate the circuit's response to PEV demand. Specifically, the analysis identifies what assets are potentially at risk, the likelihood and severity of impacts, as well as any circuit characteristics that increase impact risk. Distribution system impacts evaluated in the study include thermal overloads, low voltage conditions, system losses, and voltage imbalance that were all found to be either be negligible or within satisfactory limits.

Based on the analysis, significant impacts are not expected to occur on Don Bosco circuit 17W55 for the near-term planning horizon. Nonetheless, any existing conditions not captured in the circuit model, such as low customer voltages or overloaded transformers, may be aggravated by the additional PEV load. Still, these issues can arise for any per-capita load growth. While minor impacts cannot be completely ruled out, few impacts, if any, are expected to occur and will be limited to assets located closest to the customer.

Analysis Methodology

The study methodology was designed to capture potential near term distribution system impacts in response to customer adoption of the new load type. Assuming a near term planning horizon, only those characteristics expected from the majority of first generations of PEVs are considered. Specifically, PEV are modeled as simple loads whose characteristics are mainly dictated by customer behavior. Controlled dispatching or vehicle-to-grid operations of PEVs are not included in this evaluation. Additionally, growth in the base load is not included as no particular planning year is being evaluated in any given scenario. Finally, only residential customers are considered as possible locations of PEV interconnections, as initial adopters are expected to most likely charge at their residence.

As with any load, PEV demand exhibits its own unique diversity characteristics. In particular, PEV load diversity will be both spatial and temporal in nature; as every utility customer will not own a PEV nor will every PEV charge at the same point in time. Data detailing expected customer driving behaviors as well as PEV market projections are used to model the load diversity. The PEV characteristic data used in the study are outlined in more detail in Chapter 4. The three stage analysis, illustrated in Figure 5-1, was developed to fully evaluate effects on distribution circuits in light of these characteristics. Each analysis serves as a tool for examining system response from a different conditional perspective and used in conjunction provides a complete perspective of potential impacts. Specifically, the analysis identifies assets at risk of being impacted, and the likelihood and severity of impact.

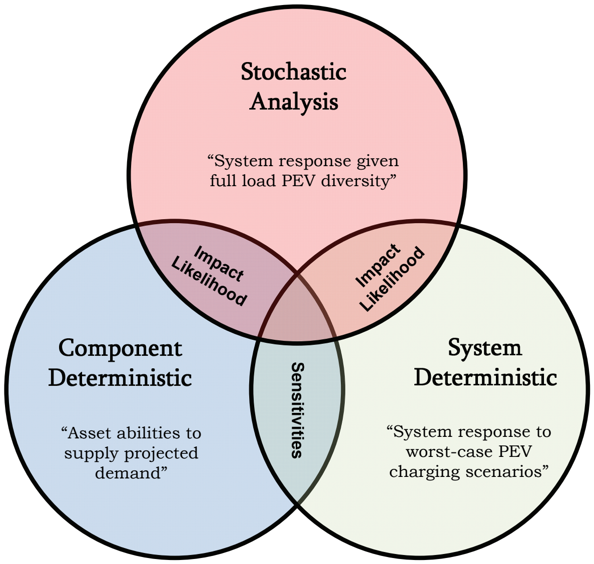

Figure 5-1
PEV Distribution Impact Evaluation Methodology

Market Penetration / Residential Customer Adoption

Each analysis scenario is evaluated under an assumed level of customer adoption. Typically, the level of adoption is expressed in terms of market penetration or the percentage of non-commercial vehicles in service that are plug-in electric. In the New York metropolitan area, and the United States in general, the number of vehicles exceeds the number of residences. As such, the percent PEV market penetration does not directly equate to percentage of utility customers owning a plug-in electric.

Recognizing market penetration as the probability that a vehicle is plug-in electric, *m,* the distribution for the number of PEVs out of *q* vehicles, the random variable *X*, is defined by the Binomial distribution as given in (1).

$$b(x;q,m) = \begin{cases} \binom{n}{x} m^x (1-m)^{q-x} & x = 0,1,\ldots,q \\ 0 & otherwise \end{cases} \quad (1)$$

Translation of market penetration into number of PEV per residential utility customer is based on the probability distribution $p(y)$ where Y is the discrete random variable for the number of vehicles per household. This probability distribution is derived from Department of Transportation statistics in the study region. Therefore, distribution for the random variable for the number of plug-in electric vehicles per residential customer, Z, can be found using (2); where the variable k is the maximum number of vehicles considered for a single residence.

$$p(z) = \sum_{j=z}^{k} P(Y = j) * b(z; j, m) \quad (2)$$

Department of Transportation statistics for vehicles per residence is provided in Table 5-1 for the New York metro area. Using (2), the probability distributions for number of PEVs per residential household are provided in Table 5-2 for three different penetration levels.

Table 5-1
New York Metro Household Vehicle Ownership Statistics[6]

Vehicles Per Household				Total Household Vehicles	Total Households
0	1	2	3+		
28.7%	32.4%	28.0%	11.0%	9,743,069	7,735,264

Table 5-2
Probability Densities of PEV per Residential Customer

Market Penetration	PEV Per Household			
	0	1	2	3+
2%	97.70%	2.38%	0.02%	0.00%
4%	95.34%	4.66%	0.10%	0.00%
8%	90.77%	8.95%	0.37%	0.01%

Component Deterministic

The Component Deterministic analysis stage identifies components or assets at risk of experiencing thermal overloads due to PEV adoption. Each asset's remaining capacity is compared to a conservative projection of the worst-case PEV demand that asset could experience. Assets with sufficient capacity to serve the projected demand are deemed highly unlikely to be impacted while the remaining assets are considered "at risk". Note that the "at risk" classification does not mean an asset is likely to be impacted; instead, the possibility cannot be confidently ruled out. The likelihood of thermal overload occurrence is determined in the subsequent stochastic analysis.

The remaining capacity for every distribution feeder asset is derived from the circuit's peak hour load flow solution and asset thermal ratings. While the peak hour is typically used, evaluations could be performed for other hours of interest in a similar fashion. While the normal rating is used to calculate the remaining capacity of most assets, the emergency rating is typically selected for transformers due to their ability to handle higher loadings over equivalent periods of time.

Projected PEV demand is calculated using the probability distributions representing customer behavior and projected PEV market conditions introduced in Chapter 4 . Furthermore, the projected demand must take into account the difference in demand due to the number of

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[6]Journey to Work Trends: in the United States and its Major Metropolitan Areas 1960 - 2000, US Department of Transportation

customers served off that asset. That is to say, an asset serving a single customer will not experience the same magnitude and spatial diversity of PEV load as an asset serving thousands of customers. Spatial diversity is incorporated into the projection through the number of PEV per household distribution defined earlier in (2). As only a single point in time is considered, the probability that a PEV is charging during this period is simply represented by the probability p. The number of PEV charging at peak hour for a single residence, C, is then defined by (3). In this study, 30% of the plug-in vehicles are assumed to charge during the peak hour. This assumption provides a conservative estimate of the temporal diversity based on analysis of the home arrival time and miles driven statistics provided in Chapter 4 .

$$p(c) = \sum_{j=c}^{k} P(Z = j) * \binom{j}{x} p^{c}(1-p)^{j-c} \quad (3)$$

Equation (3) is the probability distribution that a single residence will have one or more charging PEVs. The distribution when considering n customers is determined by n-fold convolutions of $p(c)$, as shown in (4).

$$p(c_n) = p_1(c) * p_2(c) * \dots * p_n(c) \quad (4)$$

As such, every possible value of n requires it own probability distribution. To simplify the evaluation process, a discrete value $c_{n,max}$ is determined for every n such that (5) is satisfied. This value represents the maximum number of charging PEVs for an asset serving n customers given P_{Lim} confidence. A high confidence value of 99.99% is assumed for P_{Lim} in this analysis.

$$\begin{gathered} P(C_n \leq c_{n,max}) \geq P_{Lim} \\ P\left(C_n \leq (c_{n,max} + 1)\right) < P_{Lim} \end{gathered} \quad (5)$$

The projected demand is then found by scaling $c_{n,max}$ by an assumed fixed value for individual PEV charger demands, S_{PEV}. A high value of S_{PEV} is typically assumed in order to retain the conservative nature of the projection. The worst-case projected demand, normalized by the number of customers served, can then be found using (6).

$$S_{n,PEV} = \frac{C_{n,max} * S_{PEV}}{n} \quad (6)$$

At this point, the remaining capacity for an asset serving n customers can easily be compared to its projected worst case demand in (6).

System Deterministic

The goal of the System Deterministic analysis is to capture feeder response to forced system-wide PEV penetration/charging scenarios. These deterministic scenarios are designed to identify system sensitivities to PEV characteristics in addition to system impact boundaries under increasing levels of penetration. The system deterministic analysis consists of 24-hour peak-day simulations of the full system model in OpenDSS with increasing PEV penetration levels from 0 to 20%. The PEV are randomly distributed throughout the system with locations remaining fixed as subsequently higher penetration levels are evaluated. While such high penetration levels are clearly unlikely, the analysis seeks to identify any particular system characteristics that may change nonlinearly with increased penetration.

Each allocated PEV is characterized by a full charge profile, each starting at the same point in time as well as with the same demand magnitude. The peak and off-peak hours are selected based on the measurement data for the peak day shown in Figure 5-2. In this study, 4:00 PM and 9:00 PM are selected to represent the peak and off-peak demand respectively.

Demand profiles are selected using 120V 12A and 240V 30A demand charger profiles assuming 8kWh of useable battery storage for each. While these scenarios do not represent likely scenarios, they provide indications of system sensitivities as well as response to worst-case conditions. Diversified charging scenarios are also introduced to provide a basic indication of how a "smart-charging" control scheme might alter or influence system impacts. Diversified charging scenarios are composed of staggered PEV interconnections that take place over a five hour period with 20% of the PEV interconnecting at each hour.

The following charge type and start time combinations:

- 120V 12A peak hour charging
- 120V 12A off-peak (75% peak) charging
- 120V 12A diversified charging
- 240V 30A peak hour charging
- 240V 30A off-peak (75% peak) charging
- 240V 30A diversified charging

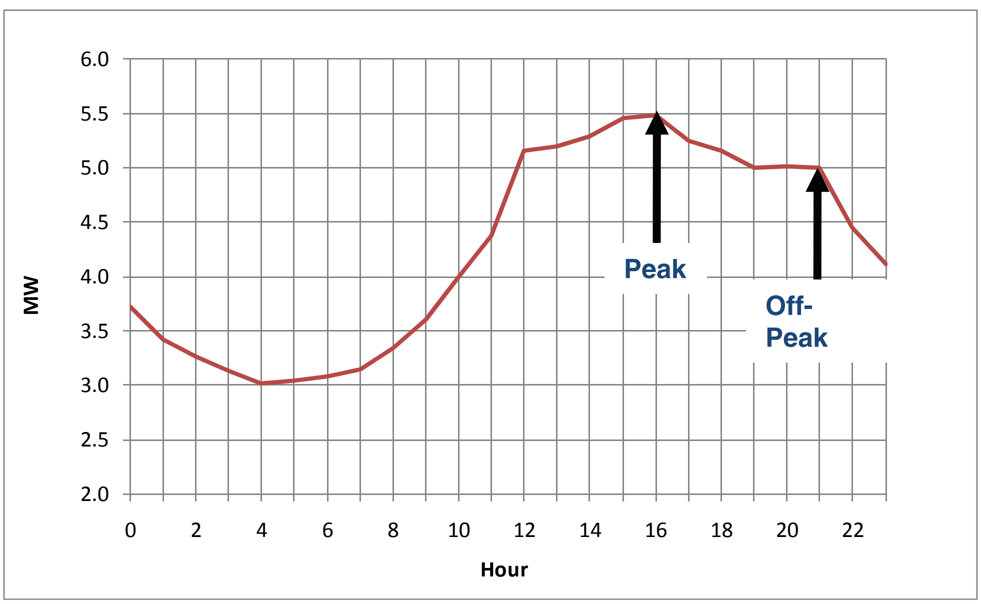

Figure 5-2
Don Bosco Peak Day Loading Profile

Stochastic Analysis

The stochastic analysis, outlined in Figure 5-3, is designed to assess likely impacts of PEV loading on the study circuit through full representation of PEV spatial and temporal diversity. The process uses the defined PEV probability distributions to assign PEV locations, types, and full calendar year charge profiles for one hundred randomly generated test cases.

The goal of this analysis is to provide the most reasonable projection of the impacts that are likely to occur under the assumed PEV penetrations. During the course of the analysis, this stochastic process is performed for low (2%), medium (4%), and high (8%) penetration levels.

Aggregation and post-processing of the results provide quantitative results, including system voltages, asset loading, system losses, and aggregate demands. The test case inputs and results are all retained through the analysis process such that specific conditions resulting in a particular impact can be tracked down and identified during the post-processing of the results. Additionally, impact results are statistically evaluated in conjunction with the network data to identify system conditions under which impacts are more likely to occur.

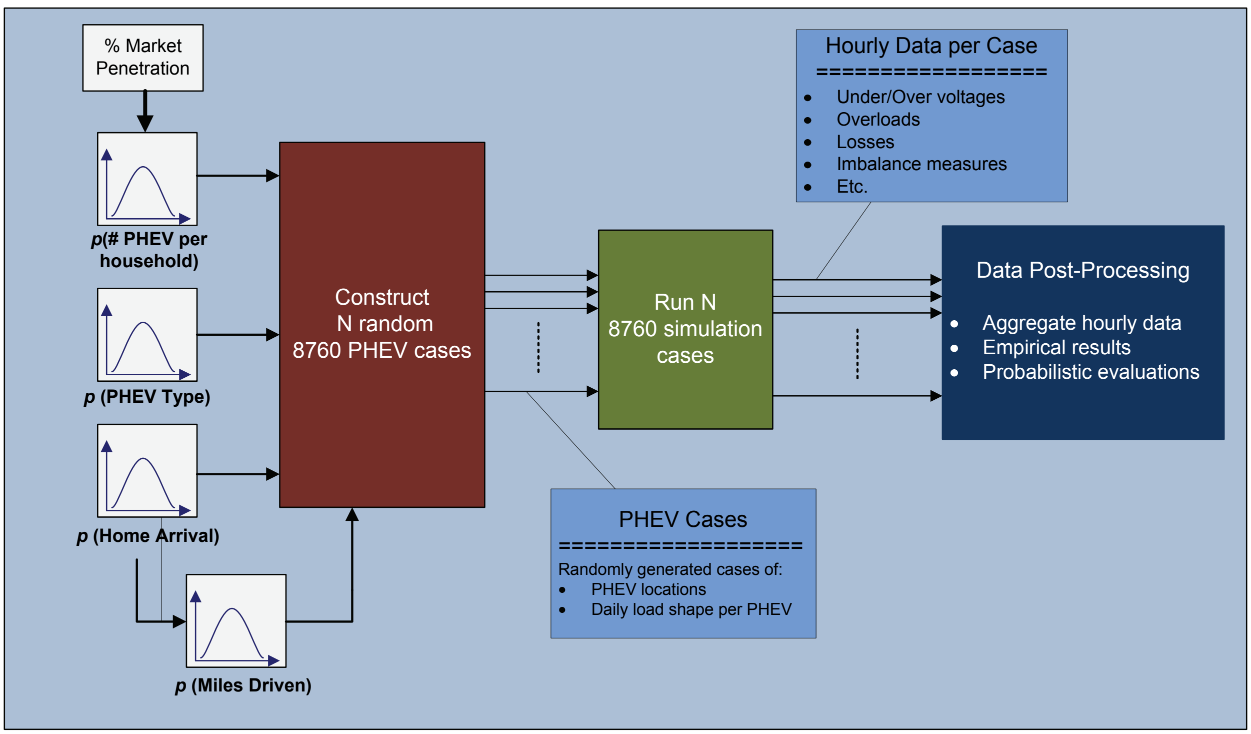

Figure 5-3
Stochastic Analysis Framework

Don Bosco 17W55 Circuit Model

The Don Bosco circuit was selected as a representative suburban circuit at possible risk of distribution system impacts due to residential customer adoption of plug-in electric vehicles. The radial circuit is served out of the Harrison substation and supplies a total of 1,652 customers, of which 95% are residential. This study only considers residential customers as possible candidate locations for PEV interconnection, with each residential customer having equal odds of adopting a PEV. Additionally, this circuit is actually designed and operated in an auto-loop configuration where specific secondaries are connected and served by multiple primary circuits. Nonetheless, secondary networks fed by this configuration are assumed to serve industrial and commercial loads that are not considered likely PEV adopters in this study. As such, the feeder can be considered and modeled as a radial circuit in the study without impacting the final results.

The circuit model used in the analysis was converted from Con Edison's existing CYMDIST load flow model into OpenDSS. Hourly average current measurements taken at the substation during the 2007 and 2008 years were used to generate a normalized load profile of over 8,760 hours, or the full calendar year. This load profile is used in the OpenDSS model to represent the hourly variation in each load from its allocated peak demand. The average hourly and seasonal variations captured in the profile are summarized in terms of feeder demand in Figure 5-4. Other feeders served off the same substation transformer as Don Bosco 17W55 are also represented in the model by an aggregate load connected to the substation transformer secondary with its own 8,760 hourly load shape definition.

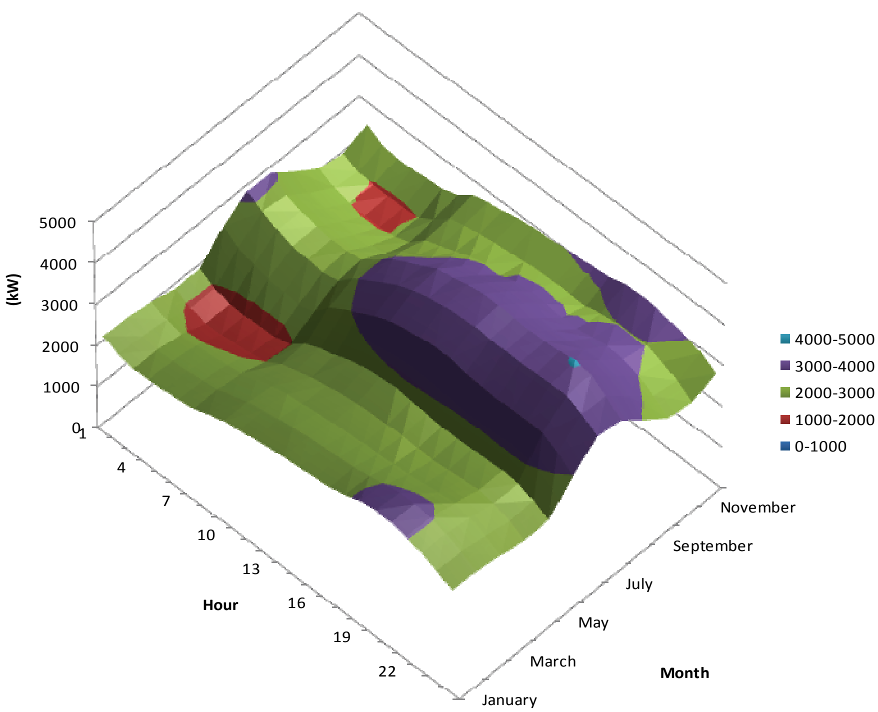

Figure 5-4
Feeder Average Hourly and Monthly Demand Profile

Given that the majority of the load is located toward the end of the six mile circuit, as seen by the service transformer locations in Figure 5-5, the voltage drop along the circuit can be fairly significant at peak demand. To counteract the voltage drop along this large span, the substation LTC control settings are varied as a function of load. These controls can increase the substation voltage as high as 128 volts (on a 120V base) during peak demand. As this type of control functionality is currently not available in DSS, the LTC control settings are approximated using a LTC voltage set point of 125 V with a 3V bandwidth. This approximation will be shown to provide reasonable voltages during most hours of the year. Nevertheless, during peak hours the calculated voltages may be lower than expected. Recognizing this limitation, subsequent peak voltage results are interpreted as additional voltage drop incurred from PEV loading and by snapshot load flow cases.

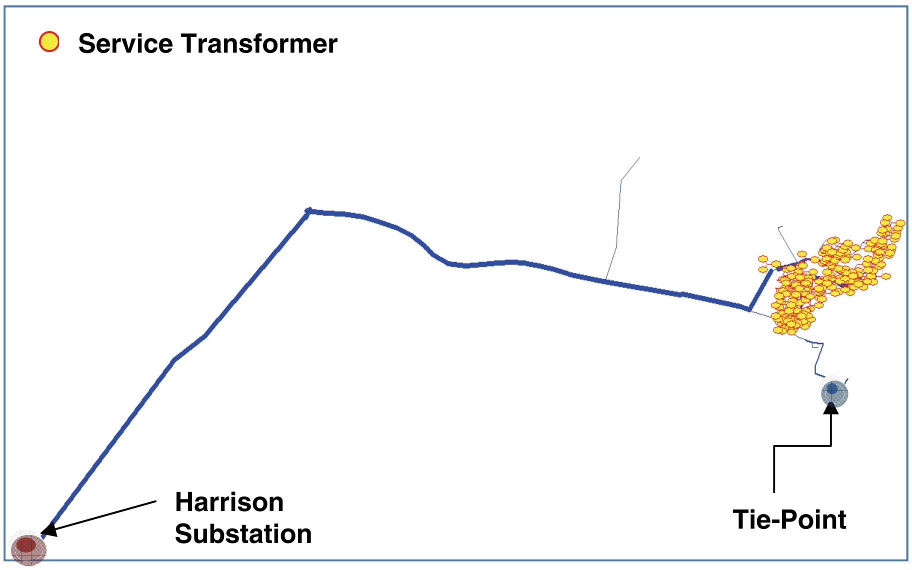

Figure 5-5
Don Bosco 17W55 Service Transformer Locations

To reflect PEV dissemination across the feeder it is necessary to identify the number of residential customers served off each service transformer in the model. This data was provided by Con Edison and integrated into the OpenDSS model. The only adjustment made to the data was the number of customers served off a single 25 kVA transformer, that was reduced from 128 to 10, based on a typical number for transformers of the same size. The box-and-whisker plots shown in Figure 5-6 and Figure 5-7 characterize residential customer allocations across the various transformer sizes. Figure 5-6 and 5-7 shows the potential PEV customers and the transformer count for the different transformer sizes. The error bars in the figures indicate the maximum and minimum customers while the colored bars (red and blue boxes) indicate the 25th-50th and 75th percentile. In addition, the dashed lines in these figures provide the number of transformers installed on this circuit. In general, 50 kVA transformers comprise the majority of transformers in service on the feeder with approximately a third of the residential customers being served by this transformer size. Another third of residential customers are served off the three-phase transformers, including a few customers sharing a transformer with larger commercial or industrial loads, see Figure 5-7. Another important feeder characteristic is the slightly high number of customers on average served off each single phase transformer.

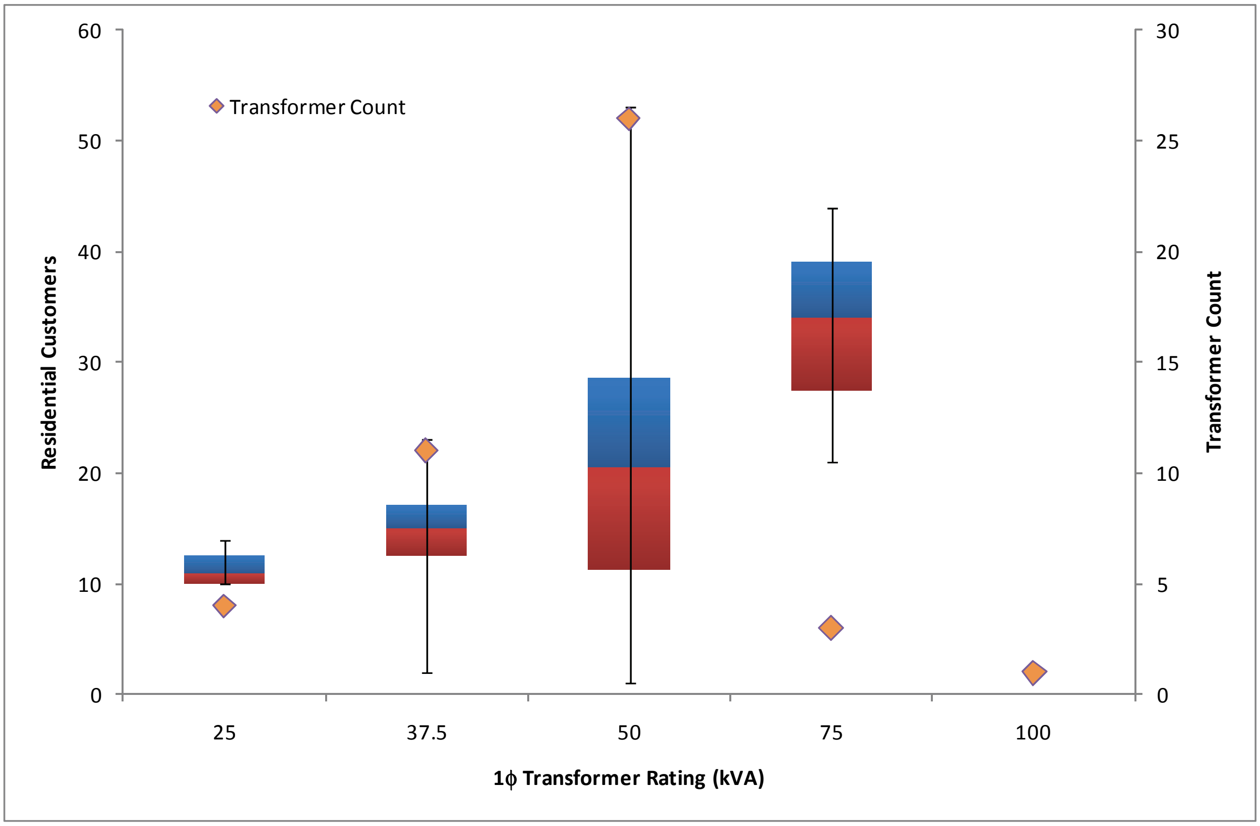

Figure 5-6
Single-Phase Transformer and Residential Customer Feeder Allocation

Figure 5-7
Three-Phase Transformer and Residential Customer Feeder Allocation

Model validation was performed by comparing modeled results to available measurements data, and comparison plots are provided in Figure 5-8 through Figure 5-11. As shown, the model provides a very good approximation of demand at both the feeder and substation level with only minimal differences between the modeled and measured data. Furthermore, a reasonable approximation of the voltage at both the substation as well as the tie point is realized, as indicated in Figure 5-10 and Figure 5-11 respectively. As previously noted, the model predicts lower voltages during peak hours than indicated by the measured data. Again, this limitation is accounted for during the interpretation of the findings. In general, the model provides a reasonable representation of the overall physical operation of the actual circuit.

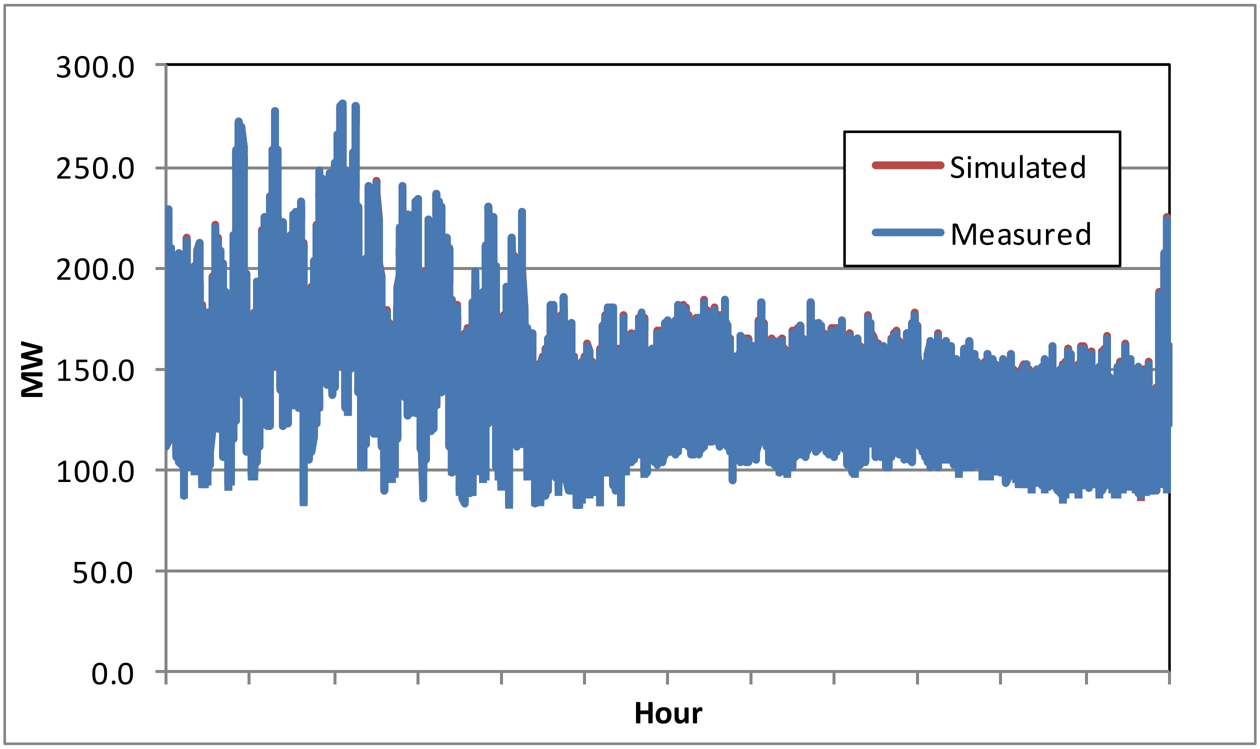

Figure 5-8
Model Validation of Feeder Current

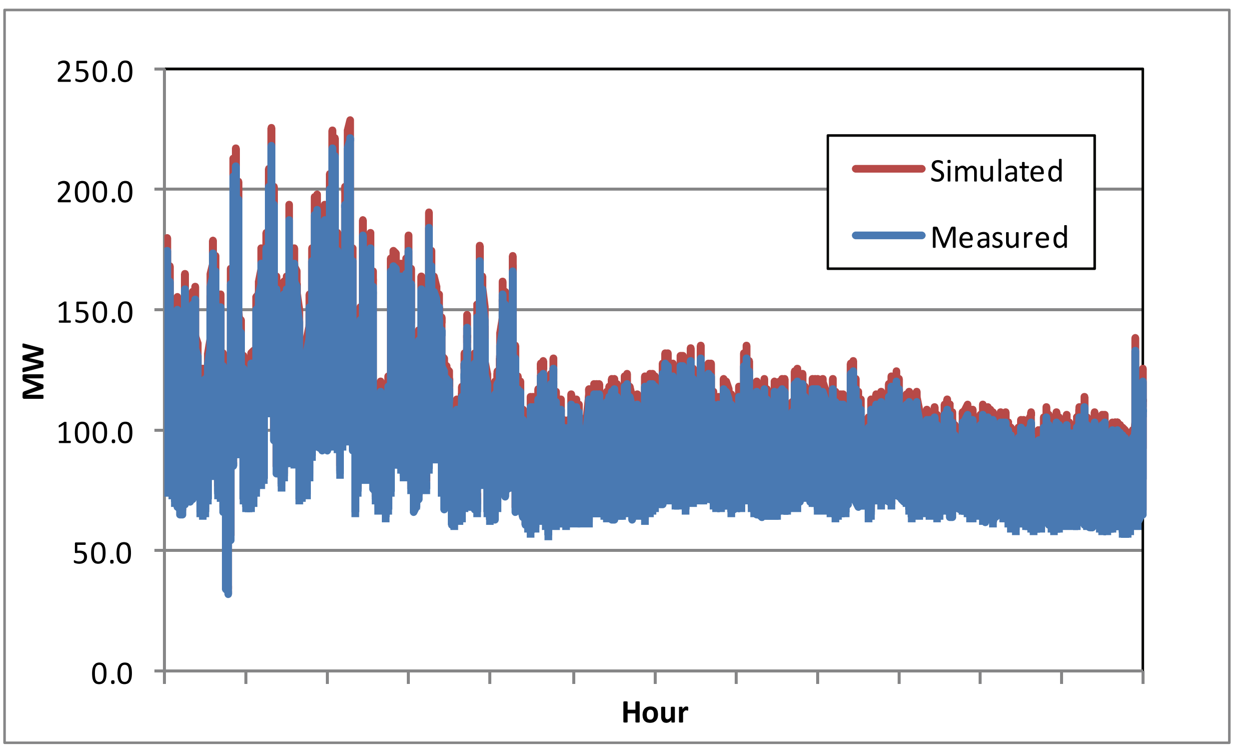

Figure 5-9
Model Validation of Total Substation Total Load

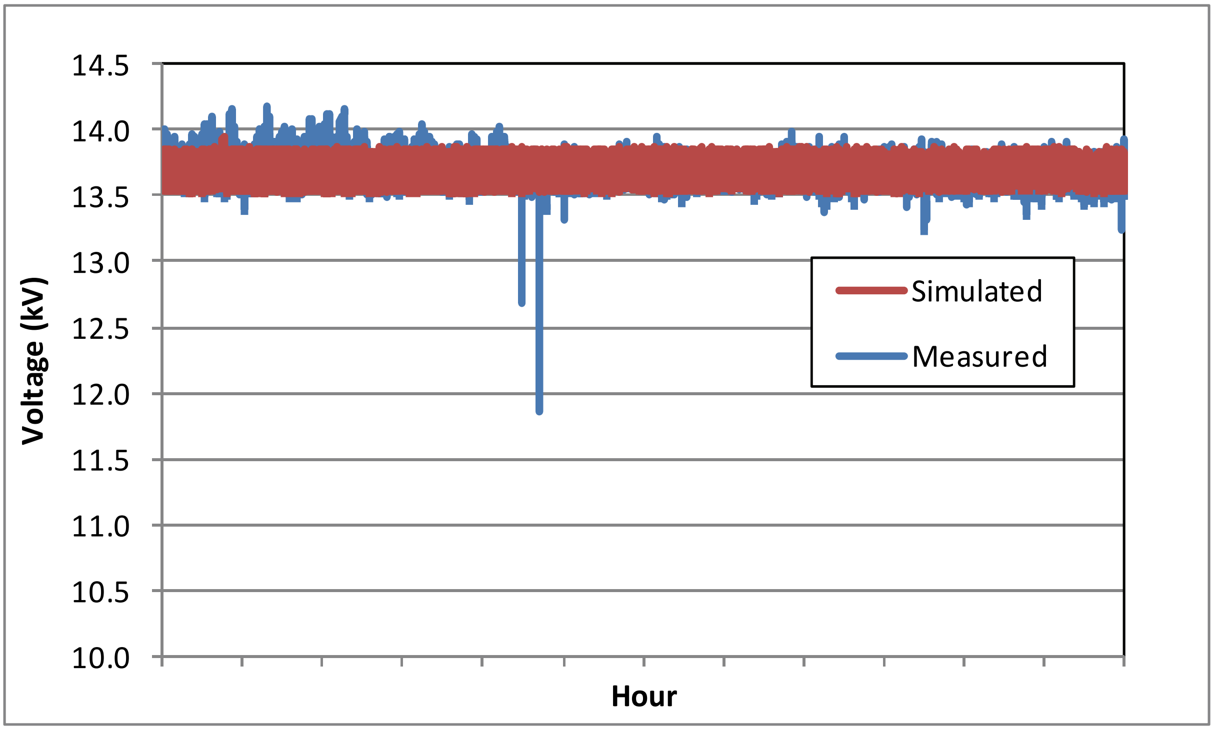

Figure 5-10
Model Validation of Harrison Substation Voltage

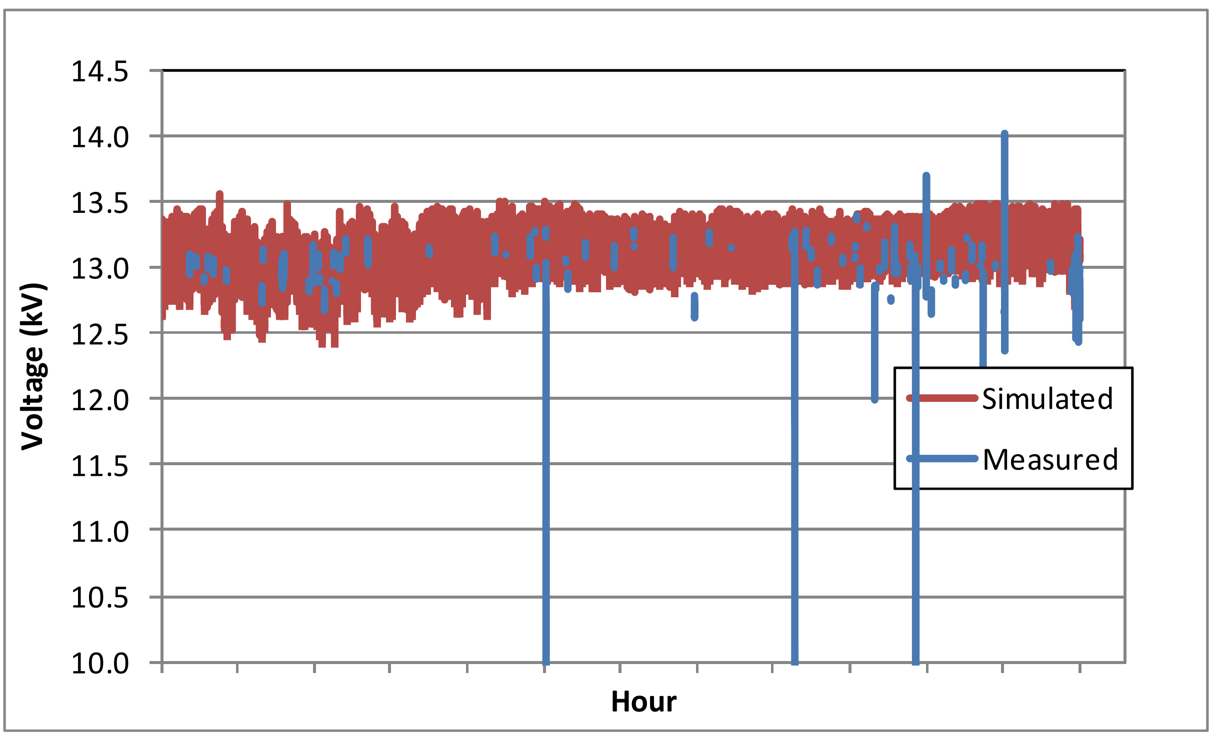

Figure 5-11
Model Validation of Tie Point Voltage

Don Bosco 17W55 Projected Impacts

Results are grouped based on the evaluated distribution system impacts to aggregate demand behavior, steady-state voltages, voltage unbalance, total network losses, and asset thermal overloads. While a large amount of data are produced during the course of the analysis, only those results fully describing the nature and degree of projected impacts are provided. During the course of the analysis it was determined that running the stochastic portion of the analysis was unnecessary as minimal or negligible impacts to the worst-case scenarios were observed for the other two analyses.

Aggregate Feeder Demand

Projected hourly PEV demand is provided in Figure 5-12 on an average per vehicle basis. The figure is derived using Monte Carlo analysis of the full PEV diversity model, and formatted future load growth can quickly calculated for multiple scenarios. Is this projection, PEV demand peaks at 5:00 PM and averages to approximately 720 Watts per plug-in vehicle due to the diversity in the aggregate load. The additional demand expected at the head of the feeder can be found by scaling by number of vehicles representing each market penetration level and subsequent results being provided in Table 5-3. The importance of customer behavior is indicated by the demand profile's strong correlation with projected customer home arrival times. Overall, feeder load growth is expected to increase only slightly due to PEV adoption.

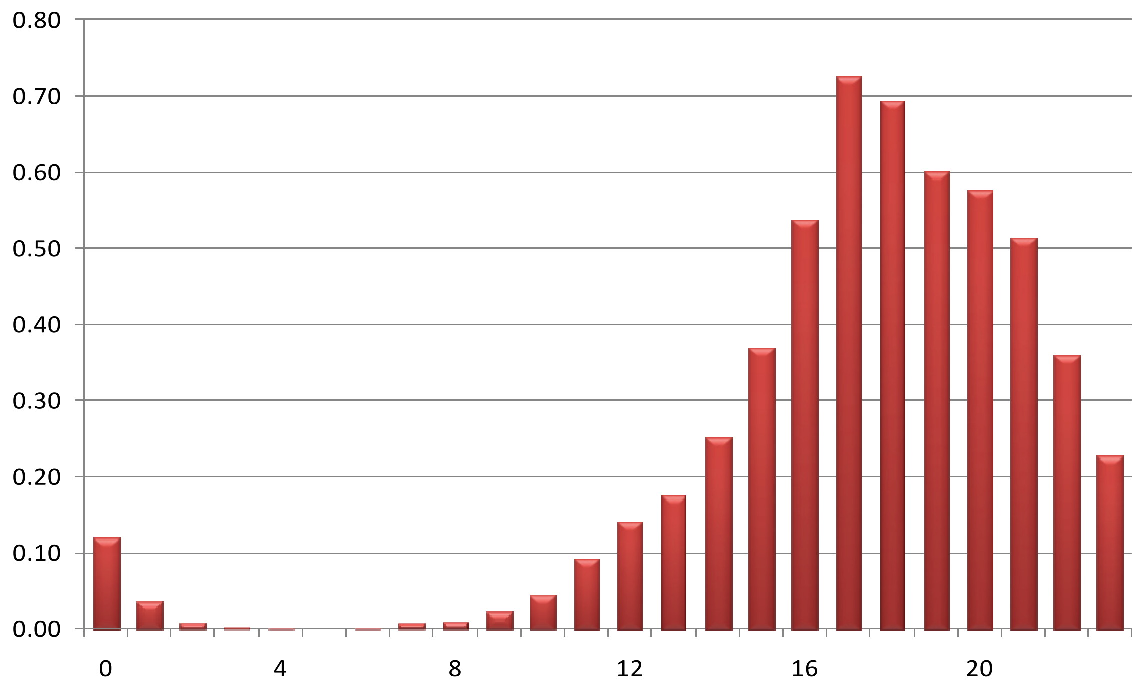

Figure 5-12
Average Hourly (Charge Power per Vehicle) Projected Plug-In Electric Vehicle Demand

Table 5-3
Projected Head of Feeder Average Demand Statistics

Market Penetration	Total Number Plug-in Vehicles	Peak PEV Demand (kW)	% Increase to Peak Demand
2%	34	24.5	0.5
4%	68	49.0	0.9
8%	136	98.6	1.8

Thermal Overloads

Identifying the extent to which particular distribution asset classes may be affected by PEV demand requires first examining how PEVs are expected to be distributed across the feeder. As PEV adoption occurs the locations of these loads are expected to vary with customer preference, which can appear random to the distribution engineer without some level of market acceptance data. This spatial variation in PEV demand across the feeder is not only determined by the aggregate PEV adoption rate but by the system design and configuration as well. As such, correlating expected PEV demand against the remaining capacity of each asset will provide a strong indicator of the number and type of assets most at risk from PEV adoption. Assets which are potentially at risk of exceeding their thermal ratings due to PEV adoption can be then identified by comparing their existing remaining capacity to the projected PEV demand. The peak hour remaining capacity for every distribution feeder component (asset) is determined from the peak hour load flow solution and each component's specified thermal ratings. While peak hour is typically examined, similar evaluations could be easily performed for other loading hours of interest.

The calculated peak hour remaining capacities for an example circuit are plotted in Figure 5-13 and Figure 5-14 as a function of the number of customers served from the component. Using the previously described Component Deterministic analysis, each asset is evaluated against projected PEV demands calculated and shown in Figure 5-13 and Figure 5-14. The remaining capacity of each asset is plotted as an individual point, and sorted based on customers served and asset class; while the projected demands are superimposed as lines for the three market penetration levels examined.Additionally, the estimated maximum PEV demand is also plotted permitting the quick identification of which assets are unlikely to be impacted and those which are at risk of impact. Each asset with a remaining capacity falling above the projected demand is unlikely to be impacted by 2%, 4%, and 8% PEV market penetration as shown in Figure 5-13 and Figure 5-14. Given the 99.99% value used for *Ptest* and the conservative construction of the maximum projected demand lines, the probability of exceeding the thermal ratings of these assets is less than 0.01%.

The analysis indicates Don Bosco 17W55's assets are at low risk of thermal overload in response to customer adoption of plug-in electric vehicles. A conservative estimate of 150% of nameplate kVA for the emergency rating was assumed for the Don Bosco circuit. Con Edison indicated that this rating could reach as high as 180% of nameplate. The plotted capacities/demands are also normalized by the number of customers served.

Examination of Figure 5-13 clearly indicates each asset to have sufficient capacity to meet the projected demand. Given the highly conservative nature of the projections, all assets are said to be unlikely to become overloaded. This is especially true for the lateral and primary line sections. While not likely at the penetration levels studied here, transformers, and other assets located close to customer loads, will most likely be the first asset type to be impacted at higher penetration levels. This is to be expected given the nature of distribution system design. A closer look at the transformer assets evaluation is provided in Figure 5-14 for the 8% market penetration. While service transformers are not at risk, some underlying risk factors can still be pulled from the relationships. Namely, transformers with a low capacity per customer ratio will be the most at risk of becoming overloaded as penetration of PEV continues to increase.

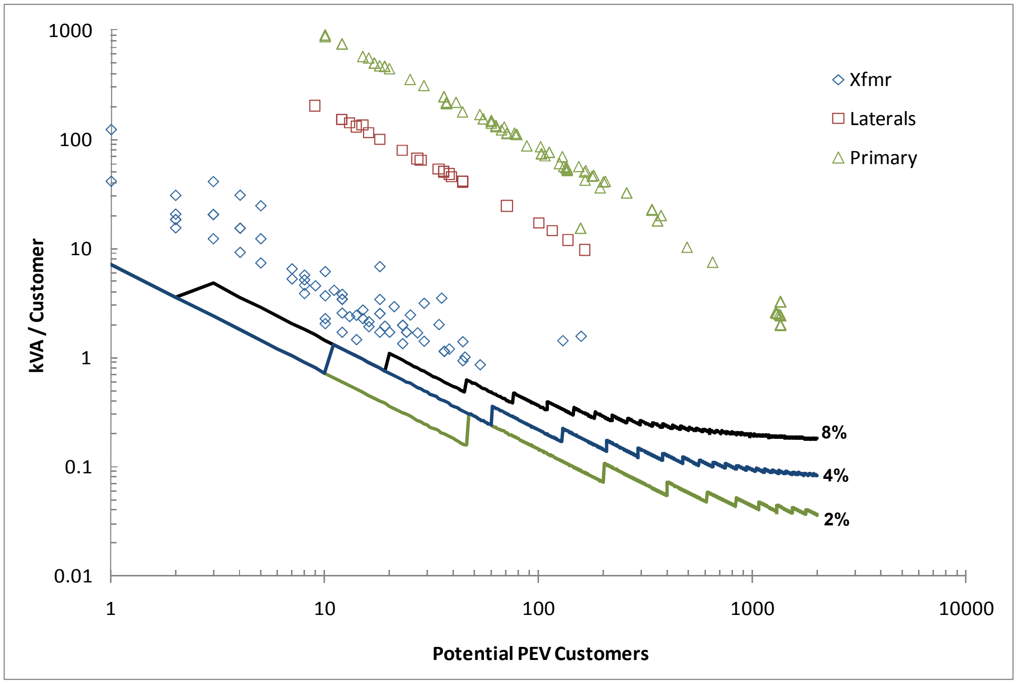

Figure 5-13
Feeder Asset Thermal Overload Risk Evaluation

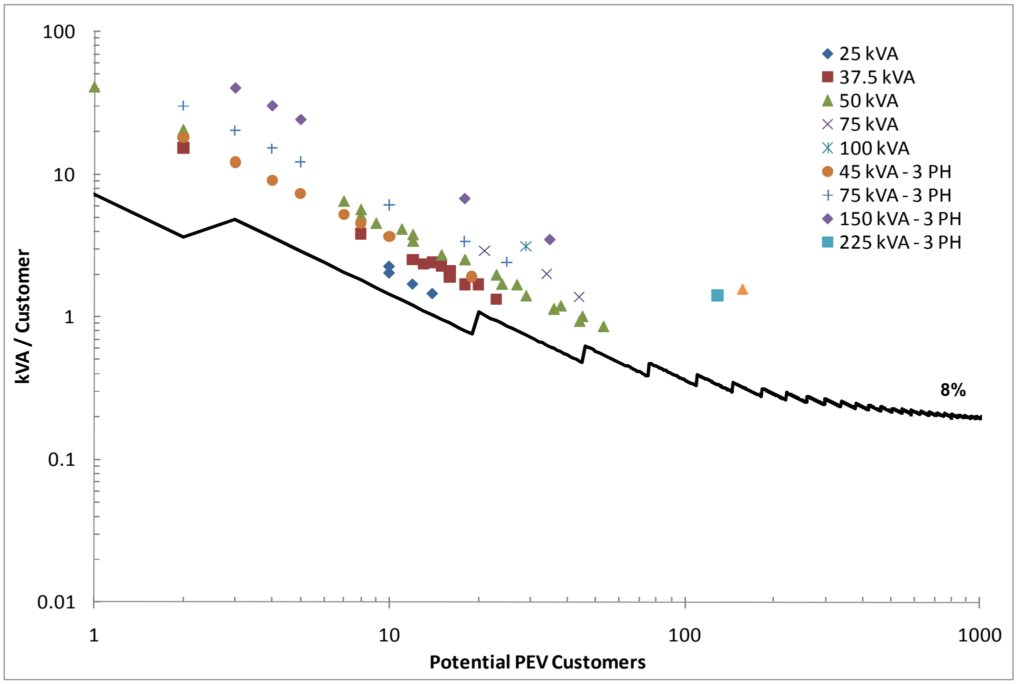

Figure 5-14
Service Transformer Overload Risk Evaluation

It is also important to note that circuit model limitation may limit the accuracy of the projections. Specifically, circuit models based on allocation of customer load per transformer kVA do not capture innate variations in transformer loadings. As such, transformers that may be heavily loaded in the field cannot be completely discounted from being overloaded due to PEV charging. Nonetheless, recognizing the conservative nature of the projected demand, the conservative estimation of transformer thermal ratings, as well as transformer sizes typically installed on this circuit (Figure 5-6 and Figure 5-7) few, if any, thermal overloads are expected. Additional customer load data and further analysis is required to obtain a more accurate assessment.

Steady-State Voltage

Vehicle charging is not expected to significantly impact primary voltages based on the model results. The minimum daily voltages observed during the system deterministic cases are plotted in Figure 5-15 and provide boundaries of what the worst-case voltage impacts would be. For instance, the 240V 30A peak hour worst-case results in more than 2% voltage drop at 8% market penetration. As shown in the feeder's voltage profiles (Phase A-red, Phase B-blue, Phase C-green) for both cases, Figure 5-16, the additional voltage drop in this case lowers the primary voltages on the primary below the favorable 117 V but above the tolerable 114 V limit. Nonetheless, this particular worst-case boundary point is fairly extreme and the actually additional voltage drop is expected to much lower when the full load diversity is taken into account. This is illustrated by insignificant levels of voltage drop for the other charging profiles, except at unrealistically high penetration levels. Overall, near-term PEV demand is not expected to significantly decrease primary voltages below tolerable levels.

In the analysis, voltages are calculated across the entire circuit down to the secondary side of each service transformer. Cases where secondary lines, which are not included in the model, are nearly or already experiencing voltage issues, will be further aggravated by additional PEV demand. These cases are true for every distribution feeder experiencing any type of unexpected per capita increase in load and are usually handled by the utility on a case by case basis. Nevertheless, such cases are not necessarily expected to be widespread across the feeder at the projected penetration levels.

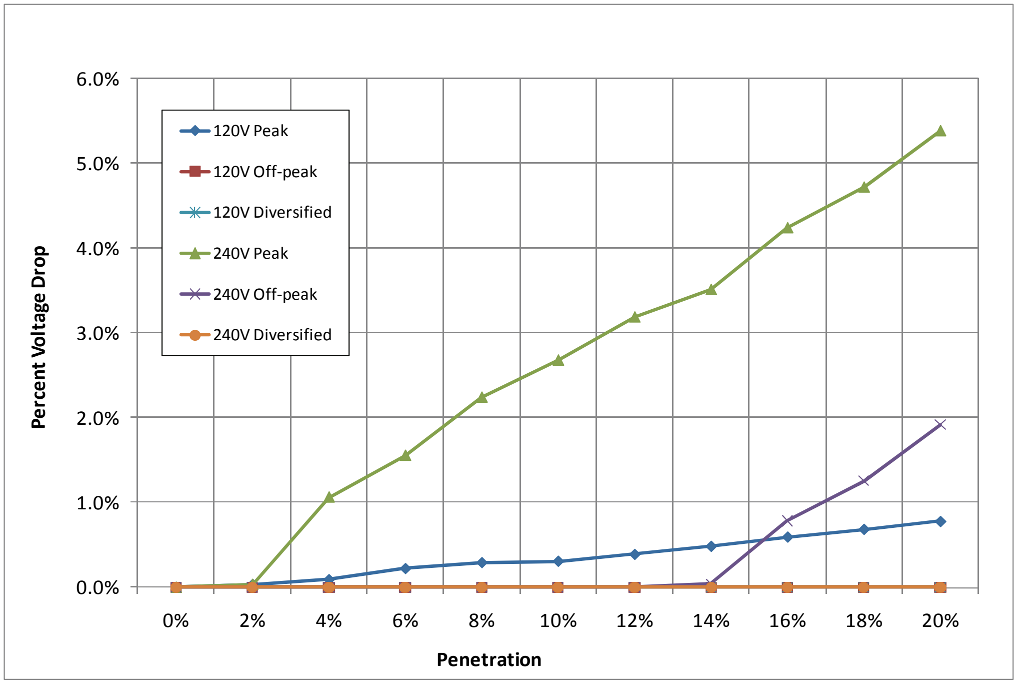

Figure 5-15
System Deterministic Minimum Transformer Secondary Voltages

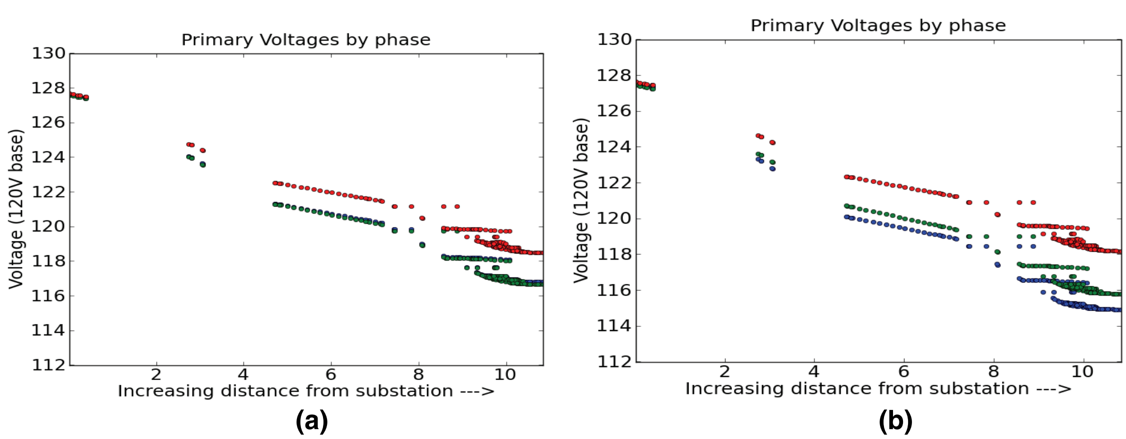

Figure 5-16
Feeder Peak-Hour Voltage Profiles (a) Base Case (b) 8% Market Worst-case

Voltage Unbalance

Unbalanced voltage conditions can result in motor damage due to excess heat. ANSI standard C84.1-1995 sets the maximum no-load voltage unbalance at the meter to 3%. Still, both NEMA and the IEC recommend motors should be derated at higher than 2% unbalance. The voltage unbalance factor (VUF), percent ratio between the negative and positive sequence voltages, was calculated based on the modeled voltages at the tie point location. The results from the system deterministic analysis, plotted in Figure 5-17, show the modeled voltage unbalance to fall with acceptable ranges even under worst-case conditions.

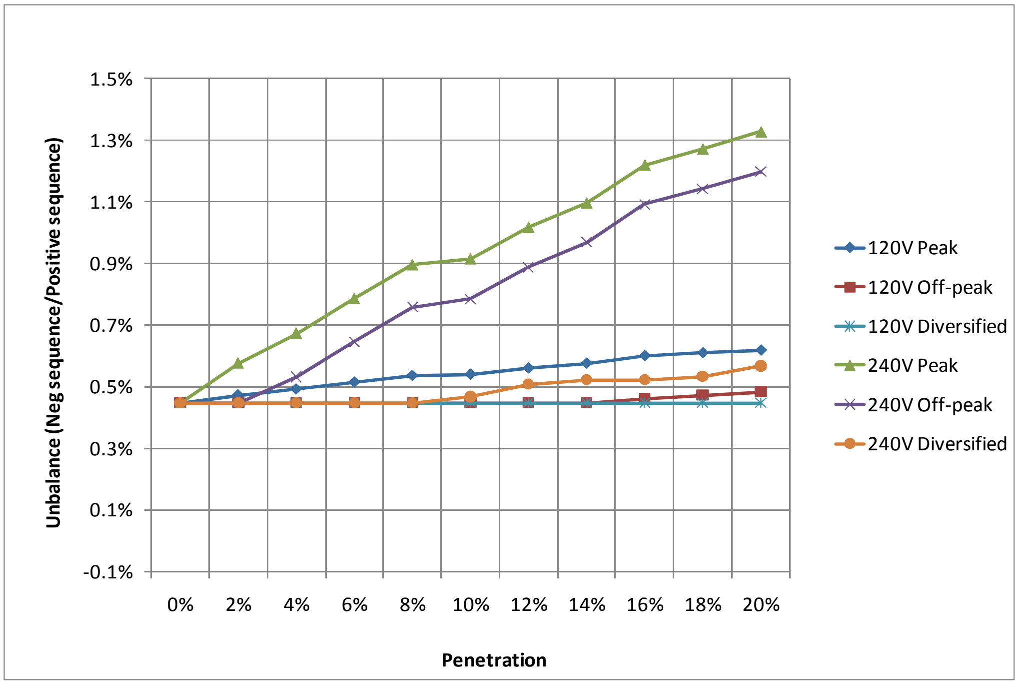

Figure 5-17
System Deterministic Case Voltage Unbalance Factors

Network Losses

PEV adoption is not expected to significantly impact system losses. Total losses incurred during the simulated peak day, for the system deterministic cases, are given in Figure 5-18. Only a minor increase in losses is shown to occur for the different charging scenarios with the diversified and slower charging scenarios providing the lowest increase to total losses. This is not unexpected; these scenarios tend to shift most of the charging to hours where base demand is lower, thus providing lower percent copper or no-load losses.

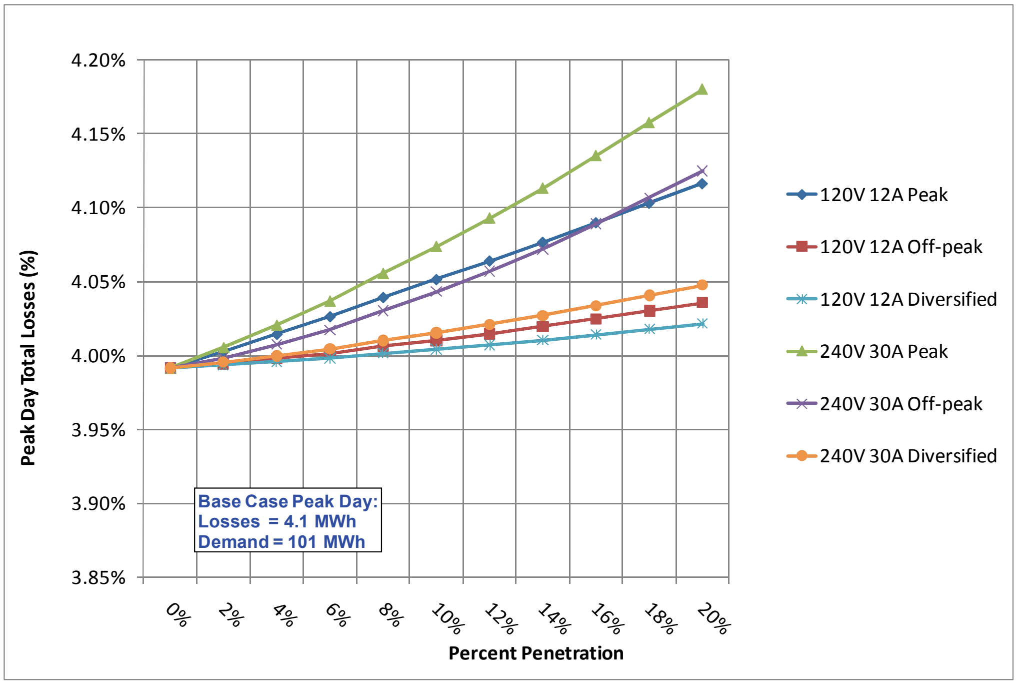

Figure 5-18
System Deterministic Case Total Peak Day Losses

Summary

Based on the analysis, significant impacts are not expected to occur on Don Bosco circuit 17W55 for the near-term planning horizon. Nonetheless, existing conditions not captured in the circuit model, such as low customer voltages or overloaded transformers, may be aggravated by the additional PEV load. This response is true for any per-capita load growth and requires additional data concerning existing conditions to fully evaluate. While minor impacts cannot be completely ruled out, few impacts, if any, are expected to occur and will be limited to those assets located closest to the customer.

6
PEV IMPACTS FOR YORKVILLE SECONDARY NETWORK

Executive Summary

This chapter describes an evaluation of plug-in electric vehicle (PEV) capacity available in a low-voltage secondary network in Manhattan. The geographic area is the Upper East Side, between Central Park and the East River from roughly 77th Street to 110th Street, plus Ward Island and Randall's Island. The network peak load (including losses) was about 300 MW in 2007. This neighborhood of Manhattan is called Yorkville.

The Yorkville network load and operation characteristics differ from those of a typical suburban radial feeder. There are very few single-family homes and relatively few driving commuters to or from Yorkville. The area is all served by subway, bus, and taxi. There are very few (if any) opportunities for on-street, driveway, or detached chargers owned by the resident. It was assumed that PEV chargers can be installed at existing public parking facilities, and those can be served from the Yorkville network as new loads. In addition, there may be commercial fleet (taxi) chargers not considered in this project. Service to fleet chargers would be planned and engineered by Con Edison like any other large spot load.

Additionally, Con Edison designs the secondary networks in Manhattan to be reliable under N-2 contingencies, which means that loads are served even with two primary feeders out of service. It is important to note that this criterion is not used on radial feeders, even those owned by Con Edison. Consequently, the analysis procedures in this project were customized to fit the N-2 planning process.

Con Edison uses software called PVL for network analysis, and the Yorkville model was converted from PVL to EPRI's OpenDSS software. The PVL and OpenDSS solutions do not match exactly, but they both show that Yorkville is already operating at its limit when the load is at the 2007 system peak. Both PVL and OpenDSS show the same two network transformers that already have significant overloads, even with no PEV load and no feeders out of service. Those base-case overloads were "fixed" in the model before evaluating PEV impacts.

Network transformer overload is the main limiting factor. At the system peak, approximately 2,800 chargers can be accommodated with 1% or fewer transformer upgrades. At 90% of the system peak, the limit increases to about 9,350 chargers. This means many more PEV can be accommodated if the charging times can be controlled to avoid system peaks, which only occur on a few days during summer, and during afternoon and evening hours.

These results, 2,800 vehicles at 100% load or 9,350 vehicles at 90% load, are representative of what should be expected in Yorkville. As the system and load evolved from 2007, and the PEV distribution may differ from that assumed in this study, the specific transformer overloads will change. But the total network capacity for PEV should be about the same.

Base Case Modeling Details

This section covers some of the background and modeling used in evaluating the Yorkville Network for PEV

Circuit Selection and Project Background

Plug-in Electric Vehicle (PEV) technologies allow vehicles to plug into the electric grid to charge their high capacity batteries for use during the drive cycle. This results in a vehicle capable of achieving very high fuel economy at a reduced vehicle fueling cost, and with reduced tailpipe emissions. As PEV penetration levels increase, the aggregated impact on the grid and associated emissions could be substantial. While the implications of increased penetration of PEVs have been studied generally on a national level and in several more localized regions, the specific impact to New York State has not yet been fully understood.

Consolidated Edison of New York (Con Edison) partnered with EPRI to initiate a project with NYSERDA to assess the impact of increased penetration of PEVs on the distribution system of New York. The focus of the distribution system analysis was to understand the impact of PEVs on design and operating features of the New York State distribution system, including violation of thermal ratings of all system components from the primary distribution 13.2 kV system and network transformers through the secondary networks, violation of voltage criteria for both steady-state loading.

Con Edison has wide latitude in circuit selections, and was ultimately responsible for selecting candidate circuit for distribution impact analysis. The selection depends on several factors, including the overall goals of the study and the type of circuit in which they are most interested. Of particular interest was the impact on Zones J and K, i.e. downstate, due to the concentrated electric demand and vehicle population in those areas. The three main criteria considered when selecting the PEV Circuits are:

- Diversity – Do the circuits represent a good cross section of circuits and customer load types?
- Metering – Do the circuits have AMI or other advanced metering? Are there voltage and current measurements available at the substation on all three phases?
- Modeling – Are circuits modeled in CYMDIST, SYNERGEE, WindMil, or other circuit modeling program with accurate phasing and customer data?
- Loading – Are the loadings representative of the Con Edison circuits? Yorkville was the largest network and the most heavily loaded network in Con Edison.

Other considerations include ability to control voltage and that the circuits were readily accessible to local personnel. Con Edison’s Yorkville secondary network in Manhattan satisfied the necessary criteria. Con Edison provided to EPRI source data for these circuits in the form of PVL text files and other supporting data files. The circuit and loading information were then converted to OpenDSS. The model was augmented with other additional data to obtain a base case for Con Edison Yorkville secondary network. The base case was validated with measurement data provided by Con Edison.

Secondary Network Background

Secondary networks are used to provide highly reliable distribution service to dense, urban loads. Figure 6-1 shows a typical but simplified secondary network with its primary feeders, used to explain some of the terminology and operating principles. This figure and its labels are adapted from Con Edison's User Manual for the PolyVoltage Loadflow (PVL) program. PVL is the main tool that Con Edison uses to plan and evaluate the capacity of its secondary networks. Con Edison also operates radial feeders, but the secondary networks are markedly different in design and operation.

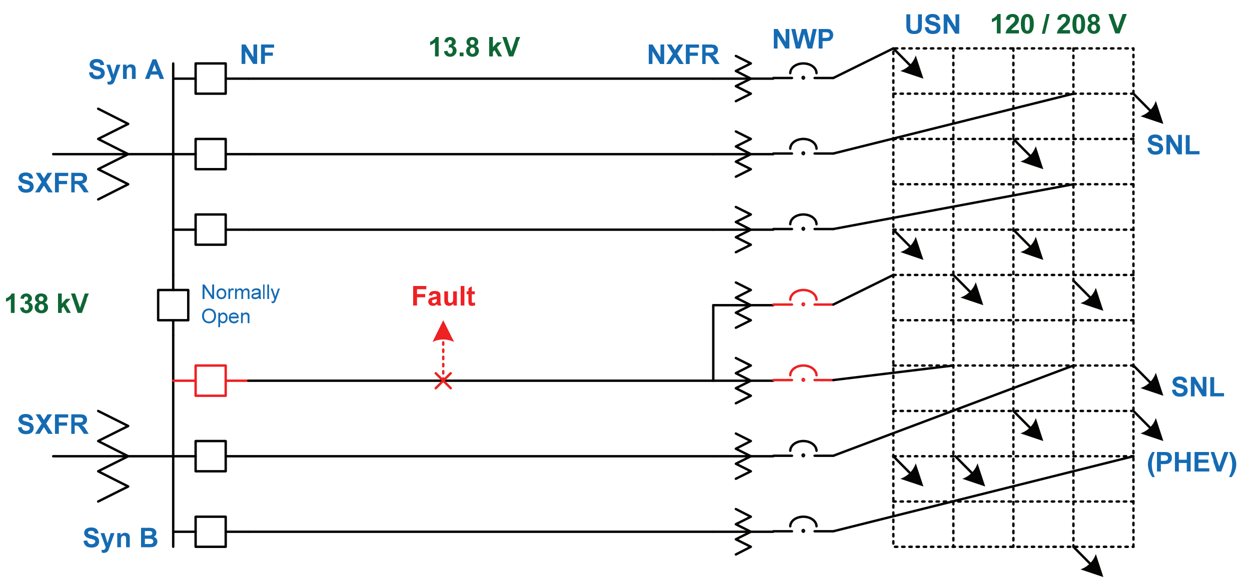

Figure 6-1
Example Secondary Network

Working from left to right in Figure 6-1, the two substation transformers (SXFR) step down from the transmission voltage of 138 kV, to the primary distribution voltage of 13.8 kV. There are two synchronizing buses (Syn Bus) separated by a normally open 13.8 kV circuit breaker. The 13.8 primary feeders (NF) are fed from the two syn buses. In general, each NF will consist of underground cable sections, and each will serve a number of network transformers (NXFR). Figure 6-1 is simplified to show only one or two NXFR per NF, but 10 to 12 would be more typical. The NXFR steps down to the secondary network three-phase voltage of either 208 volts, or less often, 460 volts. In this project, all evaluated PEV locations were in 208-volt networks. Typical NXFR sizes are 1000 kVA and 500 kVA.

The secondary cables (USN) distribute power to a number of secondary network load (SNL) points. Each load is served at usage voltage, 120 volts single phase or 208 volts three phases, so there will be metering for each SNL but no additional transformers. A partial exception occurs for the 460-volt networks; those customers may have transformers inside the facility, not visible to Con Edison. The secondary network spreads over a wide area and is served by many NXFR.

The network protector (NWP) plays a key role in operating the network. The NWP comprises a low-voltage breaker and a specialized relay. The system in Figure 6-1appears to be not radial, but if reverse power flows through a NXFR, its associated NWP is set to trip. Some of the NWP may trip under lightly loaded conditions, so that in practice there should never be any loop flow over the NF and through the substation.

Figure 6-1shows one of the NF as faulted. In that case, the feeder breaker at the substation will trip, much the same as for a radial feeder. Two of the NXFR still energize the fault, but their NWP will detect this as reverse power flow and trip, which finally isolates the fault. The system is stiff enough that the SNL sees no interruption of service, and usually not even a voltage dip. Fault currents in a secondary network can be very high, so the NXFR and NWP components are specialized. The network also includes fuses and cable limiters not shown in Figure 6-1.

In this project, PEV charging stations are represented as additional SNLs connected to a network bus, as shown at one point in Figure 6-1. As with any other new or expanded SNL, Con Edison would consider the possibility of overloaded NF, NXFR, or USN components under contingency conditions. Another concern will be the possibility of low voltage at nearby existing SNL. These planning criteria are discussed in the next section.

Con Edison's Network Planning Criteria

Con Edison plans the secondary networks to operate under any second contingency, which is sometimes referred to as "N-2" reliability criteria. With reference to Figure 6-1, there should be no overloads (NF, NXFR, or USN) or dropped loads (SNL with low voltage), for any one or two NF out of service. In contrast, a typical radial feeder has N-0 reliability. Some radial feeders achieve partial N-1 reliability with automated switching devices (such as Con Edison's auto-loop design) or by including manual switching to an alternate feeder. The strict N-2 criterion is justified by the social and economic cost of an outage in New York City, and by the regulatory and political directives for Con Edison to avoid such events.

In this project, the PEV loads are evaluated on the basis of whether they might cause N-2 reliability criteria to be violated. For any new load of significant size, Con Edison's planning procedure would take the same view, specifying system upgrades as needed to maintain N-2 reliability.

Con Edison uses a single-tier threshold for overload or low voltage, depending on the N-0, N-1, or N-2 state of the system. Other utilities more commonly use normal/emergency ratings, or normal/short-term/long-term ratings. Focusing just on the thresholds evaluated in this project, Table 6-1 shows the applicable criteria.

Table 6-1 applies to NXFR rated 500 or 1000 kVA as used in the Yorkville network, and to SNL served from 208-volt networks. Different thresholds apply to different sizes or voltage ratings of NXFR, and to SNL served at 460 volts. They are not relevant to this project because public garages were not identified at 460-volt locations, nor served by other NXFR sizes. NF criteria are not included because no NF overloads occurred for the PEV levels under study (NXFR overloads occur first). USN criteria are not included because the secondary cable ratings are calculated "on the fly" by PVL, and those ratings were not available in data files to use in this project.

Table 6-1
Selected Network Reliability Evaluation Thresholds Used in PVL

System State	NXFR Limit [% of Normal kVA]	SNL Minimum Voltage [p.u. / Volts]
N-0 (i.e., no outages)	100	0.9833 / 118
N-1	125	0.9667 / 116
N-2	140	0.9250 / 111

Whenever USN overloads are predicted by PVL, Con Edison would take action on a case-by-case basis. These overloads would be local in nature, whereas NXFR and NF overloads would impact more customers. In this project, SNL voltage is used to evaluate PEV impacts on the secondary networks.

Because N-2 conditions allow for lower SNL voltage and higher NXFR overload, it sometimes occurs that the N-1 thresholds are more limiting. The PEV evaluation considers N-0, N-1, and N-2 criteria.

Con Edison provided another document, EO-2065, "Low Tension A.C. Service Voltage Limits", revision 4, August 1993. For a 2nd-contingency design system, EO-2065 lists broader low-voltage limits than used in PVL cases:

- 0.9833 / 118 for N-0
- 0.9500 / 114 for N-1
- 0.9000 / 108 for N-2

A third source of low-voltage criteria comes from ANSI C84.1:

- 0.9500 for A range (normal operation)
- 0.9167 for B range (temporary operation)

So EO-2065 permits voltage below the ANSI B range for N-2 conditions. Because of the different voltage criteria, more weight is given to NXFR overloads in the PEV evaluation for this project.

Yorkville Network Description

The Yorkville secondary network serves a dense load in Manhattan's Upper East Side (see Figure 6-2), with a projected summer peak load exceeding 300 MW. Most of the network operates at 120/208 volts, but some loads operate at 265/460 volts. In addition, ten large customer loads are served from the primary feeders; these are called HTV customers and have a peak load just over 40 MW. Figure 6-3 shows that the network load factor is relatively high, compared to typical suburban and rural circuits. At the beginning of the project, a 2007 base case was selected for evaluation.

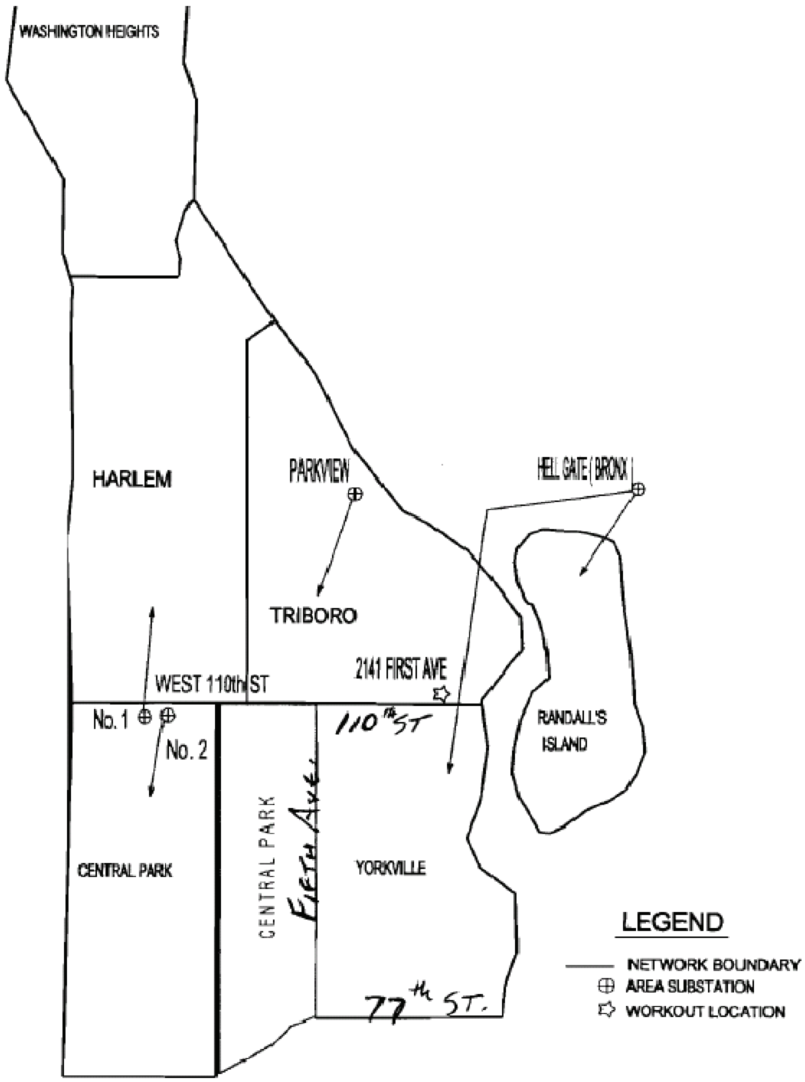

Figure 6-2
Geographic Area of the Yorkville Network

This network is supplied from Hellgate substation in the Bronx. As shown in Figure 6-4, there are four split-secondary transformers serving two distribution buses, each having two switched capacitor banks of 20 MVAR each. Each bus supplies 14 or 15 primary feeders, which in turn supply more than 500 network and HTV transformers. Through a secondary network, these transformers supply almost 2,300 aggregated loads.

The system operators switch the substation capacitor banks to help maintain the bus voltage level as the load varies. They also change the regulated bus voltage according to the total substation load, by adjusting the setpoints of the substation transformer tap changers in Figure 6-4. In addition, each tap changer includes line drop compensator (LDC) R and X settings. There are no utility-owned capacitor banks or voltage regulators out on the feeders.

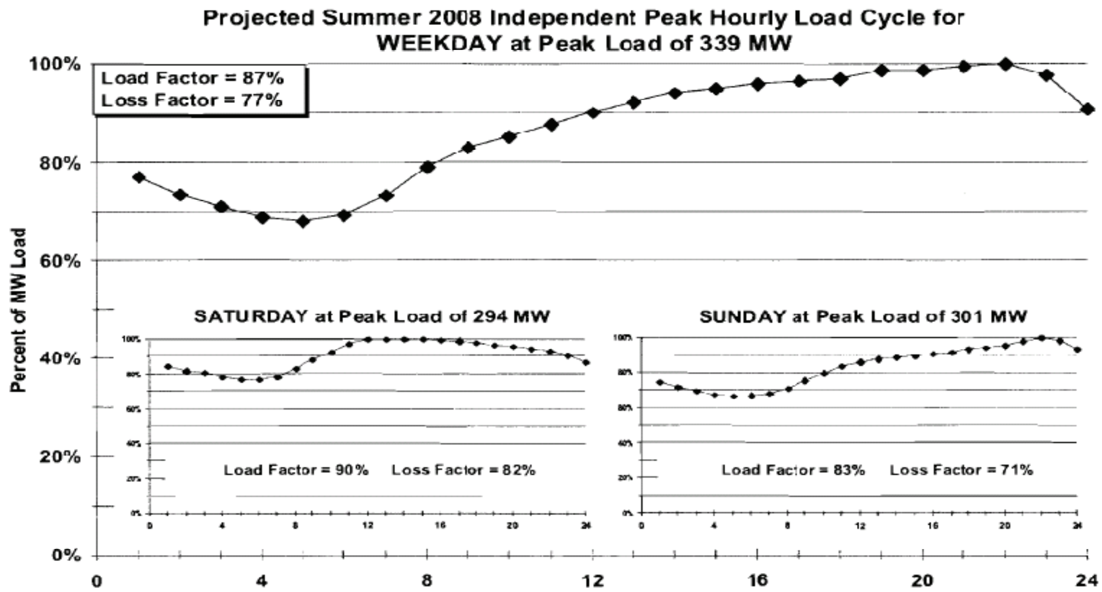

Figure 6-3
2008 Weekday and Weekend Load Variations in the Yorkville Network

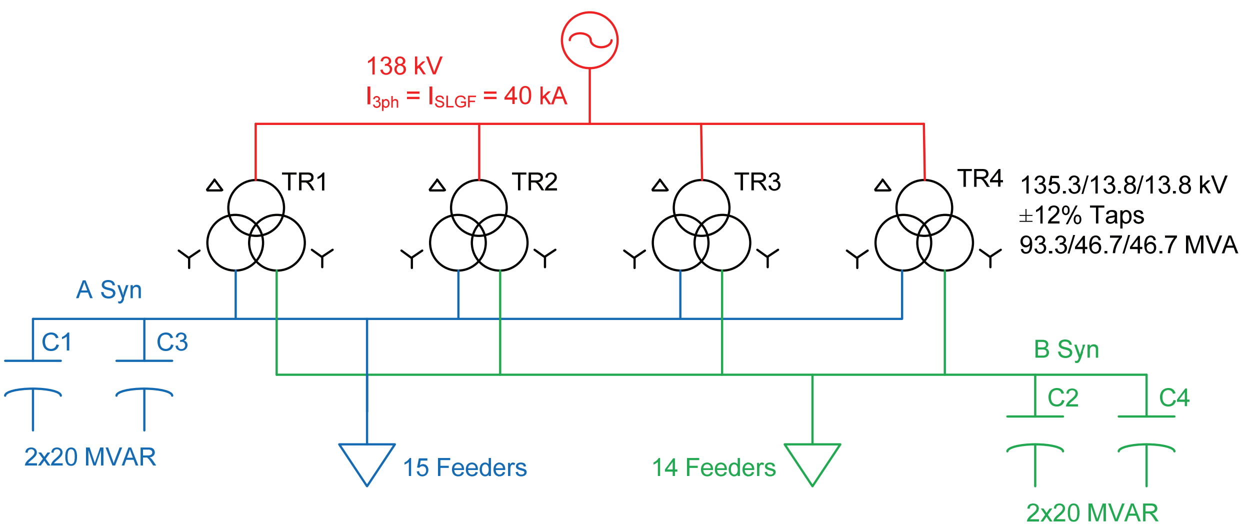

Figure 6-4
Simplified One-line Diagram of the Hellgate Substation

Base Case Modeling Approach

The main steps to develop a 2007 base case are:

- Conversion of the PVL model to OpenDSS
- Augment model to include substation capacitor and tap changer controls
- Validate model against the PVL solution

The Open Distribution System Simulator (DSS) is a comprehensive electrical system simulation tool for electric utility distribution systems. The OpenDSS is provided as an open source program to the electric power system analysis community at large by EPRI under a Berkeley Software Distribution (BSD) license. The OpenDSS is available at http://electricdss.wiki.sourceforge.net/. The main advantages of OpenDSS for this project include:

- *Scripting from a spreadsheet* – The OpenDSS can run contingency cases and load flow simulations with varying levels of system load and PEV load, identify overloads and low-voltage load points, and place outputs directly onto a spreadsheet for plotting and other post-processing. It becomes very efficient to re-test modeling assumptions and PEV levels.
- *Custom control modes* – Custom controllers for switched capacitor banks and for voltage regulators can be readily implemented.

The majority of the circuit data used for modeling came from the PVL model provided by Con Edison. This data was converted to the OpenDSS format for analysis. The substation voltage control elements then received special attention in the model. Table 6-2 shows the bus voltage set point, **Vbus**, for different ranges of total substation load, **Pmin** to **Pmax** in MW. The OpenDSS model includes a potential transformer (PT) ratio of 120, so different bus voltage targets are implemented as different **Vset** values on the PT secondary voltage base. In addition, the LDC settings of R=2 and X=3 are always active in this study. For a CT primary rating of 2,300 amperes, the LDC settings correspond to 0.1043 + j0.1565 ohms on the feeder primary. This is approximately the impedance from a substation transformer secondary to the center of the Yorkville network. The tap changer operates with a 60-second time delay.

Table 6-2
Hellgate Substation Bus Voltage Schedule

Pmin	Pmax	Vset	Vbus	Vpu
0	50	110.83	13300	0.9637
50	100	111.67	13400	0.9710
100	150	112.50	13500	0.9783
150	200	113.33	13600	0.9855
200	250	114.17	13700	0.9928
250	300	115.00	13800	1.0000
300	1000	115.83	13900	1.0072

The operator instructions for substation capacitor switching were emulated with a reactive power control feature in OpenDSS. Each capacitor bank switches on if the reactive power demand exceeds 13 MVAR, and switches off when more than 12 MVAR flows back through the substation. Because the step size is 20 MVAR, these thresholds provide a dead-band of 5 MVAR to avoid hunting. The four steps are coordinated by using different time delays; one bank has a delay of 5 s, the next 10 s, the third 15 s, and the last one 20 s. The OpenDSS will then switch one bank at a time, until the total reactive power flow through Hellgate substation falls between 13 MVAR lagging and 12 MVAR leading.

Circuit Model Construction

The data conversion from PVL to OpenDSS is semi-automatic using AWK scripts, with some manual edits and supplemental processing required. The necessary base case files and scripts are provided in several zip archives:

- *Sed_gawk.zip* - contains the GNU AWK program, to be unzipped into a directory on the user's path. AWK is a text-processing language, tailored to converting one text format to another one.
- *Yorkville_scripts.zip* – contains the AWK scripts and batch files to convert a PVL case, to be unzipped into a "data" directory
- *Yorkville_case.zip* – contains the PVL data files for the year 2007 base case, to be unzipped into the "data" directory
- *Yorkville_supplement.zip* – contains extra input files, to be unzipped into the "data" directory
    - *Yorkville_phev.dss* – master input file for OpenDSS, incorporates the auto-converted PVL data along with manual edits
    - *Yo.usn.impedances.txt* – secondary cable impedances for the PVL model. Con Edison had to generate this separately, because PVL calculates the secondary cable impedances "on the fly". There was no external file containing this data.
    - *Yorkville.nwp* – saved output of parsing the PVL RMS file to determine network protector (NWP) open/closed states during the base case solution. This file is auto-generated by an AWK script, but then requires manual editing to comment out three non-existent transformers: 03M46_V7380, 03M44_V2509, and 03M49_HV743.
- *Yorkville_pvl_results.zip* – selected PVL solution files and AWK scripts that extract PVL solutions into CSV files, which can then be pasted into Excel for comparison to OpenDSS results. These should be extracted into a <u>different</u> data directory than the other files, for better organization.
- *Yorkville_excel.zip* – contains an Excel spreadsheet that runs a single OpenDSS solution at peak load, and loads data onto various sheets for comparison to the PVL solution. To run this sheet, OpenDSS must be installed and the OpenDSSEngine.DLL must be registered as a COM server. Also, Excel macros must be enabled on the directory where the spreadsheet resides.

To perform the PVL model and solution extractions, issue the commands "go.bat" from the main data directory, and "go_pvl.bat" from the directory where *Yorkville_pvl_results.zip* was extracted. The master input file, *Yorkville_phev.dss*, contains these manual edits:

- Add high-side switches and an OpenDSS EnergyMeter to the Hellgate substation 138-kV bus, along with a 138-kV equivalent source impedance
- Add four three-winding substation transformers, with tap changer controls
- Add four switched capacitor banks, with reactive power controls
- Define transformer "specs" for the HTV customer transformers, which don't have specific data in the PVL model
- Manually set some of the load voltage bases to 460
- Resolve all overloaded NXFRs in the N-0, N-1, and N-2 system configurations at peak load, with no PEV loads. This provides a clean baseline for evaluation of different PEV penetration levels
- Incorporate PEV charging station loads. The next section describes this in more detail
- Set up default OpenDSS solution options.

All simulations are performed by first loading *Yorkville_phev.dss*, and then making COM scripted edits to the base model. Figure 6-5 shows the OpenDSS model cable segments, plotted from the NXFR x-y coordinates available from the PVL model. The Hellgate Substation is located to the upper right. This plot is consistent with Figure 6-2.

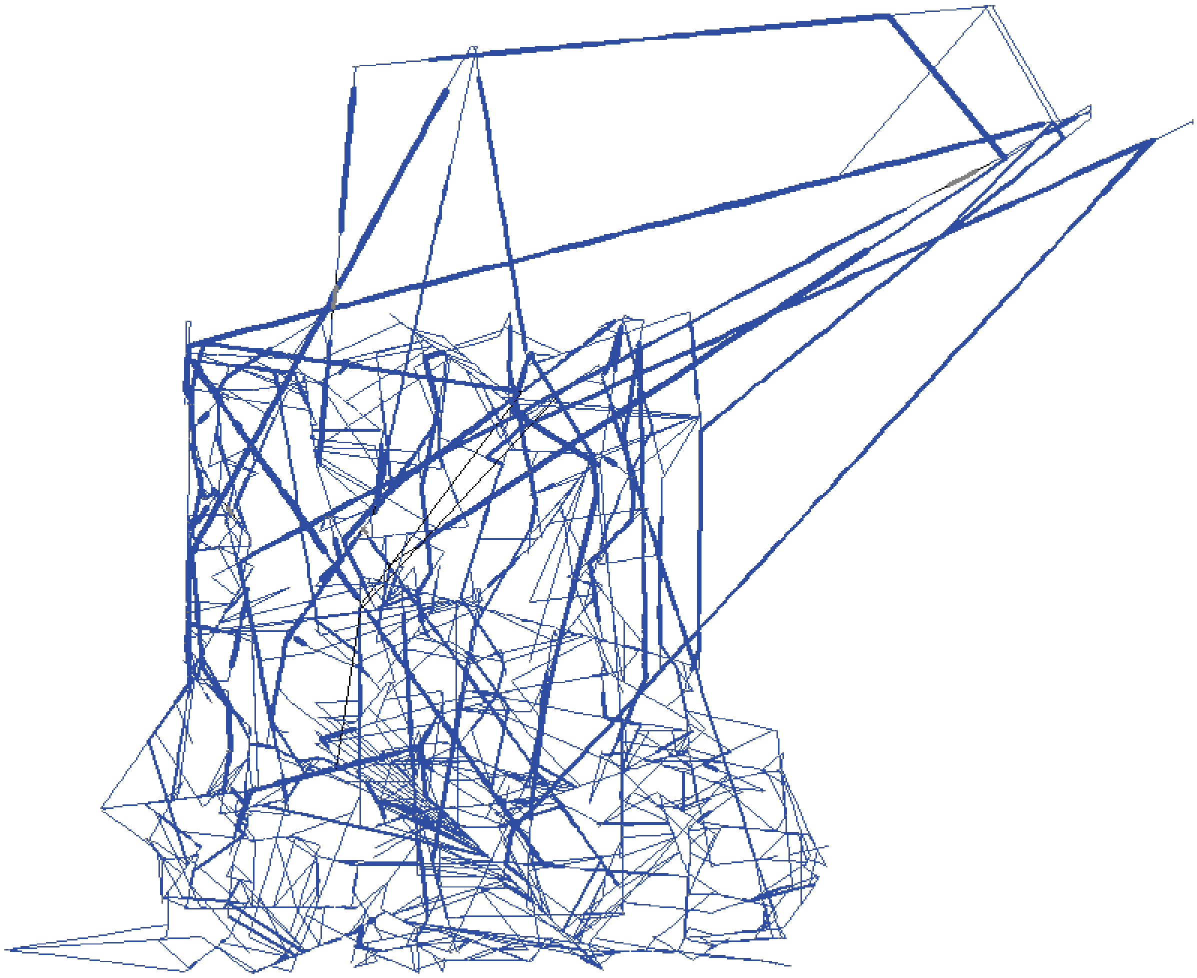

Figure 6-5
Current-Weighted Plot of OpenDSS Model Cable Segments

The model size in OpenDSS comprises 10,132 buses and 17,818 cable segments. Inherently the model is unbalanced three-phase, but OpenDSS simplifies it internally to a balanced positive sequence model, matching the PVL assumption. There are 552 transformers in the model, including four substation transformers, 16 transformers serving 10 high-tension (HTV) customers, and the remaining 532 are NXFRs. There are 2272 network load points (SNL), plus 10 more HTV load points.

In a base-case solution of the peak load at 0.85 power factor, the OpenDSS bus voltages range from 0.94585 to 1.0617 per-unit, with most of the variation coming at HTV load points. Con Edison does not model the HTV transformers and loads with as much accuracy, since the HTV customers are responsible for their own systems connected to Con Edison at 13.8 kV. The total active power at the substation is 290.822 MW, which includes 12.7522 MW in losses (4.39%).

Existing Load Levels

The substation monitoring data for 2007 shows a peak substation load of 308.3858 MW, including losses, which is higher than the 2007 peak planning load in the PVL model. The load factor is 62.2% over the whole year, which is relatively high. On peak days the load factors are higher than 62.2%, as shown in Figure 6-3. Figure 6-6 shows daily substation load profiles for the average hour (over the whole year), the peak hour (again, over the whole year), and for August 8, 2007, on which the peak load occurred.

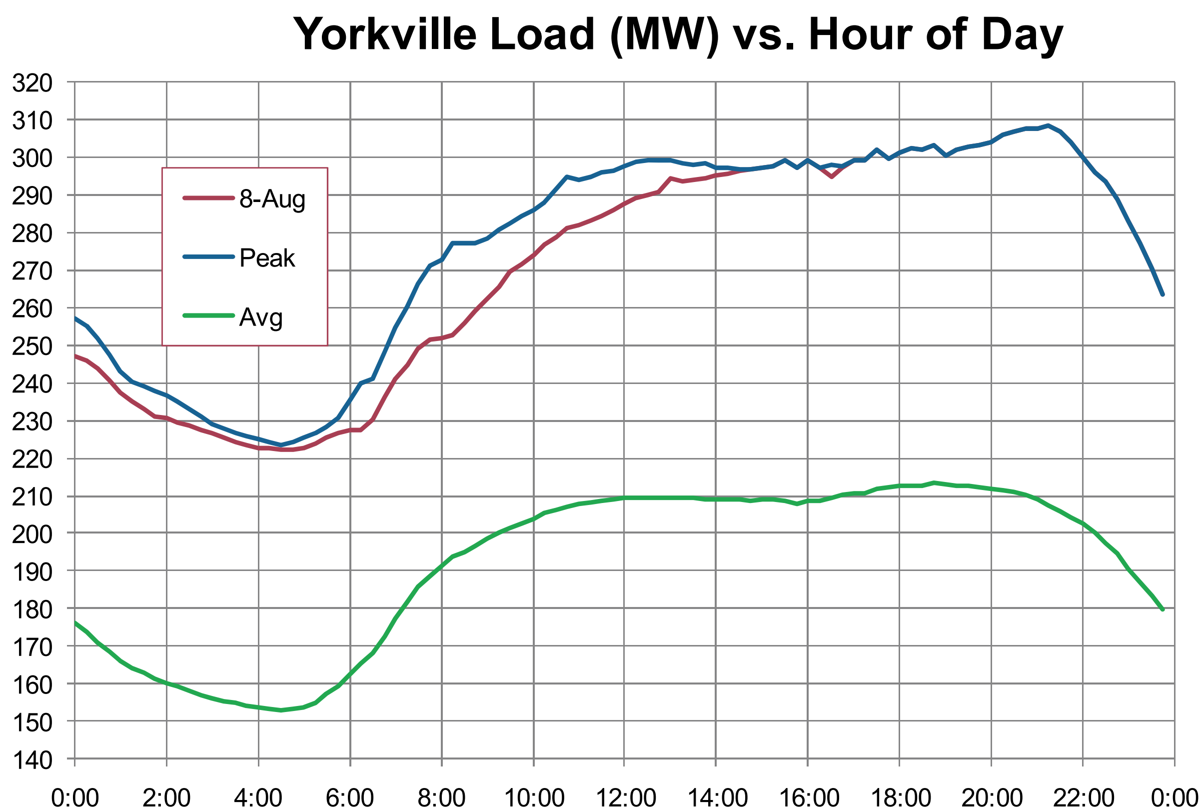

Figure 6-6
2007 Load Duration Curve for One Hellgate Substation Transformer

The peak load occurs around 9:00 PM, and the average load profile is relatively flat from around 9:00 PM to 10:00 PM. The two peak profiles take longer to build up to the flat portion, which begins from around 10:00 PM till noon. The blue and red curves differ because, for example, the peak load at 8:00 PM was 273 MW, on a different day than August 8th. For PEV evaluation, the blue curve is most important because it describes the maximum load in time periods to which charging might be shifted.

This area is mixed residential and commercial load, including multi-family residences, restaurants, schools, retail establishments, medical offices, and other offices. The HTV loads comprise about 42 MW, including several large transit rectifiers, two hospitals, Columbia University, Randall's Island, Ward Island, and the NY Post. The overlapping residential and commercial profiles may account for the relatively flat hourly load profiles, and the late-occurring peak loads.

Figure 2-6 does not include local impacts of new PEV load, but at the substation level, it seems that 8:00 AM to 10:00 AM offers the best window for widespread PEV charging on the peak days. Another window opens at 11:00 PM for overnight charging.

Model Validation

The OpenDSS solution was compared to the 2007 PVL base case solution at a load power factor of 0.85 (Note: the PVL contingency analysis is done at 0.88 power factor). Figure 6-7 shows the ratio of OpenDSS to PVL secondary bus voltage at each load point. This result was obtained after increasing the substation line drop compensator R and X settings by a factor of 1.73 to properly account for PT connections. Before that change, the OpenDSS voltages were uniformly low by approximately 2.3%.

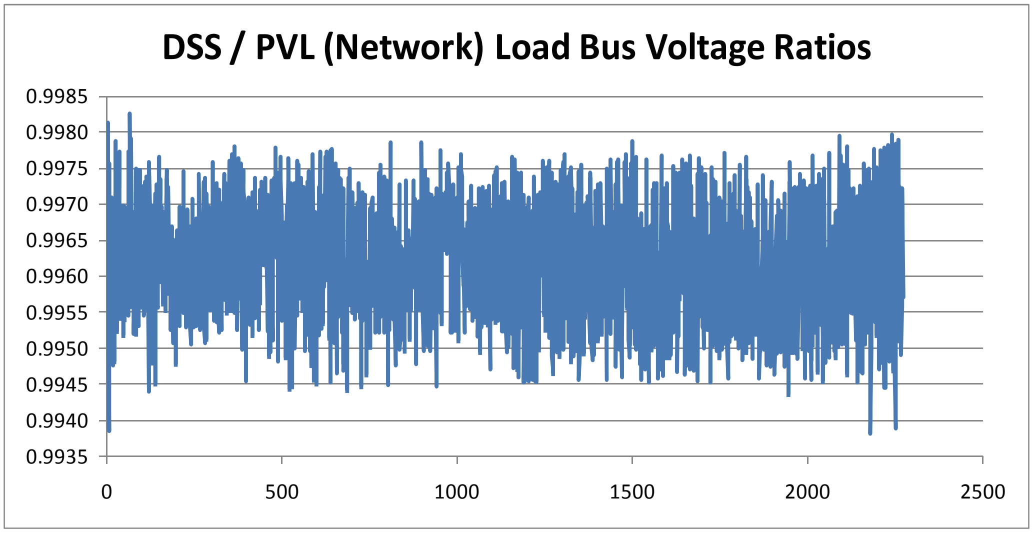

Figure 6-7
Ratio of OpenDSS to PVL Secondary Load Bus Voltages

Figure 6-8 shows the ratio of OpenDSS to PVL voltage magnitudes at the high-tension (HTV) customer load points. The outlier point is for Ward Island, which is a 19 MVA load served by four transformers. The PVL model does not include specific data on the customer-owned HTV transformers; it uses four 2500 kVA network transformers for the solution. This leads to a large voltage drop in the solution, due to the size of Ward Island's load compared to its transformers in the PVL model. Con Edison is not responsible for HTV customers beyond the primary feeder connection point.

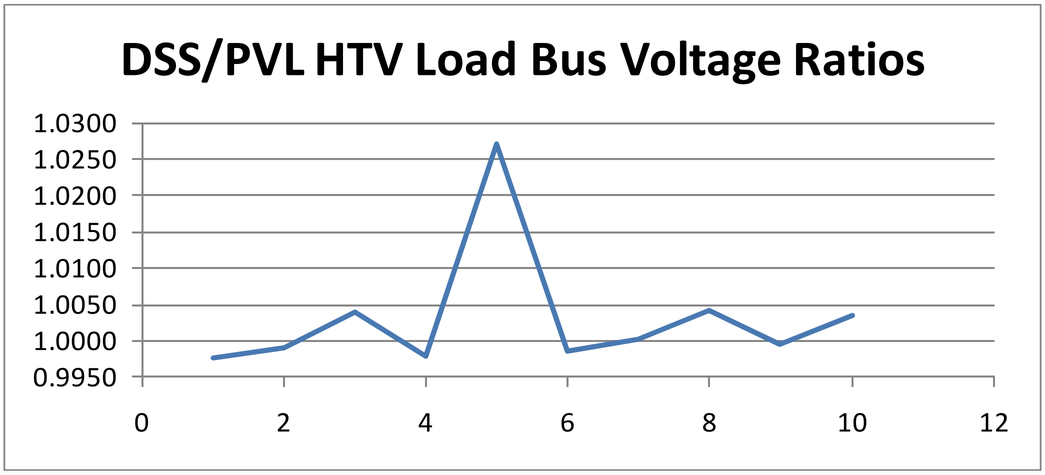

Figure 6-8
Ratio of OpenDSS to PVL HTV Load Bus Voltages

Figure 6-9 and Figure 6-10 compare the network transformer and primary feeder current flows in the OpenDSS and PVL solutions. In feeders served by the B syn buses (1B, 2B, 3B, 4B) the OpenDSS feeder currents are uniformly lower than the PVL currents. Conversely, the OpenDSS currents are uniformly higher than PVL for feeders served by the A buses. This may indicate that the PVL case actually used a different model of the substation transformers, referencing codes 1x, 2x, 3x, 4x, 1y, 2y, 3y, and 4y, which do not appear in the PVL standards files.

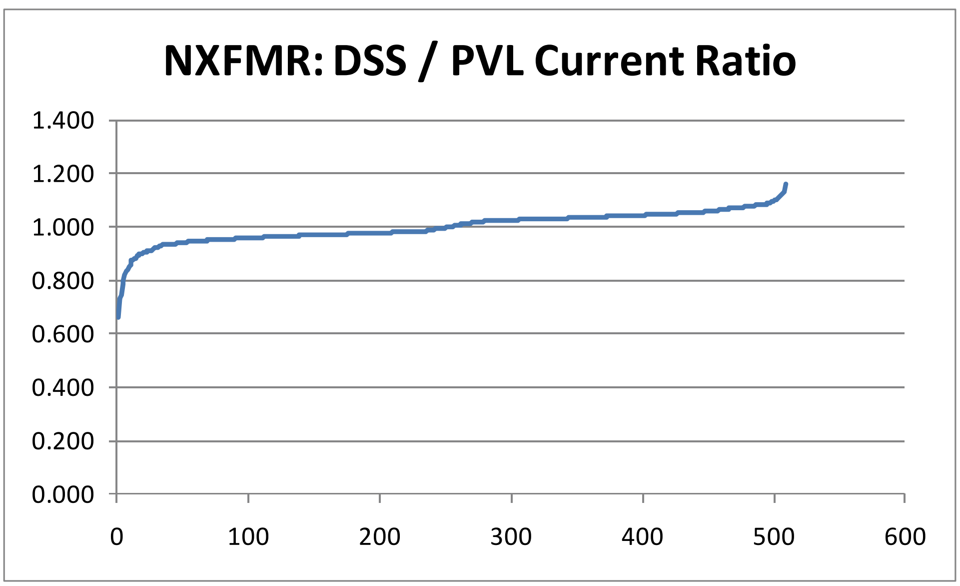

Figure 6-9
Ratio of OpenDSS to PVL Network Transformer Currents

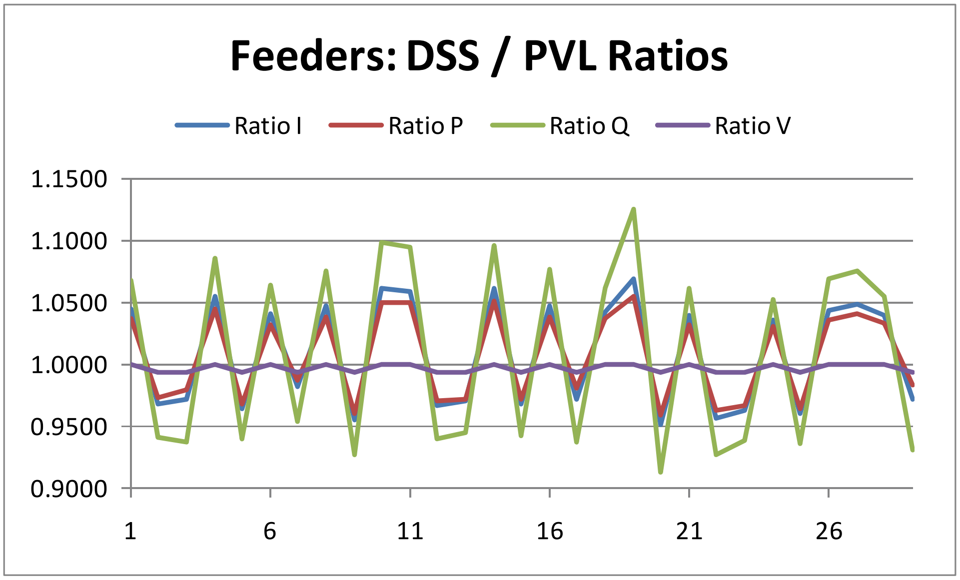

Figure 6-10
Ratio of OpenDSS to PVL Primary Feeder Voltage and Flow Quantities

Comparisons of the secondary cable flows have not been made. There is not a one-to-one correspondence between the number of cables in the OpenDSS and PVL model. There are two ways of aggregating cables in the PVL USN files:

1. Parallel sets, on different lines of the USN file – these are combined in both the OpenDSS and PVL models
2. Segments, on the same line of the USN file – these are combined only in the PVL solution

Based on manual comparisons, it is expected that correcting the primary feeder flow quantities in Figure 6-10 should lead to better agreement in Figure 6-9 and the secondary cable flows.

PEV Characteristics for Yorkville

This section covers the PEV charging load assumptions for the Yorkville Network. Unlike typical suburban areas, the Yorkville Network has very few single-family detached residences. Many residents do not own a car, using public transportation instead. In Manhattan, it is practical to completely avoid owning a car, and it is also fiscally responsible because it is very expensive to park and insure a car in Manhattan. A limited amount of on-street parking exists, but not with access to private vehicle chargers.

For this project, it was assumed that public parking garages and lots will provide the main opportunity for installing PEV chargers. People driving to Yorkville for work, shopping, or entertainment are generally forced to use these public garages and lots. Data on public parking location and capacity for Manhattan is available on the internet, and used in this project.

In addition, there may be some privately owned garages in condos or apartment buildings, but no data was available for them. They should follow a similar geographic distribution to the public parking facilities. Therefore, they should not skew the results after conversion to an equivalent number of vehicles.

Also, taxi companies and other commercial fleets may install their own PEV charging stations. Con Edison would address those locations the same way as any other significant spot load expansion. The PVL User Manual outlines a "Carve" procedure for extracting a customer service model to perform this analysis.

Load Characteristics

Figure 6-11 and Figure 6-12 show maps of two public parking facilities in the Yorkville network area, obtained from Google maps. The area consists of light commercial and residential loads in a dense mix. Most of the residences are in apartment buildings and condominiums, such as the building at the Northeast corner of Lexington and 83rd in Figure 6-12. Many of the commercial loads are there mainly to serve local residents. Other commercial loads, such as hospitals and medical offices, high-end restaurants, and specialty shops, will have people commuting from outside Yorkville. The area is well-served by subway lines and bus routes. On the other hand, driving a personal car within Yorkville can be unattractive due to traffic and parking conditions.

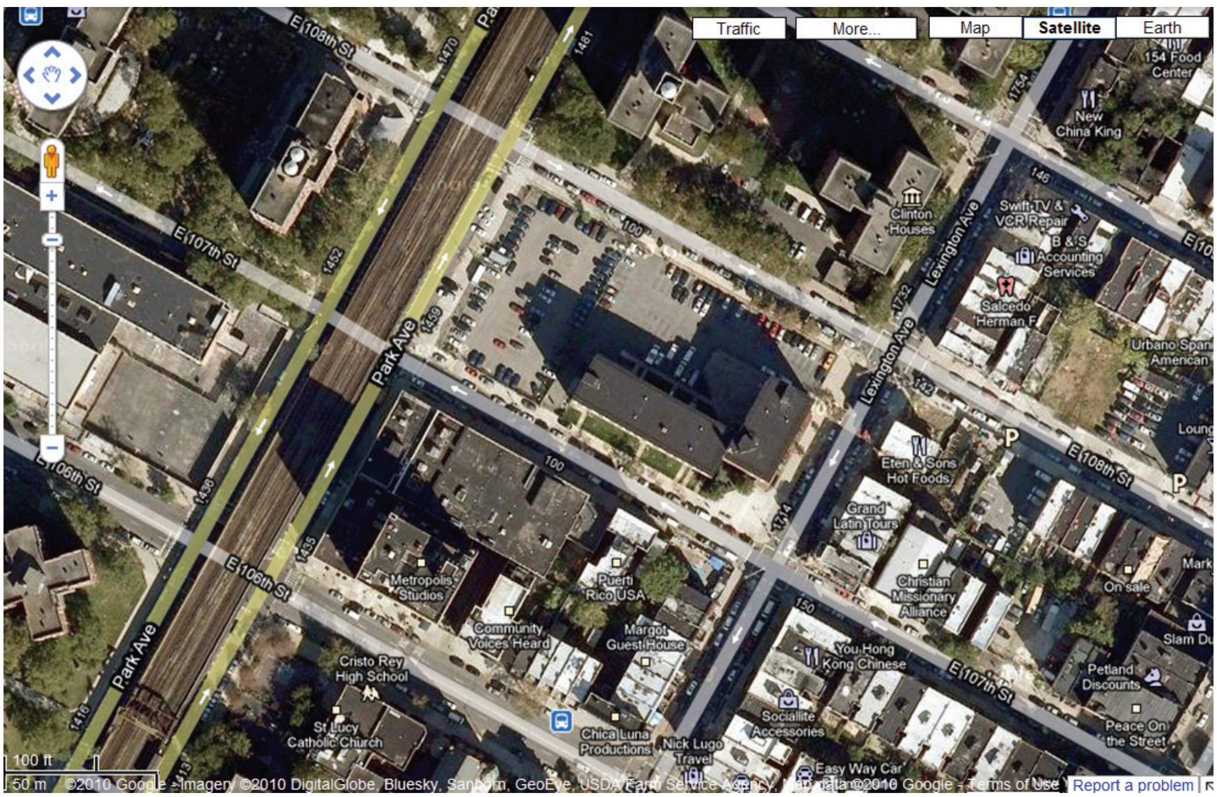

Figure 6-11
EZ Going South Parking, 128 East 107th Street

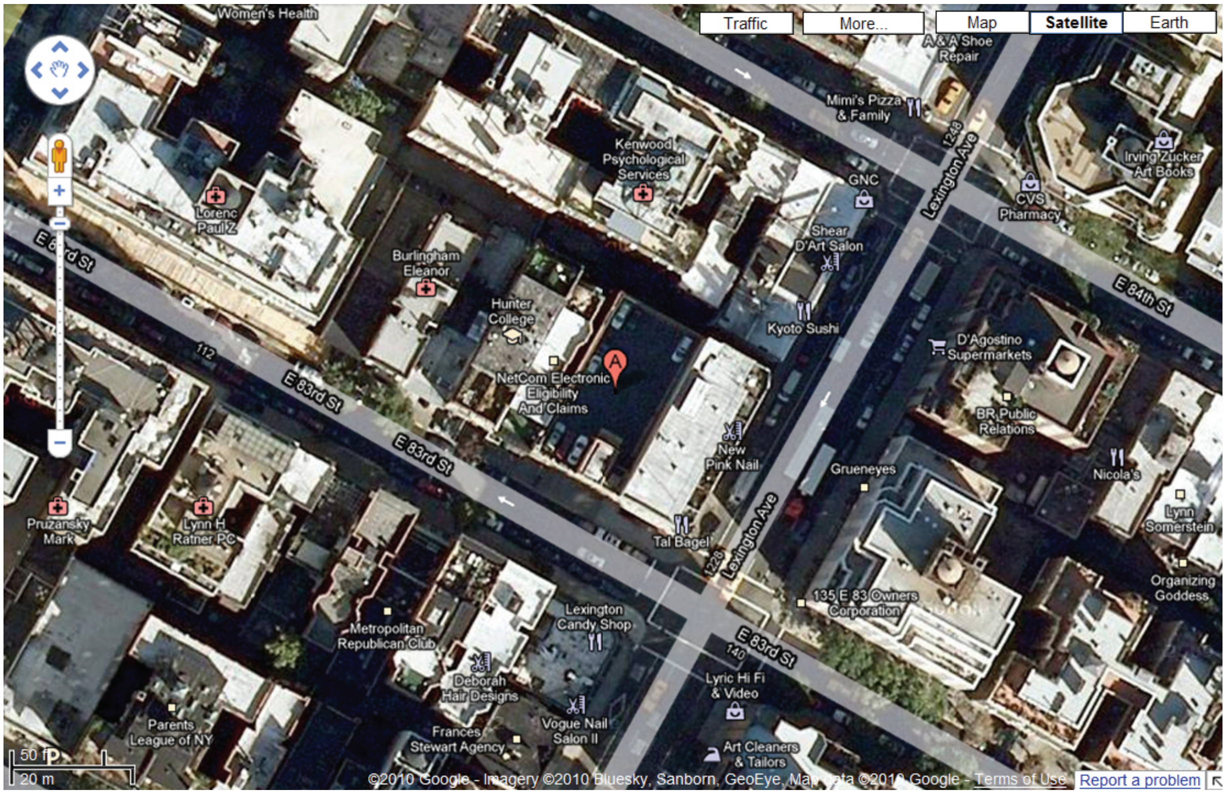

Figure 6-12
GMC Duford Studio Parking, 127 East 83rd Street

Commercial Garage Identification

PEV load points were identified from public parking facilities in the Yorkville area. Data sources for this process include:

- Municipal Parking Map:
  http://www.nyc.gov/html/dcp/html/parking/pidpindex.shtml
- Private Parking Map:
  http://nyc.bestparking.com/index.php#
- Con Edison Outage Map (illustrates network service areas):
  https://apps.coned.com/WebOutageInfo/Outage_Info/OutageInfoMap.aspx?OM_MapType=80&OM_ZipCode=#
- Cross Street Estimates:
  http://www.thenewyorkseason.com/Manhattanstreetlocator.htm

Table 6-3 lists public parking facilities that were found on the two maps listed above. The number of parking spaces (capacity) was published for all but one facility, GMC Embassy at 121 E 80th Street. For that facility, ***148*** spaces were estimated from the average of all other facilities in Table 6-3.

The garage locations were then matched, approximately, to existing load points in the PVL model. The primary source for this matching was a file of Yorkville services, containing addresses and load points. The column labeled “Load” has the best matched load point for each garage. The remaining columns labeled “Bus”, “Load kVA”, and “Load kV” describe the existing load at that point. All of these loads are served at 208 volts (216 volt base in the PVL model). The Load kVA is the existing peak demand at the given Bus. Two further notes on the matching process:

- Some of the facilities on or near the Yorkville boundary are not actually served by the Yorkville network. These **addresses** are highlighted in red.
- Some of the facilities could not be matched closely with an existing load. These ***load points*** are in bold italics. Usually, this happens when the nearest geographic load point is on the wrong side of the street from the parking facility, and the nearest load on the correct side of the street is more than one block away. Some attempts were made to identify a nearby cross-street or cross-avenue address. It is also possible that some facilities are served from the street behind.

There are 16,171 parking spaces listed in Table 6-3, and 15,619 of those are matched with existing load points. Assuming 0.72 kW average peak hour demand per vehicle, the peak PEV load would increase to a total of 11.2457 MW.

The Excel spreadsheet *ConEd_PHEV.xlsm* is used to write a file of PEV loads, matched to the nearest PVL secondary buses, in a file called *phev_load.dss*. This file is included by *Yorkville_PHEV.dss*. The spreadsheet *PVL_Contingencies.xlsm* then runs all N-0, N-1, and N-2 contingencies for the Yorkville network at different levels of system and PEV load.

Table 6-3
Public Parking Garages and PEV Nominal Charging Loads in Yorkville

Owner	Address	Capacity	Load	Bus	Load kVA	Load kV
GGMC	19 E 111	36		#N/A	#N/A	#N/A
Icon Merit	12-14 E 107	1000	***17869***	46I__17869	106.3	0.216
EZ Going South	128 E 108	228	***18014***	47J__18014	11.9	0.216
Icon East 105	156 E 105	89	17651	46J__17651	15.5	0.216
Glenwood Hampton Court	334 E 103	155	M17440	45K__M17440	20.8	0.216
Parking Guys 99 PM	1559-1563 Lex	80	39060	44J__39060	11.4	0.216
Central Parking (Mt. Sinai)	86 E 99	400	BC6534	42I__BC6534	613.8	0.216
Imperial 1955 1st	480 E 101	109	BC8504	45L__BC8504	306.1	0.216
Imperial Lexington	150 E 97	150	16759	43J__16759	29.8	0.216
Imperial East 97th	174 E 97	209	***16764***	43J__16764	16.9	0.216
MPG MP 97	266 E 97	416	***16775***	43K__16775	20	0.216
MPG Metropolitan Storage	385 E 97	95	***16775***	43K__16775	20	0.216
MPG Metropolitan Storage	1918 1st	233	M57204	44K__M57204	0.6	0.216
Rapid Park 334	302-04 E 96	90	16674	43K__16674	2.6	0.216
Icon 215 E 95	201-239 E 95	320	16550	43J__16550	15.2	0.216
Icon Gallant	182 E 95	112	16544	43J__16544	16	0.216
Imperial East River	1831 1st	36	53650	42K__53650	11.8	0.216
Park-It 9495	1832 2nd	180	***54827***	43K__54827	394.2	0.216
GMC Yorkville	231 E 94	390	16425	42J__16425	22.6	0.216
Ulltra Majestic	115 E 94	74	BC7181	42I__BC7181	418.8	0.216
GGMC Carnegie	40-60 E 94	110	M16397	42I__M16397	40.6	0.216
Rapid Park Rockmill	340 E 94	124	BC28	42K__BC28	901	0.216
Central Parking	246 E 94	112	***M16426***	42K__M16426	42.4	0.216
Imperial Carnegie	200 E 94	90	BC1172	42J__BC1172	1018.9	0.216
GMC Plymouth Tower	340 E 93	146	16309	42K__16309	59.9	0.216
Glenwood Brittany Realty	441 E 92	137	BC1738	42L__BC1738	406.9	0.216
Glenwood Barclay Realty	480 E 92	150	***BC1738***	42L__BC1738	406.9	0.216
GGMC Plaza	280 E 92	104	***16149***	42J__16149	45.4	0.216
GGMC 92nd Street	230 E 92	301	***16149***	42J__16149	45.4	0.216
David Garage - Eli's Leasing	422 E 91	135	16048	41L__16048	8.6	0.216
Glenwood Hamilton Realty	479 E 90	92	***15914***	41L__15914	49	0.216
Hertz E 90	412 E 90	150	15917	41L__15917	31.8	0.216
Impark 90 HSW	400 E 90	31	M53619	41K__M53619	338.8	0.216
Champion Ability	590 E 90	41	***15921***	41L__15921	35	0.216
GGMC Knickerbocker	251 E 90	220	***15900***	41K__15900	17.9	0.216
GGMC 200 E 90	200 E 90	109	15896	41J__15896	15.6	0.216
Sylvan Madison	60-72 E 90	268	15876	41I__15876	164.5	0.216
Impark 89	40 E 89	43	BC4286	41I__BC4286	203.5	0.216
GMC Park Regis	50 E 89	153	BC9210	41I__BC9210	512.1	0.216

Owner	Address	Capacity	Load	Bus	Load kVA	Load kV
Icon Royal 89	200-210 E 89	70	BC9839	41J__BC9839	511.8	0.216
Imperial Gracie	401 E 89	114	BC5210	41K__BC5210	419	0.216
Glenwood Andover Realty	480 E 89	136	***M57371***	41L__M57371	54.3	0.216
Icon 1725	475 E 89	104	***M57371***	41L__M57371	54.3	0.216
Waterview	590 E 89	115	15795	41L__15795	20	0.216
Icon Mansion 88	580 E 88	35	***15655***	40L__15655	20.3	0.216
Quik Park East 87	1664 York	66	15480	40L__15480	489	0.216
Central Parking	200-206 E 88	218	15618	40J__15618	46.1	0.216
Icon Swift	1305 Lexington	36	M38984	40J__M38984	75.7	0.216
Icon 1056 Fifth Avenue	10 E 87	55	15420	40I__15420	84	0.216
Rapid Park East 87th	55 E 87	57	15421	40I__15421	300	0.216
1065 Garage	105 E 87	30	15429	40I__15429	20.6	0.216
Central Parking	115 E 87	198	15429	40I__15429	20.6	0.216
PAC Garage	120 E 87	150	15442	40J__15442	163.2	0.216
Central Parking (Meyers)	154 E 87	515	15442	40J__15442	163.2	0.216
Champion SCR	169 E 87	175	15439	40J__15439	44.3	0.216
Imperial 525-535	535 E 86	40	BC5146	40L__BC5146	435.7	0.216
Central Parking	1623 York	126	M48665	40L__M48665	182.4	0.216
GMC Fairmont	401 E 86	46	BC6390	40K__BC6390	482	0.216
Safeway	345 E 86	56	15285	40K__15285	280	0.216
Icon 305 East 86th	305 E 86	168	***15289***	40K__15289	44	0.216
Icon Newbury	249-257 E 86	146	15272	40K__15272	187.9	0.216
GMC Savoy	118 E 86	184	15256	40I__15256	140.1	0.216
1050 Garage	15 E 86	49	M15232	40I__M15232	380.4	0.216
Croyden	15 E 85	72	15069	40H__15069	41.5	0.216
Icon Alert	30 E 85	43	M15074	39I__M15074	650.1	0.216
Imperial Millenium	35 E 85	72	BC4692	40I__BC4692	193.6	0.216
Central Parking	185 E 85	320	BC5898	40J__BC5898	976.4	0.216
Champion Parking 85	234 E 85	280	M15116	39J__M15116	129.2	0.216
Imperial 400	400 E 85	80	BC5258	39K__BC5258	379	0.216
Glenwood Cambridge Realty	500 E 85	77	15150	39L__15150	75.7	0.216
Imperial 110	570 E 85	40	M31658	39M__M31658	234.7	0.216
Impark 83	611 E 83	91	BC3460	39M__BC3460	100	0.216
GMC 80 East End	585 E 83	35	BC3460	39M__BC3460	100	0.216
Central Parking	450 E 83	44	***M48637***	39L__M48637	707.9	0.216
MPG Hope	415 E 83	63	14791	39L__14791	39.1	0.216
Rapid Park 83rd Street	351-353 E 83	138	M53557	39K__M53557	345.5	0.216
GMC Adams Tower	351 E 84	92	14953	39K__14953	8.8	0.216
Champion Parking 83rd Street	303 E 83	115	M60317	39K__M60317	450	0.216
GMC Evans Tower	167 E 84	75	M14928	39J__M14928	260	0.216
GMC Duford Studio	127 E 83	200	14745	39J__14745	50.9	0.216
GMC Gelmont	113 E 84	125	14917	39I__14917	7.4	0.216

Owner	Address	Capacity	Load	Bus	Load kVA	Load kV
Imperial 1025 Fifth Avenue	25 E 83	95	BC1451	39I__BC1451	379	0.216
GMC Vicmar	8 E 83	48	14732	39I__14732	238.5	0.216
GMC Wayne (Chapland)	111 E 82	143	14591	39I__14591	11.2	0.216
ELCO Welcome	240 E 82	48	BC5418	38K__BC5418	150.4	0.216
Glenwood Marlowe Realty	145 E 81	22	M38944	38J__M38944	211.1	0.216
Quik Park East 82nd Street	350 E 82	53	***14627***	39K__14627	30.1	0.216
Standard Parking	585 E 82	120	***BC451***	39M__BC451	318.6	0.216
GMC Mutual	605 E 82	132	BC451	39M__BC451	318.6	0.216
Imperial Intertown	55 East End Ave	110	***31635***	38M__31635	90.1	0.216
Central Parking	45 East End Ave	77	***31635***	38M__31635	90.1	0.216
Imperial 30	30 East End Ave	51	31634	38M__31634	108.1	0.216
MPG East 80	525 E 80	52	14353	38L__14353	289.1	0.216
Waterview	540 E 80	60	BC4477	38M__BC4477	266.9	0.216
Icon Superior	515 E 79	125	BC4544	38L__BC4544	436.3	0.216
East 79th Street Parking	505 E 79	57	BC5514	38L__BC5514	254.3	0.216
Ulltra Emerald	510 E 80	31	M14357	38L__M14357	234.5	0.216
Bricin	511 E 80	50	14351	38L__14351	38.1	0.216
Glenwood Caldwell Realty	1514-1520 York	100	BC9113	38L__BC9113	351.9	0.216
Double Garage	495 E 81	114	***14500***	38L__14500	33.9	0.216
Quik Park Chesapeake	400 E 81	129	***14489***	38L__14489	35.5	0.216
Cross Garage	445 E 80	72	14343	38L__14343	50.8	0.216
Icon Instant	434 E 80	49	***14343***	38L__14343	50.8	0.216
Ulltra Express	425 E 79	99	BC4060	38L__BC4060	221.8	0.216
Rapid Park 79th Street	474 E 78	130	***14089***	37L__14089	11.6	0.216
Parking Guys 78 PM	415 E 78	73	14080	37L__14080	36.7	0.216
Surrey Garage	439 E 77	96		#N/A	#N/A	#N/A
Impark HSW	300 E 77	28		#N/A	#N/A	#N/A
70th Street Realty	350 E 79	83	BC152	38K__BC152	1169.8	0.216
GMC Continental Towers	301 E 79	225	BC9197	38K__BC9197	932.3	0.216
Central Parking	340 E 80	88	BC6143	38K__BC6143	366.7	0.216
Imperial 345 East	345 E 80	129	14330	38K__14330	53.9	0.216
GMC Sterling	305 E 80	233	14327	38K__14327	27.2	0.216
Alliance 345 East 81st Street	345 E 81	53	BC8383	38K__BC8383	381.5	0.216
Champion Lenox	176 E 77	79		#N/A	#N/A	#N/A
Rapid Park 165	165 E 77	200		#N/A	#N/A	#N/A
Impark HSW	180 E 78	31	14048	37J__14048	66.4	0.216
MPG Manhattan	286 E 80	42	M54679	38K__M54679	50.6	0.216
Central Parking	204 E 80	67	***BC295***	38J__BC295	475.6	0.216
Zeta Parking	213 E 80	51	14321	38J__14321	190.5	0.216
Champion Parking 77th Street	51 E 77	113		#N/A	#N/A	#N/A
GGMC Continental	50 E 79	48	BC4635	38I__BC4635	443.5	0.216
GMC Embassy	121 E 80	***148***	14294	38I__14294	35.9	0.216

Owner	Address	Capacity	Load	Bus	Load kVA	Load kV
Rapid Park 920	95 E 80	27	14287	38I__14287	90.4	0.216
Icon 79th Street	90 E 80	61	14285	38I__14285	117.1	0.216
980 Fifth Avenue	5 E 79	100	14150	38H__14150	208.8	0.216
Central Parking	1000 Fifth	460	BC6180	39H__BC6180	2073.8	0.216

PEV Charging Assumptions

PEV hourly demand will inherently vary given different vehicular designs and consumer driving behaviors. In order to incorporate PEV load diversity within the N-2 planning structure, a deterministic model of the aggregate PEV demand is assumed. In this analysis, all PEV chargers are conservatively assumed to operate at the charging load of 7.2 kW (240 Volts 30 Amp connection). Lastly, the temporal diversity associated with the PEV load is incorporated via a nominal aggregate charging load of about 10% of the total connected demand, or 720 Watts per vehicle. Hence in the following analyses, the total PEV demand at each secondary load bus in Table 6-3 is determined simply by scaling the parking garage capacity by the percent of electric vehicles and the nominal 0.72 kW value.

It is important to note that the nominal demand per vehicle value conservatively represents the aggregated mean demand. In other words, the equivalent number of electric vehicles required to achieve the same level of demand as used in the model can be potentially larger than indicated. To illustrate, the projected mean demands per vehicle in New York is only about 600 watts per vehicle, see Figure 4-4. Therefore, evaluation of the results must consider the equivalent percentage of PEV penetration in light of less-than-nominal aggregate charging load. For example, 15% may be the maximum “PEV level” that can be accommodated with little impact on Con Edison’s distribution system. This is based on 15,619 public parking spaces in Yorkville, which might have PEV chargers. Taking 600 Watts as the actual nominal charging load, the equivalent number of PEV at this 15% level is:

$$PHEV = 15619\left(0.15\right)\left(\frac{720}{600}\right) = 2811$$

That figure represents 18% of the public parking spaces in Yorkville. Taking into account the percentage of vehicles associated with either workplace or shopping charging profiles, as shown in Figure 3-3, would lead to even higher parking space penetration levels; as would evaluations for hours when the aggregate demand is typically lower.

PEV Evaluations

This section presents results of the PEV evaluation for Yorkville.

Resolving Base Case Overloads

Both PVL and OpenDSS results show that the Yorkville network is already very near its capacity, even by N-0 criteria. The PVL results for N-0, at 0.85 power factor, show:

- 20 secondary bus voltages below 118 volts
- NXFR 44I_V4747 at 179% of normal rating
- NXFR 44I_V5114 at 160% of normal rating
- Two other NXFR (43I_V8324 and 39K_V6308) at 103 to 106% of normal rating

The OpenDSS base case for N-0 also shows V4747 and V5114 significantly overloaded. To clear NXFR overloads in the N-0 base case, two rating changes were made to the OpenDSS model:

- V4747 increased from1000 kVA to 1850 kVA
- V5114 increased from 1000 kVA to 1600 kVA

In addition, the customer-owned HTV transformers at Ward Island were increased from 5000 kVA to 6000 kVA. These transformers are also overloaded in the PVL solution, but Con Edison does not include them in the NXFR overload reports.

Additional changes were made to the OpenDSS model to remove all N-1 and N-2 overloads:

- V5114 increased (further) from 1600 kVA to 1675 kVA
- TM2459 increased from 500 kVA to 590 kVA
- V8987 increased from 1000 kVA to 1060 kVA
- V4995 increased from 1000 kVA to 1060 kVA
- V5950 increased from 1000 kVA to 1025 kVA
- V9239 increased from 1000 kVA to 1010 kVA
- V1441 increased from 1000 kVA to 1025 kVA
- Vs3365 increased from 1000 kVA to 1050 kVA
- TM3785 increased from 500 kVA to 505 kVA
- V6308 increased from 1000 kVA to 1060 kVA
- V8324 increased from 1000 kVA to 1050 kVA
- V5773 increased from 1000 kVA to 1025 kVA
- TM3847 increased from 500 kVA to 550 kVA
- V1164 increased from 1000 kVA to 520 kVA
- V3534 increased from 1000 kVA to 1130 kVA
- V7293 increased from 1000 kVA to 1075 kVA
- V398 increased from 1000 kVA to 1125 kVA

- V1451 increased from 500 kVA to 560 kVA
- VS2398 increased from 1000 kVA to 1050 kVA

These rating increases for N-1 and N-2 are relatively small, except for the two transformers V4747 and V5114 that are significantly overloaded in both the PVL and OpenDSS base cases for N-0. No overloaded primary feeder cables (NF) were found in either the PVL or OpenDSS solutions. With these changes to NXFR ratings, the PEV evaluations start with a "clean slate".

PEV Simulation Results

The analysis is based on load flow simulation at 60%, 70%, 80%, 90%, and 100% of the 2007 system peak planning load of 278 MW. At each of these existing load levels, the PEV level is increased from 0% to 100% of 11.3 MW, in steps of 5%. Evaluating the impacts at various combinations of base and PEV load is performed to quantify impacts not only at the peak hour but at other points in time. For example, the majority of workplace charging is projected to occur at 8 am, Figure 4-2 when the base load maxes out at 90% of the overall system peak, Figure 6-6.

Figure 6-13 shows the total Yorkville network load with no contingencies (N-0), and not including losses, during this process. Each of the total load curves increases by approximately 11 MW moving from left to right. There are 100 system and PEV load level points plotted in Figure 6-13.

Figure 6-14 shows the loss factor, defined as losses / customer load, increasing as either the system or PEV load increases. This is due to increasing I^2R losses, which dominate the no-load losses. This result is for a snapshot load flow solution. If simulating a whole year's load profile and it is possible to shift PEV charging into non-peak times, then the loss factor (defined as loss energy / load energy) may decrease. In other words, PEV loads may increase the system load factor, which is already high in Yorkville.

There are 29 primary feeders in Yorkville. The N-1 contingencies involve 29 simulations, with each feeder taken out of service one at a time, and then switched back in. The N-2 contingencies involve 406 combinations of two feeders out of service. Therefore, each of the 100 system and PEV load level points is evaluated over 436 contingency simulations.

During the simulation, both capacitor and tap changer controls are active in the Hellgate substation. These control operations will cause step changes in current and voltage in the network, as the loads change. The simulations in this report were done by switching the system into a particular N-0 / N-1 / N-2 configuration, then solving for a system load level of 60% to 100%, and then finally increasing the PEV load level in steps. By this method, the plotted quantities exhibit a monotonic behavior with respect to the PEV level, which helps to clarify interpretation of the plots. It should be noted that in real life, the system will begin at a particular system and PEV load level, and then switch in and out of each contingency. The controls respond to the contingencies in a slightly different way, depending on a starting point. By this method, the plots (in Figures 4-3 and later) are not monotonic with PEV load level. They do lie within control bandwidths or hysteresis, but the visual interpretation is not as clear.

Figure 6-15 through Figure 6-17 show the number of NXFR overloads encountered as the PEV level increases from 5% to 100%, using N-0, N-1, and N-2 criteria. At 0% PEV, there are no overloads. With 5% PEV under N-0 and 100% system load, there is 1 NXFR overload (Figure

6-15). To put that in better context, see Figure 6-18, which shows the worst NXFR overload vs. PEV level for N-0. It is just barely over 100% of normal rating. As the PEV level increases to 15% or 20% in Figure 6-15, there are 5 NXFR overloads, which is about 1% of the total number of NXFR in Yorkville. In Figure 6-16, there are no NXFR overloads under N-1 until the PEV level reaches 20%. Under N-2 criteria in Figure 6-17, the NXFR overloads appear at a PEV level of 5%, but in Figure 6-20, those overloads are again barely over 100% of the N-2 rating, which is 140% of the normal rating.

Considering NXFR overloads as presented in Figure 6-15 to Figure 6-20, at 100% system load approximately 15% PEV level can be accommodated without widespread system upgrades. As illustrated in the previous section, this represents about 2,800 vehicles. Although a few NXFR overloads do occur at lower PEV levels, they are all within 101% of the appropriate rating and would not be critical. That is well within the uncertainty of PEV modeling assumptions and geographic allocations, the distribution of existing loads, the match between PVL and OpenDSS models, etc.

At a 90% system load, there are no NXFR overloads appearing until the PEV level exceeds 50%, which would correspond to about 9,350 vehicles under charging assumptions outlined in the previous chapter. Therefore, if PEV charging can be controlled to avoid the times of system peak load, then many more vehicles can be accommodated.

Figure 6-21 through Figure 6-23 show the minimum secondary load voltage, not including those with PEV, under N-0, N-1, and N-2 conditions. At 100% of the system peak and PEV levels of 0% or 5%, the system is already at the minimum allowed 118 volts for N-0. Under N-1 conditions in Figure 6-22, the minimum voltage is below the minimum allowed 116 volts. Under N-2 conditions in Figure 6-23, the minimum voltage is always above the minimum allowed 111 volts. At lower system load levels, the voltages are comfortably above the voltage limits.

The voltage criteria used in Figure 6-21 through Figure 6-23 come from the PVL case reports. The N-1 voltages do not violate the 114-volt level allowed in Con Edison’s EO-2065. For that reason, low-voltage conditions are not considered as a limiting factor in PEV level. Figure 6-24 and Figure 6-25 show the amount of system load (called “unserved load”) that is affected by low voltage, according to the PVL thresholds. For N-1, the unserved load is about 1.3 MW, which is about 0.5% of the total system load.

Figure 6-26 through Figure 6-28 show the minimum PEV load voltage for N-0, N-1, and N-2 conditions. These voltages are higher than the non-PEV minimum load voltages, and no violations of the PVL thresholds occur. In the plot for 100% system load at N-2, Figure 6-28, not the step up in minimum voltage as the PEV level increases from 35% to 40%. This is an example of a tap-change operation in Hellgate substation, under LDC control. The substation capacitor banks are already fully on at this load level.

In summary, low voltage conditions are not expected to be a limiting factor in any contingency or loading combination; nor are significant increases to losses. The only limiting factor of note is the potential overloading of about 5% of network transformers given a 15% PEV level. As noted before, this level of PEV equates to almost three thousand electric vehicles being served on the Yorkville circuit alone.

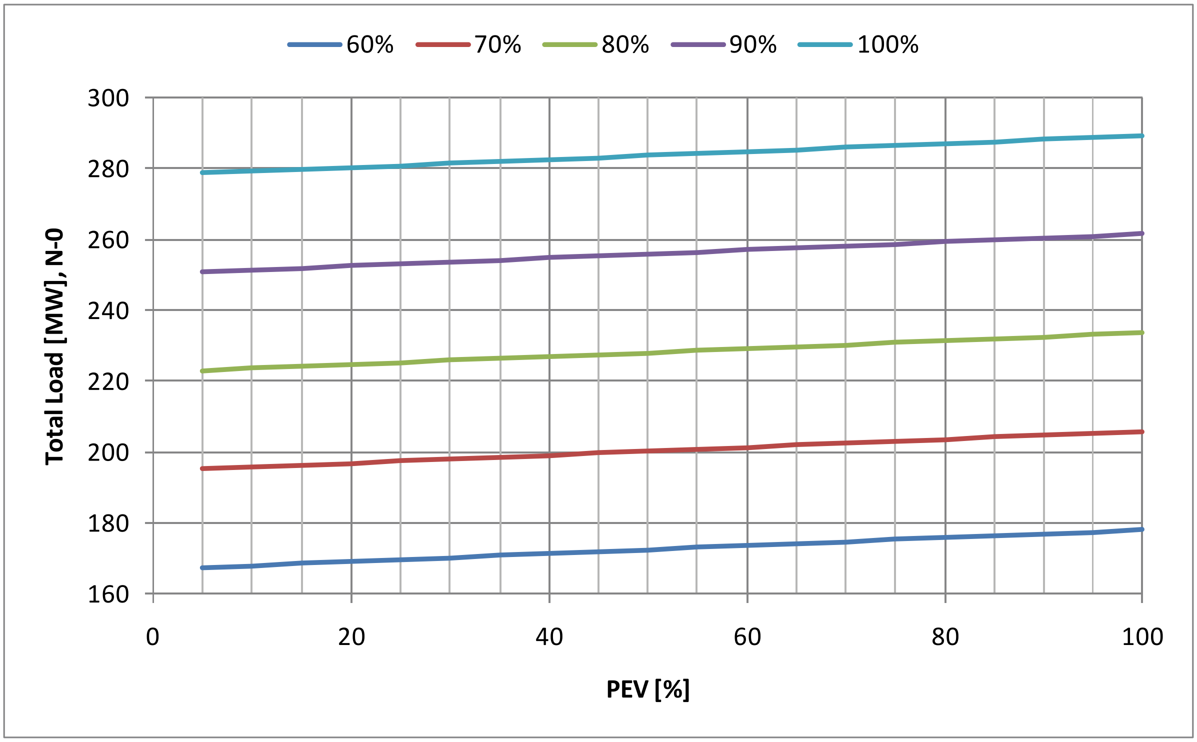

Figure 6-13
Total Load [MW], N-0

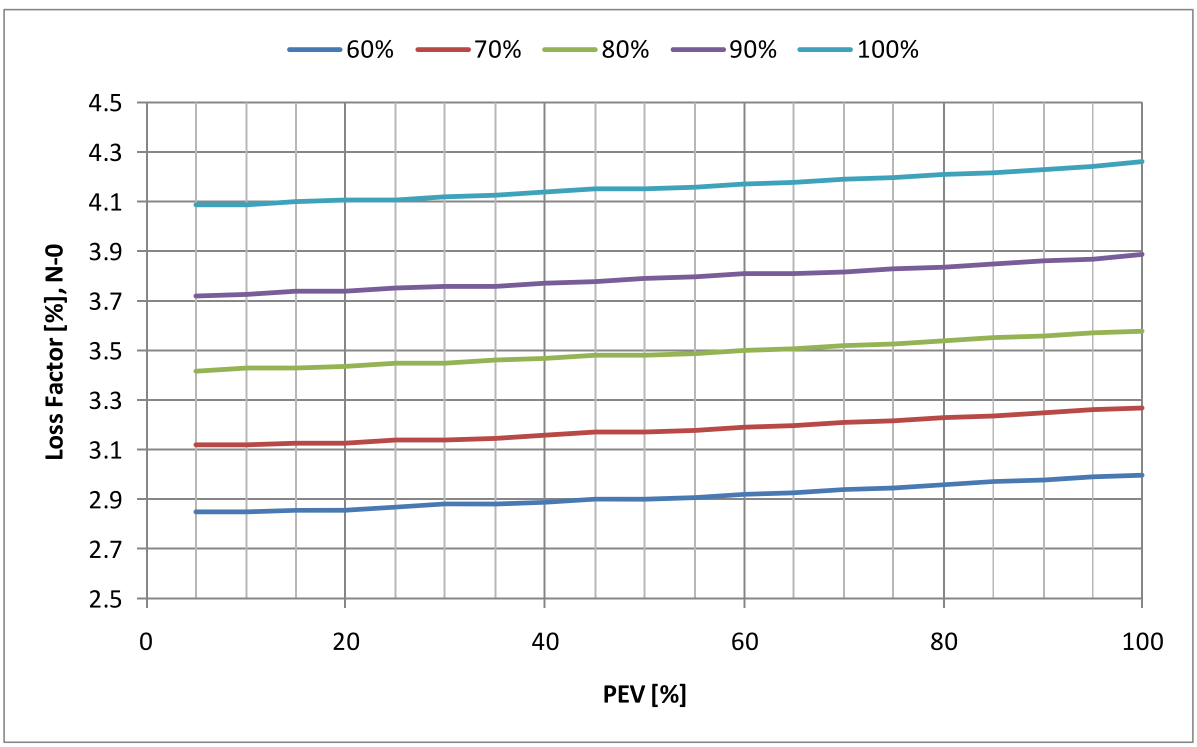

Figure 6-14
Loss Factor [%], N-0

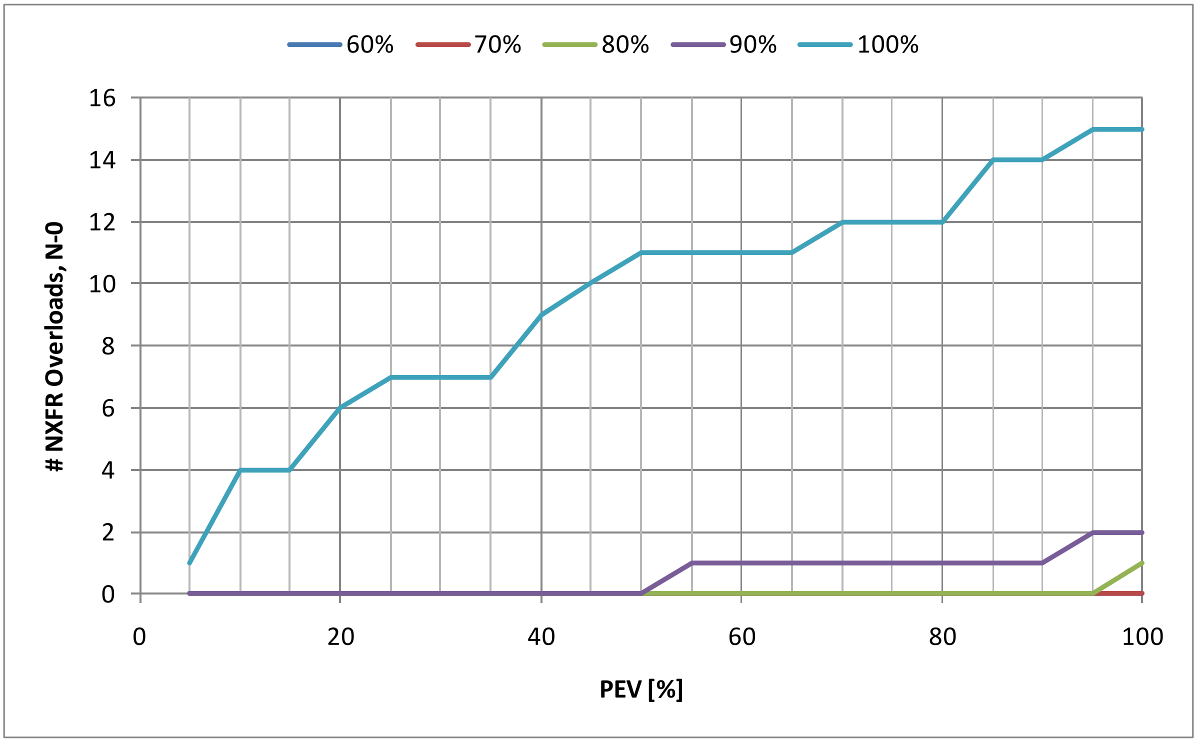

Figure 6-15
Number of NXFR Overloads, N-0

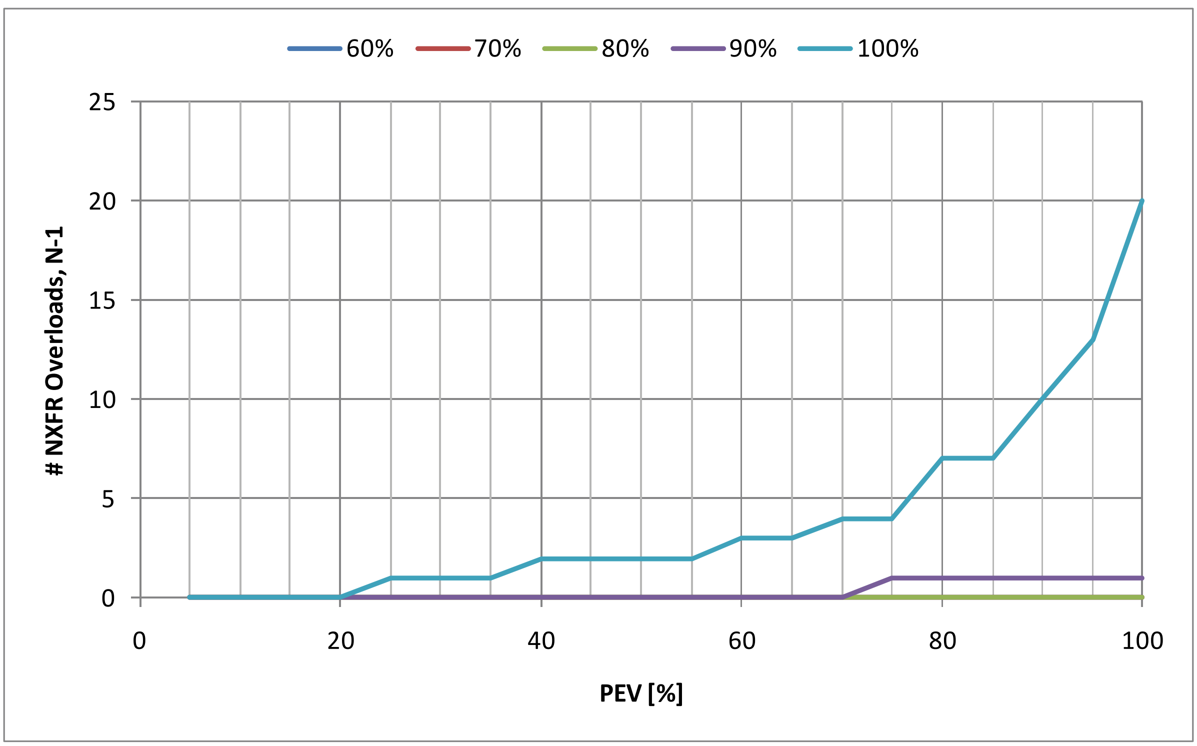

Figure 6-16
Number of NXFR Overloads, N-1

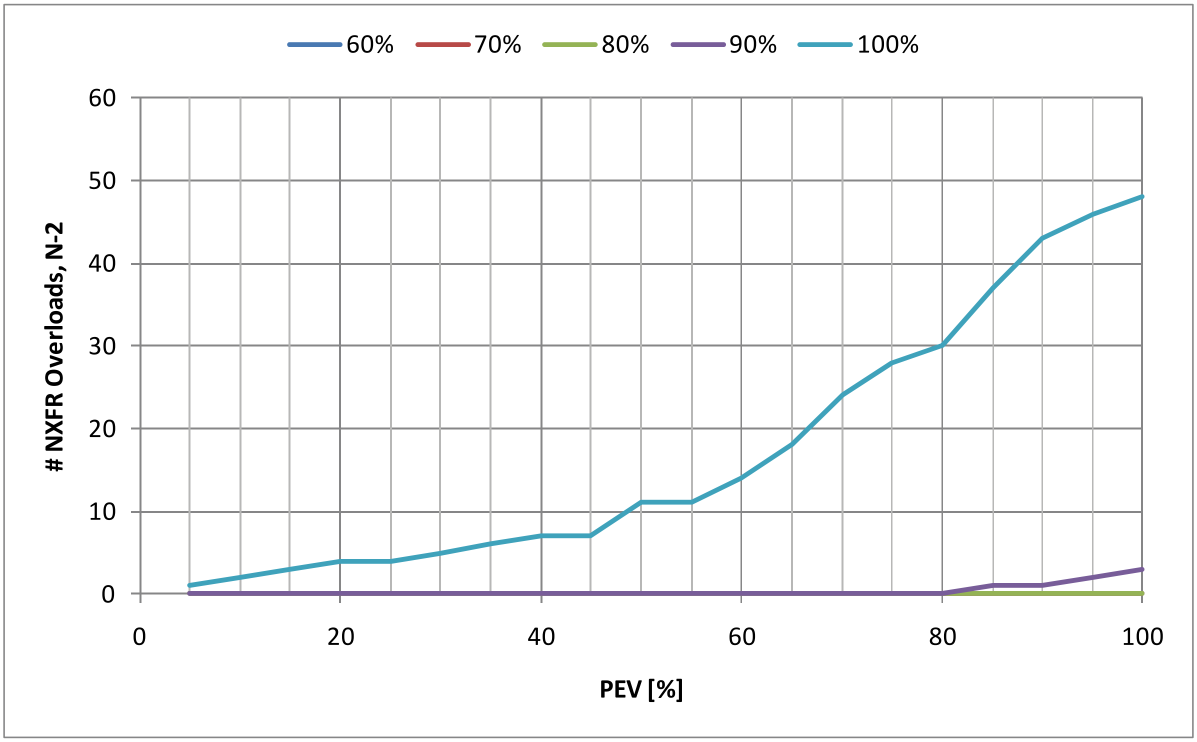

Figure 6-17
Number of NXFR Overloads, N-2

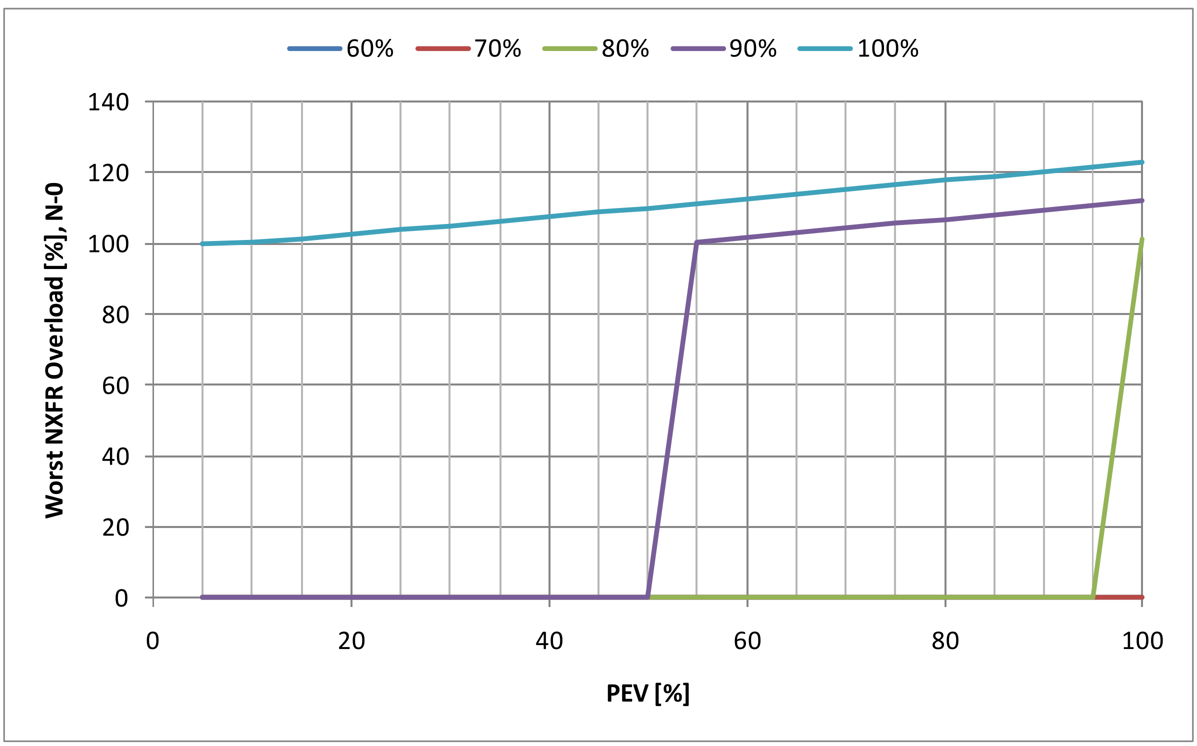

Figure 6-18
Worst NXFR Overload [%], N-0

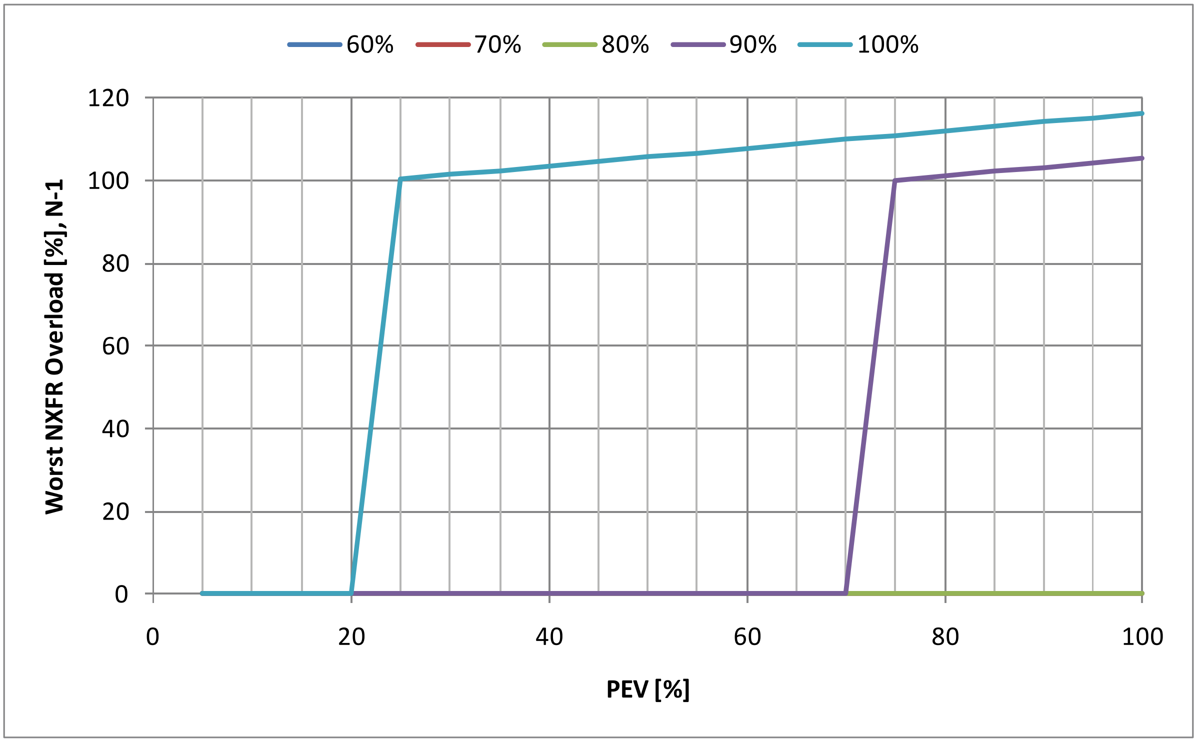

Figure 6-19
Worst NXFR Overload [%], N-1

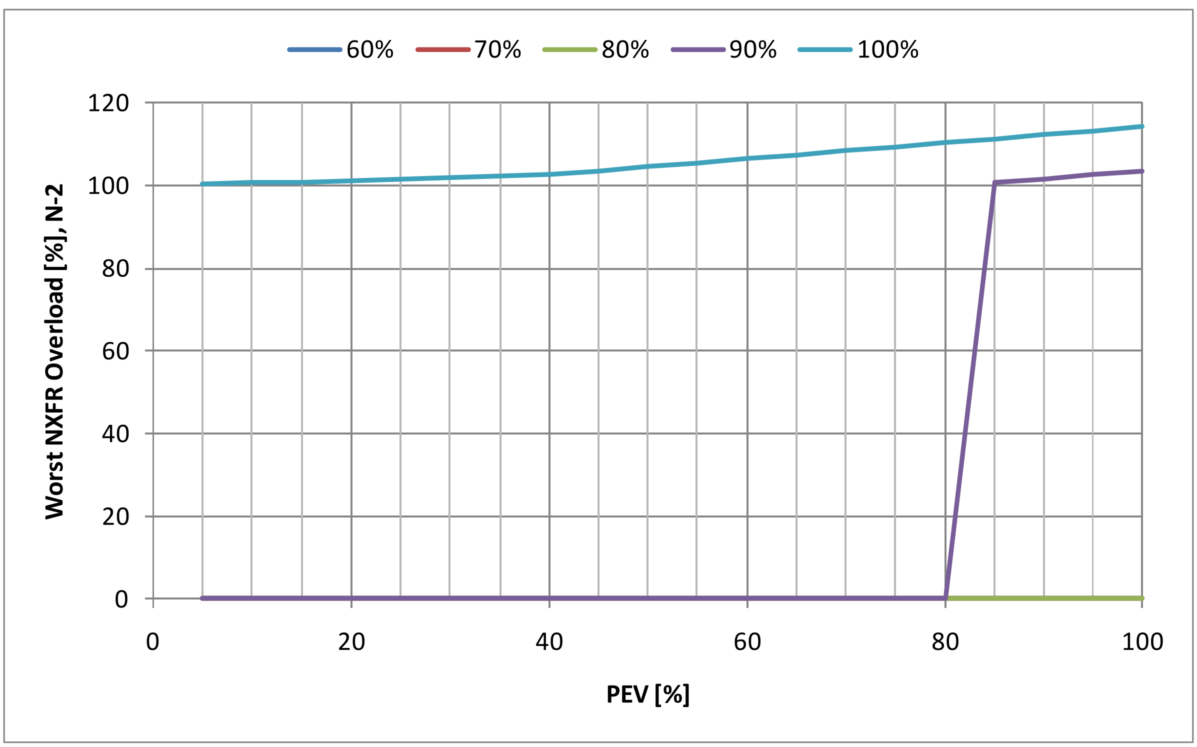

Figure 6-20
Worst NXFR Overload [%], N-2

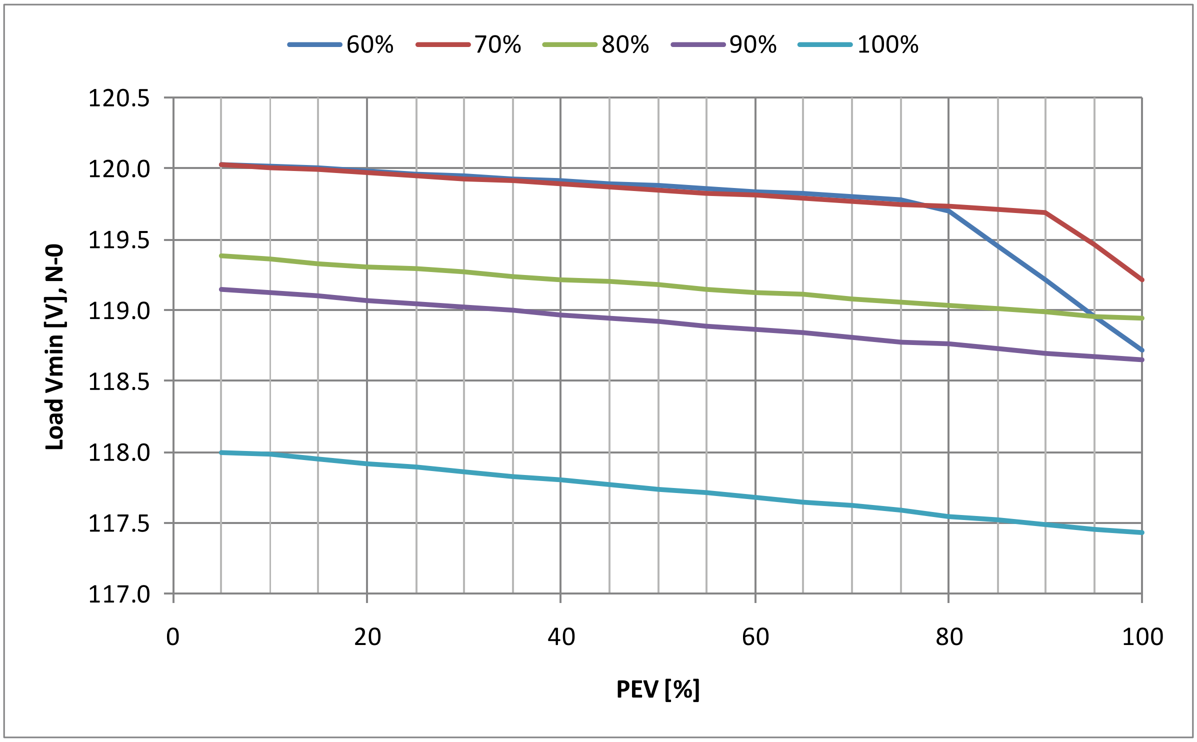

Figure 6-21
Non-PEV Load Vmin [V], N-0

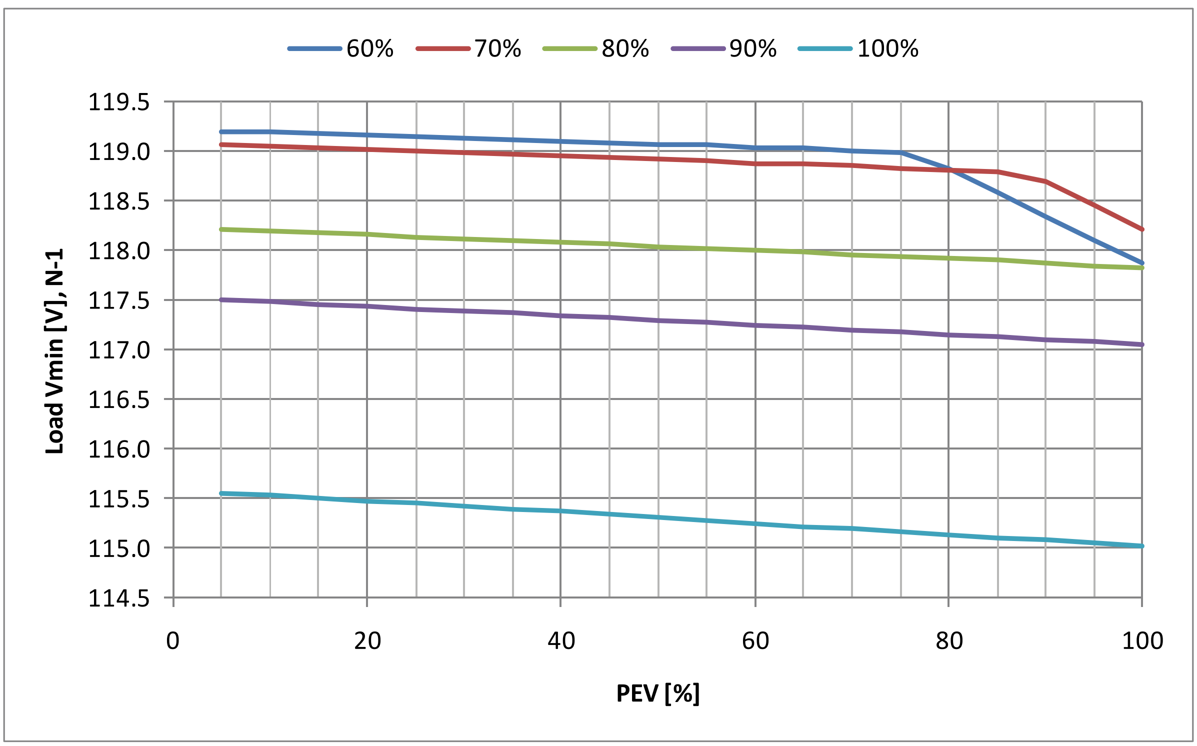

Figure 6-22
Non-PEV Load Vmin [V], N-1

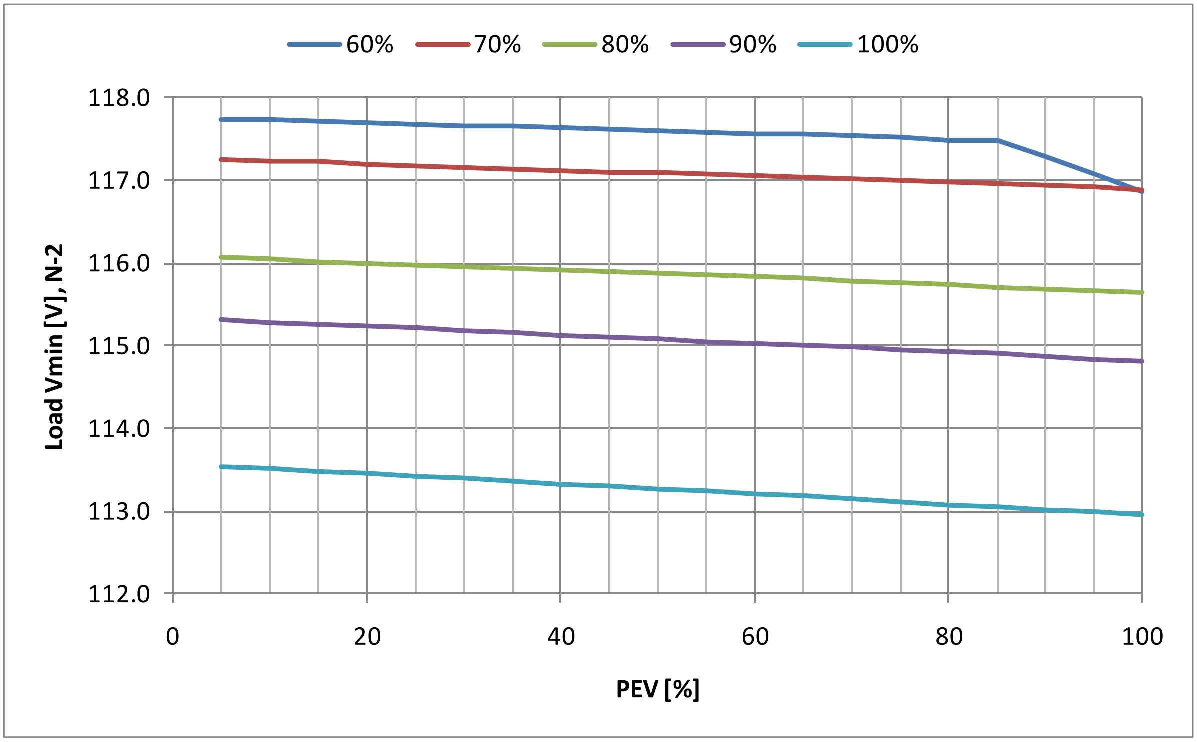

Figure 6-23
Non-PEV Load Vmin [V], N-2

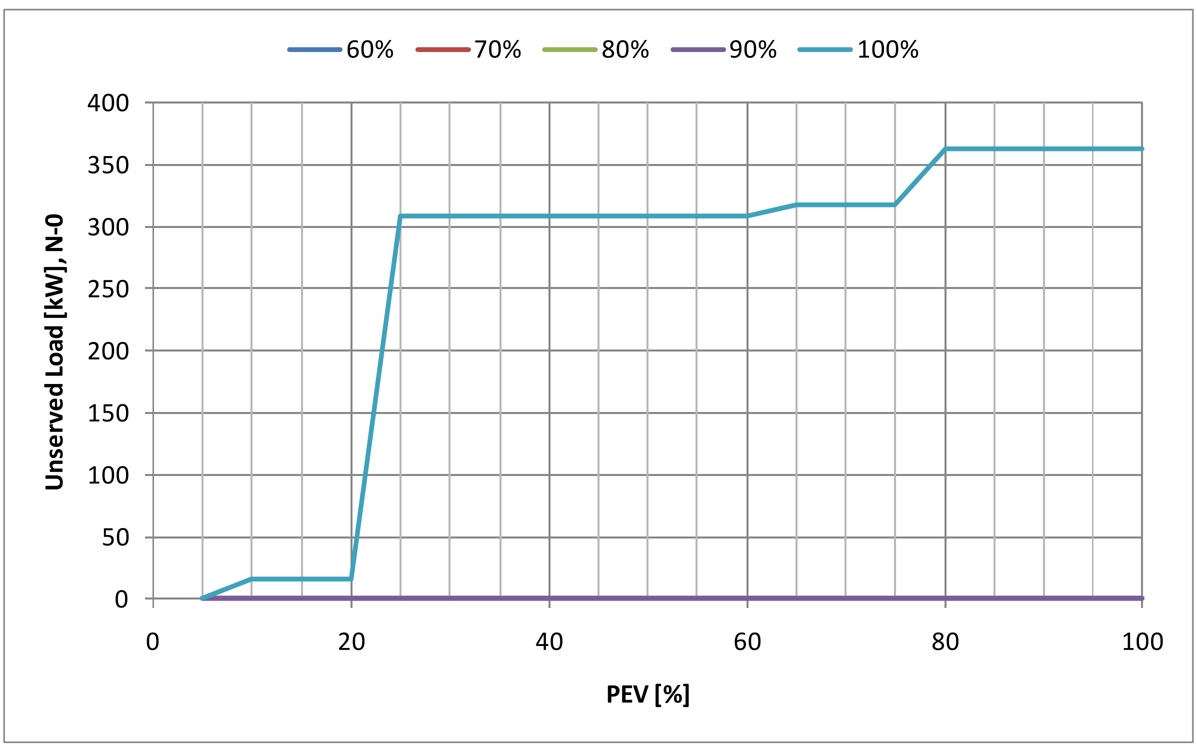

Figure 6-24
Non-PEV Unserved Load [kW], N-0

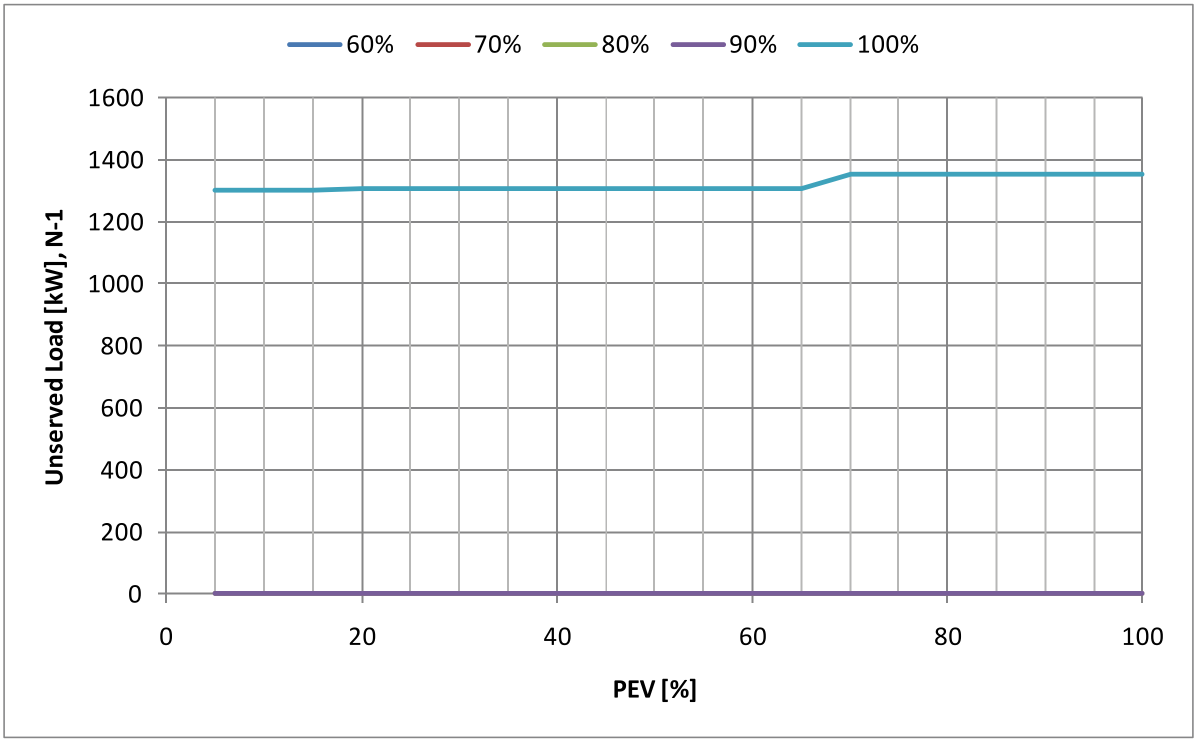

Figure 6-25
Non-PEV Unserved Load [kW], N-1

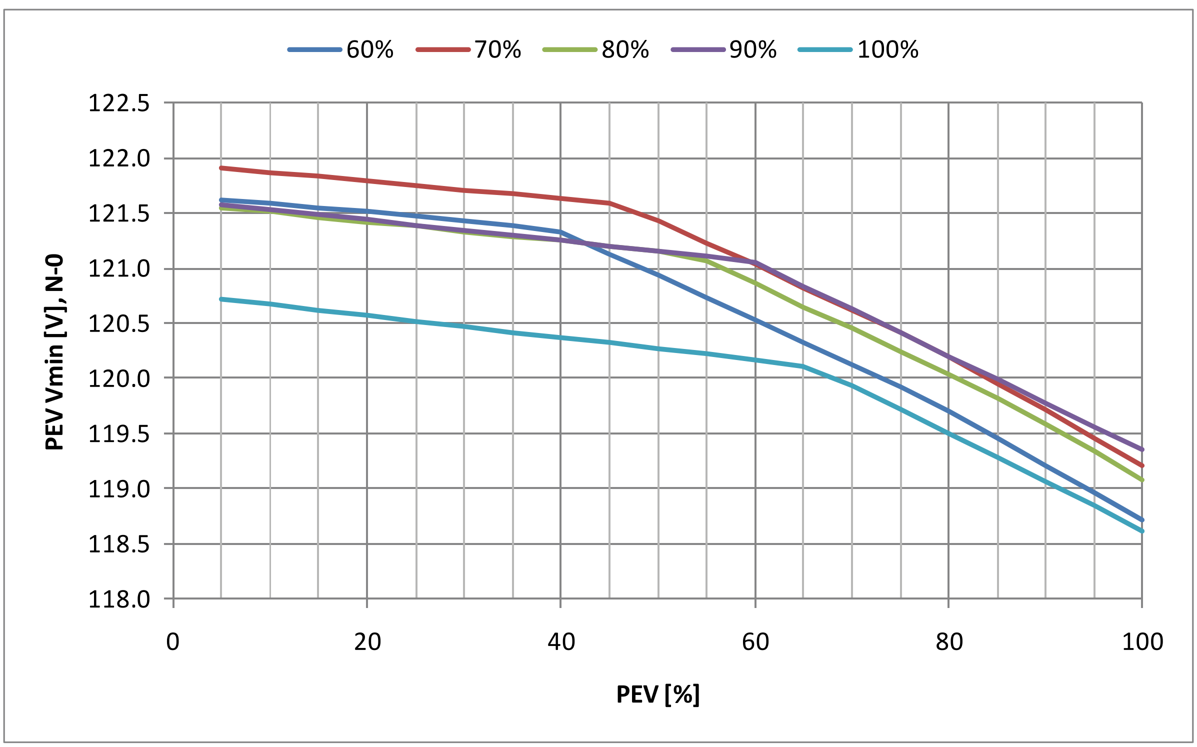

Figure 6-26
PEV Vmin [V], N-0

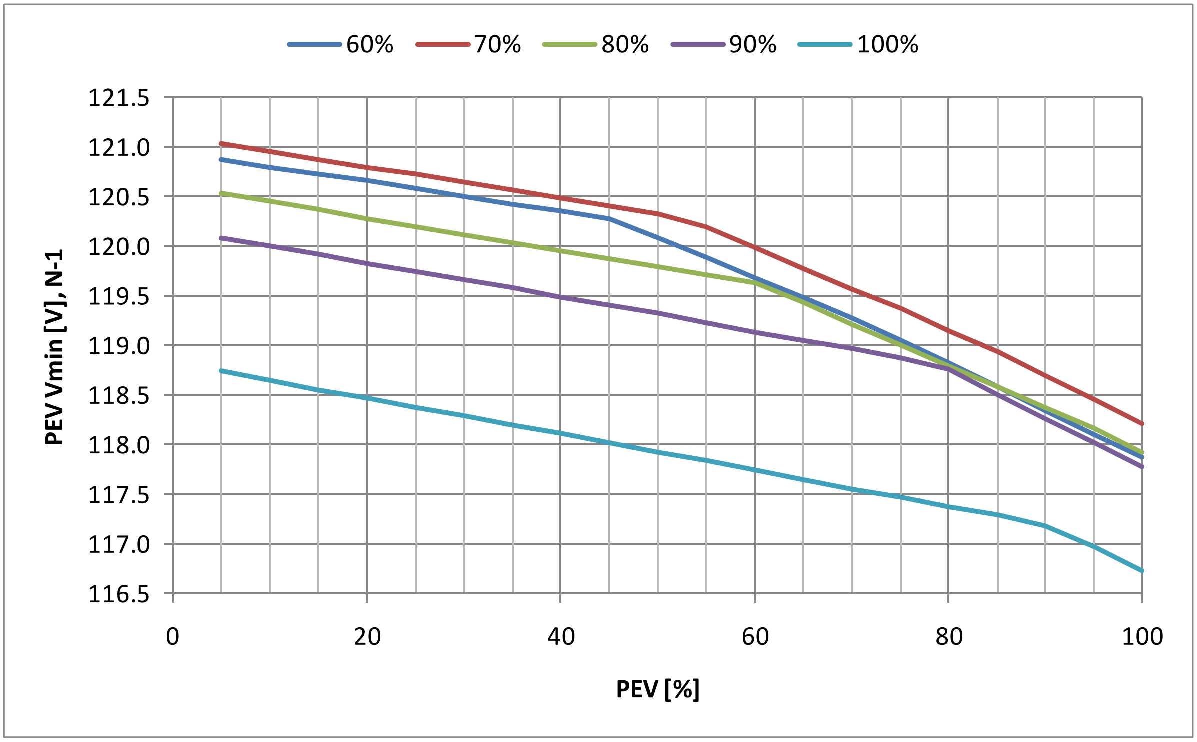

Figure 6-27
PEV Vmin [V], N-1

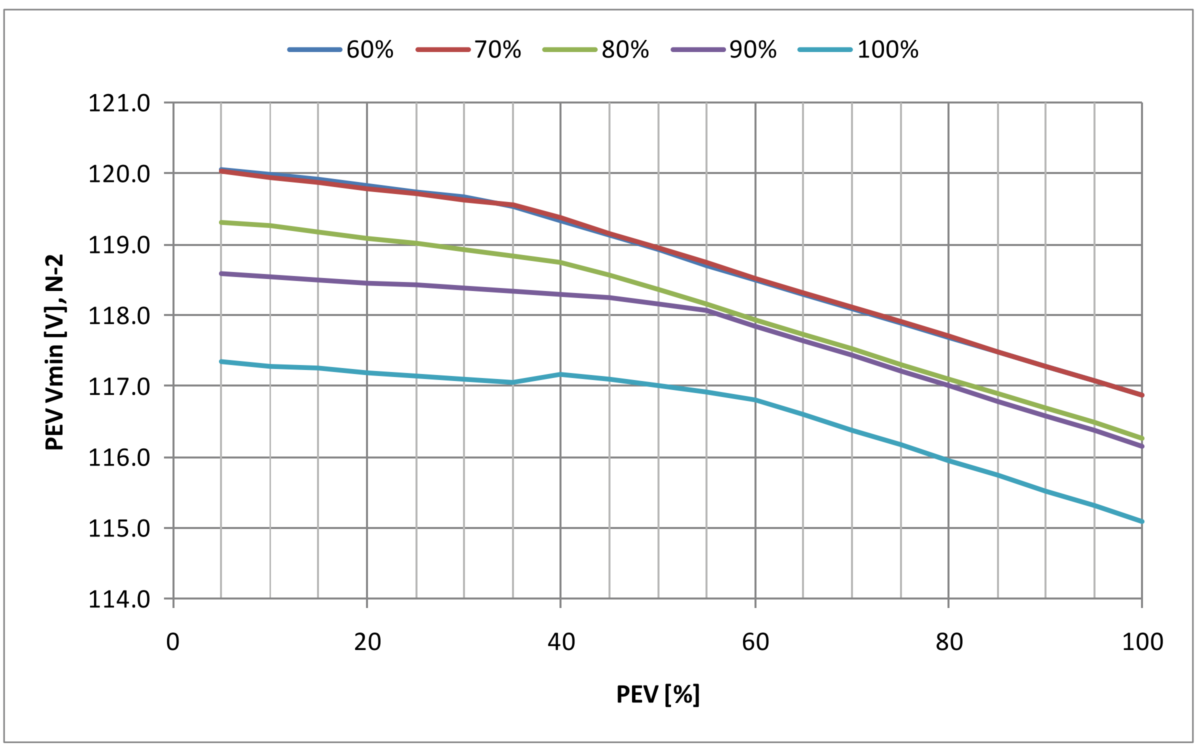

Figure 6-28
PEV Vmin [V], N-2

7 STATEWIDE ECONOMIC IMPACTS OF PEV USE IN NEW YORK STATE

Executive Summary

This study analyzes the statewide economic impacts associated with large-scale use of plug-in electric vehicles (PEVs) in New York State. Specifically, the study examines the statewide economic impacts due to petroleum displacement, increased electricity demand, and annual fuel cost savings by consumers under a hypothetical scenario where PEVs achieve 40% market penetration in the state. The study applies regional input-output analysis to quantify Gross State Product (GSP) and employment effects under four different fuel price cases. In all cases, positive economic benefits were demonstrated, ranging from $4.45 to $10.73 billion/year and 19,800 to 59,800 jobs[7] for GSP and employment impacts, respectively. These results imply that a transition to PEVs in New York could lead to large economic benefits for the state, and policies that promote the market adoption of PEVs may be warranted from a public benefit perspective.

There are certain limitations to these findings. The RIO method assumes static production functions, constant commodity prices, unconstrained labor markets, and production costs that are linear functions of production output [50]. The static nature of RIO analysis implies that future changes in the structure of the economy—such as the introduction of new industries—are not explicitly modeled. Thus, our results are applicable to future cases only inasmuch as the structure of a future economy reflects the structure of the present. Even with these limitations, we believe our results provide useful insights into the macroeconomic impacts that fuel switching could have in New York State. As we have shown in this report, the potential statewide economic impacts from PEV use are substantial. In light of this report's findings, policies that encourage PEV use in New York State could have significant economic payback.

Future analyses might apply the analytical approach employed here to examine the net impact of PEV market penetration on a smaller scale. Given the scale of potential economic impacts seen here, gaining an understanding of expected economic impacts using near-term market penetration estimates could help to inform New York policy decision-making. Moreover, additional analyses might include evaluating the economic impact of PEV owners selling excess electricity to the grid, of inclusion of PEV incremental costs, or impacts of PEV emission reductions, such as health benefits. These types of analyses will provide a more comprehensive understanding of the anticipated economic impacts due to PEV market penetration in New York State.

Introduction and Purpose

Environmental and energy security concerns are driving the development and use of plug-in electric vehicles (PEV), which combine desirable aspects of battery electric vehicles (BEV) and

[7] A "job" used here represents a single year of work. So, when we say we created 19,800 jobs, that means 19,800 people working for one year. These people remain employed as long as the same amount of petroleum is displaced by electricity and same household income savings continue.

hybrid electric vehicles (HEV). Like HEVs, PHEVs can also operate on gasoline when onboard stored electricity is no longer sufficient to power the vehicle. Therefore PHEV owners can take advantage of increased fuel efficiency without concerns of dead batteries, long recharge time, or limited range.

In contrast to other alternative fuel vehicles and HEVs, PHEVs can largely be "fueled" at the owner's home (via the grid). PHEVs could be fueled by biofuels when in hybrid mode, further reducing petroleum consumption and emissions. Because of their flexibility and beneficial characteristics, PHEVs have been described as the most promising alternative fuel vehicle option.[1] Although not currently commercialized to any significant extent, several major auto companies have plans to produce and sell PHEVs in the coming 2-3 years. The 2011 Chevrolet Volt (an extended-range PHEV) was available in United States consumers at the end of 2010 [2, 3].

PEVs can reduce lifecycle emissions of GHGs by approximately 25-100% compared to conventional vehicles (CVs) depending on charging and use assumptions [4-8]. These reductions are largely a function of electric grid (i.e., recharging) characteristics, as well as the type of liquid fuel used to power the vehicle when not in all-electric mode.

PEVs are particularly suited for use in urban areas where operation in all-electric mode produces no tailpipe emissions [9]. Compared to CVs, PEVs reduce tailpipe emissions of nitrogen oxides (NO_x), volatile organic compounds (VOCs), and fine particulate matter ($PM_{2.5}$)—pollutants associated with negative health effects, property damage, and environmental degradation [10]. From a local and state policy perspective, PEVs may be a particularly desirable transportation technology.

PEVs are also far more efficient compared to CVs, reducing petroleum consumption. PEVs with a 40 miles all-electric range (AER) could reduce drivers' petroleum consumption by 70% or more [11]. For many regions, reducing consumption of petroleum is predicted to provide economic benefits since petroleum expenditures tend to leave a region due to the high level of petroleum imports [12-15].

Further, as a transportation fuel, electricity is cheaper than petroleum on a per mile basis. For instance, a gasoline passenger vehicle with a fuel economy of 24 miles/gallon and facing fuel costs of $2.80/gal would cost 12 cents/mile to operate. A PEV with an electric-mode fuel economy of 3 miles/kWh and facing electricity costs of $0.18/kwh would only cost 6 cents/mile to operate. Consequently, the use of PEVs can lower annual fuel bills for consumers. Recent studies have shown annual fuel cost savings for PEV owners of between $500 to $940 depending on travel characteristics and fuel price assumptions [14-16]. Combined with the fact that most petroleum is imported, these fuel savings provide economic benefits beyond those that accrue to the vehicle owner.

Household fuel savings can be used to purchase local goods and services, boosting local economic activity and job growth. Those expenditures circulate through the economy, creating a *multiplier effect*. This effect has been studied at the national level with respect to PEVs and electric vehicles. A 2002 study estimated that if only 1% of light-duty cars in the U.S. were electric, 24,000 barrels of oil per day would be displaced, resulting in $1.46 billion ($1999) in economic benefits and the creation of over 14,000 jobs [17]. Another study examined a 2025 scenario where 50% of all U.S. vehicles were electric (half of which were PHEVs), finding that petroleum consumption would be reduced by 1.5 billion barrels each year, GDP would increase by approximately $38.3 billion/year, and over 440,000 jobs would be generated [18]. Similar studies have estimated extensive benefits to local economies on a regional scale [13-15].

The purpose of this study is to quantify the statewide economic impacts of a hypothetical PEV market penetration scenario in New York State. The first section presents the analytical methodology, including a description of the scenario, input assumptions for the cases we model, and a brief primer on regional input-output (RIO) analysis. The second section presents the results and discussion. The final section of the report presents conclusions and implications of the study findings.

Methodology

In this study, we examine the statewide economic impacts in New York based on a hypothetical market penetration scenario for PEVs. In particular, we ask the following question: *What would the statewide macroeconomic impacts (output and employment) be if 40% of today's NY light-duty vehicle (LDV) fleet was comprised of PEVs?* This hypothetical scenario is partially informed by the 2007 report, *Environmental Assessment of Plug-In Hybrid Electric Vehicles,* produced by the Electric Power Research Institute (EPRI) and the Natural Resources Defense Council (NRDC) [21].

We apply a RIO approach in conducting our analysis. RIO is one of the most extensively employed techniques in studying the macro-level impacts due to shifts in expenditures within an economy. RIO is valuable because it captures not only the direct impacts of regional economic shifts (for example, a shift of household spending from gasoline to electricity), but also the *indirect* and *induced* effects of these direct impacts (as discussed in a later section). RIO has been used by the New York State Energy Research and Development Authority (NYSERDA) and others in the past to explore the impacts of new energy technologies, energy efficiency practices, and energy programs [19, 20].

We use RIO analysis to determine the statewide employment and GSP impacts associated with fuel switching due to large-scale PEV deployment. We identify three economic shifts that occur due to PEV and EDV market penetration: (1) a decrease in demand for petroleum; (2) an increase in electricity demand; and, (3) reduced fuel expenditures by consumers, the savings from which are spent in other sectors of the economy. For each of these categories, we quantify the total (direct, indirect, and induced) GSP and employment impacts associated each shift. The net impacts of all shifts demonstrate the expected overall, fuel-driven economic impact of large-scale PEV use in New York State.

Our analysis consists of a series of steps depicted in Figure 7-1 and discussed below. The steps depicted in the upper portion of the figure are similar to those used in EPRI and NRDC [21], and are also detailed in that report.

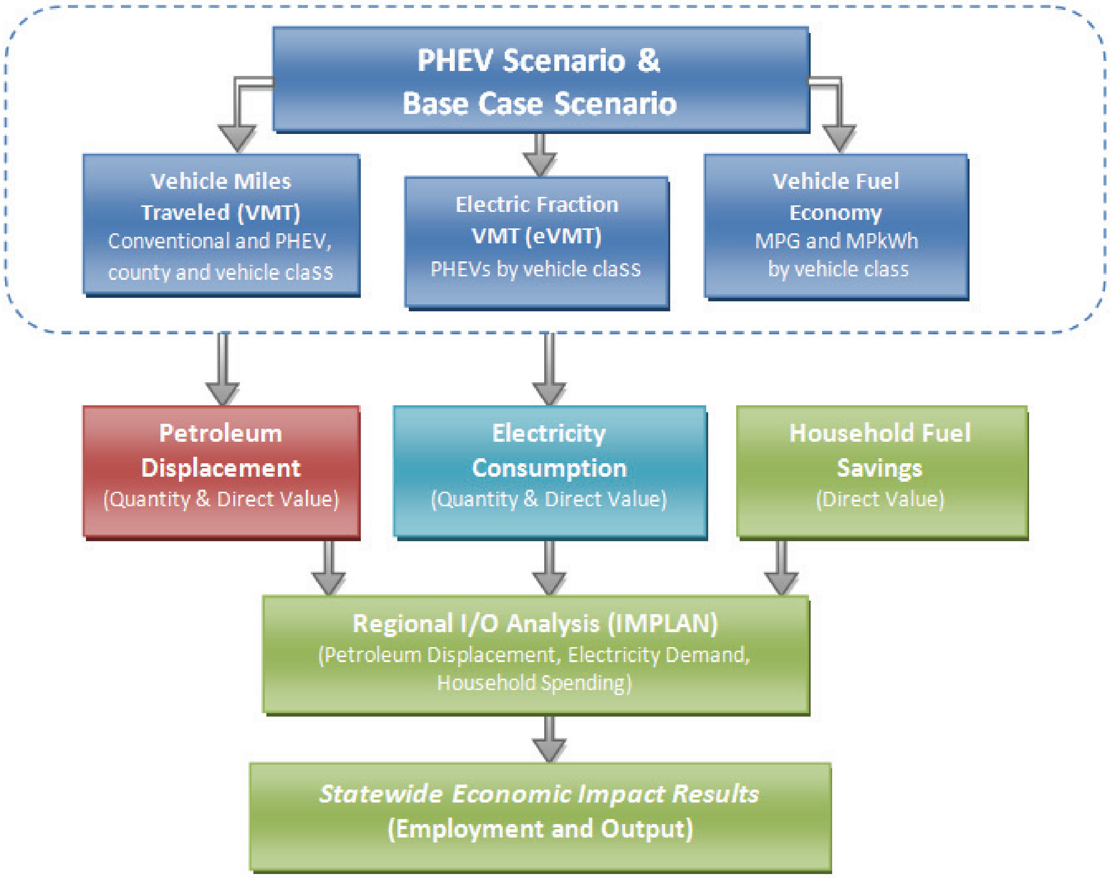

Figure 7-1
Schematic Overview of Study Methodology

PEV Scenario and Data

Scenario Overview

Economic impacts of petroleum displacement due to PEV market penetration depend upon: (1) the level of PEV market penetration in the state, including the number and use of PEVs; (2) the amount of petroleum displaced with electricity according to PEV use, and (3) the relationships between changes in fuel demand and the New York economy.

To evaluate the potential economic impacts of PEV use in New York, we construct a hypothetical scenario where 40% of the 2008 New York LDV fleet is PEVs (*PEV Scenario*). Although such a scenario is obviously contrary to the 2008 market realities, the purpose of the analysis is to show what benefits *could* accrue to New York if a large portion of the passenger transportation sector was based on PEVs. (2008 is the year in which the most recent economic data are available for populating the RIO model.) Our approach also allows for scaling to other PEV market penetration scenarios (e.g. 10%, 20%, etc.). We compare our *PEV Scenario* with a *Base Case Scenario* where no PEV market penetration occurs. We use key variables such as county- and class-specific vehicle miles traveled (VMT), all-electric fraction of VMT, and vehicle fuel economy to estimate changes in petroleum and electricity consumption, the central components of our economic analysis. We assume homogeneous percentage distributions of these vehicles across the state (PEVs comprise 40% of LDVs in each county).

Vehicle Miles Traveled

The EPRI/NRDC (2007) study used U.S. Environmental Protection Agency's (EPA) growth projections and MOBILE6 model to estimate VMT by vehicle class for each county in the US under each scenario. We take a similar approach for this study, employing EPA county-specific VMT data for the year 2006 (the most recent year for which data was available and representative of the 2008 study year) [22]. Total VMT estimates for each New York State county are shown in Table 7-1.

The EPA VMT data does not distinguish VMT by vehicle class and represents all VMT in the state, including heavy-duty vehicle VMT. As this study focuses on LDVs, we use EPA MOBILE6 VMT mix assumptions, which reflect the percentage of VMT comprised by each vehicle class for the year 2010 [23]. The assumed share of total New York State VMT comprised by each LDV class is shown in Table 7-2. LDV classes are assumed to comprise roughly 87% of total NYS VMT—or 128 billion VMT/year.

Table 7-1
New York State Vehicle Miles Traveled (VMT) by County, 2006

County	VMT (Million Miles/year)	County	VMT (Million Miles/year)	County	VMT (Million Miles/year)
Albany	3,726	Herkimer	852	Richmond	2,002
Allegany	472	Jefferson	1,259	Rockland	2,731
Bronx	4,721	Kings	4,899	Saratoga	884
Broome	2,452	Lewis	257	Schenectady	2,277
Cattaraugus	854	Livingston	854	Schoharie	1,540
Cayuga	822	Madison	801	Schuyler	542
Chautauqua	1,563	Monroe	7,680	Seneca	186
Chemung	918	Montgomery	853	St. Lawrence	497
Chenango	482	Nassau	11,920	Steuben	1,366
Clinton	808	New York	4,378	Suffolk	19,815
Columbia	848	Niagara	1,695	Sullivan	784
Cortland	673	Oneida	2,371	Tioga	689
Delaware	564	Onondaga	4,951	Tompkins	748
Dutchess	3,180	Ontario	1,464	Ulster	2,208
Erie	9,248	Orange	4,696	Warren	943
Essex	596	Orleans	346	Washington	587
Franklin	441	Oswego	1,185	Wayne	722
Fulton	397	Otsego	671	Westchester	9,166
Genesee	1,205	Putnam	3,085	Wyoming	288
Greene	811	Queens	7,839	Yates	195
Hamilton	119	Rensselaer	1,533	***Grand Total***	***146,659***

Although PEVs comprise 40% of the vehicle fleet in the *PEV Scenario*, the all-electric portion of vehicle miles traveled (eVMT) was assumed to be far less than 40% of total VMT. (Note: eVMT represents the amount of VMT that is conducted in all-electric mode in a PEV and is a function of assumptions about VMT and battery capacity for a PEV). We assume that eVMT comprises a portion of total VMT consistent with EPRI/NRDC [21] —about 20% of total VMT or 26 billion VMT, as shown in Table 7-2. In the EPRI/NRDC study, it was assumed that PEVs were charged once daily, occasional longer or overnight trips occurred (for which electric charging would be infeasible), and PEVs might not be driven on all days. As shown in Table 7-2, vehicle class specific eVMT ranges between 17.7% and 21.8% of total VMT.

Table 7-2
Vehicle Class Percentage of VMT, and VMT by Mode and Fuel Type

MOBILE6 Vehicle Class	Vehicle Class Name	Mobile 6 Vehicle Class % Total State VMT	Base Case Scenario VMT (Millions/year)	PEV Scenario VMT (Millions/year)			
			CV VMT	CV VMT	HEV-mode VMT	All-electric eVMT	% eVMT
LDGV	LD gasoline passenger vehicle	35.4%	51,871	31,122	9,466	11,282	21.8%
LDGT1,2	LD gasoline truck, Class 1 &2	38.5%	56,399	33,840	11,746	10,814	19.2%
LDGT3,4	LD gasoline truck, Class 3 & 4	13.3%	19,433	11,660	4,300	3,473	17.9%
LDDV	LD diesel passenger vehicle	0.03%	47	28	10	8	17.7%
LDDT	LD diesel truck	0.19%	284	170	63	50	17.7%
Total LDV	**Grand Total LDV Classes**	**87.4%**	**128,034**	**76,820**	**25,585**	**25,627**	**20.0%**

Vehicle Fuel Economy

Vehicle fuel economy attributes are central in calculating total vehicle fuel consumption in a region. Our fuel economy estimates are similar to those used in EPRI/NRDC [21] and are shown in Table 7-3. Class-specific fuel economy attributes from EPA's MOBILE6 model for the year 2008 are used for *Base Case Scenario* and *PEV Scenario* conventional vehicles (CV), which we validated with recent EPA LDV fuel economy data [23, 24]. In the *PEV Scenario*, when PEVs are not powered by gasoline or diesel, fuel economy estimates are equivalent to hybrid electric vehicle (HEV) fuel consumption [21]. *PEV Scenario* PEV electric-mode fuel economy estimates are obtained from EPRI/NRDC [21], which were calculated from EPRI simulation and battery test data and MOBILE6 fuel consumption data. Electricity consumption at the vehicle assumes 88% conversion efficiency from wall outlet AC energy to DC energy in the battery.

Table 7-3
Vehicle Class Fuel Economy and Electricity Consumption

Individual Vehicle Class	Vehicle Class Name	GVWR (lb)	CV Fuel Economy (mpg)	HEV - mode Fuel Economy (mpg)	PEV AC Consumption electric mode (mi/kWh)
LDGV	LD gasoline passenger vehicle	-	24.1	37.1	3.14
LDGT1,2	LD gasoline truck, Class 1 &2	0-6001	18.5	28.5	2.54
LDGT3,4	LD gasoline truck, Class 3 & 4	6001-8500	14.2	21.8	2.03
LDDV	LD diesel passenger vehicle	-	32.4	49.8	3.05
LDDT	LD diesel truck	0-8500	22.1	34	2.17*

*Two or more vehicle classes were aggregated to produce the LDDT vehicle class. For this class, average miles/kWh fuel economy of the aggregated classes is employed.

Petroleum Displacement and Electricity Consumption Calculations

Calculating petroleum displacement and electricity usage due to PEV penetration involves translating *Base Case* and *PEV Scenario* data into transportation petroleum and electricity demand estimates. We calculate petroleum displacement (PD_j) between the *Base Case* and *PEV* scenarios as follows:

$$PD_j = \frac{VMT_{j,BC,CV}}{MPG_{j,CV}} - \left[\left(\frac{VMT_{j,PHEV,CV}}{MPG_{j,CV}}\right) + \left(\frac{VMT_{j,PHEV,HEV}}{MPG_{j,HEV}}\right)\right]$$

Increase in electricity consumption (EC_j) for the PEV scenario is calculated as:

$$EC_j = \frac{eVMT_j}{MPkWh_{j,PHEV}}$$

where,

- j—represents the set of vehicle classes
- $VMT_{j\ BC,\ CV}$– represents annual vehicle miles traveled by vehicle class (j) for *Base Case Scenario* conventional vehicles (Table 7-2)
- $VMT_{j\ PHEV,\ CV}$– represents annual vehicle miles traveled by vehicle class (j) for *PHEV Scenario* conventional vehicles (Table 7-2)

- $VMT_{j\ PHEV,\ HEV}$ – represents annual vehicle miles traveled by vehicle class (j) for *PHEV Scenario* PHEVs in HEV mode (Table 7-2)
- % eVMT_j – represents all-electric VMT fraction for PHEVs by class (Table 7-2)
- $MPG_{j,CV}$ – represents conventional vehicle fuel economy in miles per gallon (mpg) by vehicle class for gasoline and diesel vehicles (Table 7-3)
- $MPG_{j,HEV}$ – represents HEV-mode fuel economy in miles per gallon (mpg) by vehicle class for gasoline and diesel PHEVs (Table 7-3)
- $MPkWh_{j,PHEV}$ – represents miles per kilowatt-hour (kWh) for PHEVs by vehicle class (Table 7-3).

We calculate fuel displacement impacts of the LDV gasoline fleet and diesel fleet separately, as gasoline and diesel prices differ; see following section for valuation methodology. Estimates by vehicle class for gasoline, diesel and electricity demand for the *Base Case Scenario* and *PEV Scenario* are shown in Table 7-4 and Figure 7-2.

Table 7-4
Petroleum and Electricity Demand in New York State LDV Fleet under the Base Case and PEV Scenario

Household Fuel Consumption	Base Case Scenario	PEV Scenario	Change in Demand
Gasoline (Million Gallons/year)	6,569	4,806	**1,763**
Diesel (Million Gallons/year)	14	11	**4**
Electricity (Million kWh/yr)	0	9,587	**9,587**

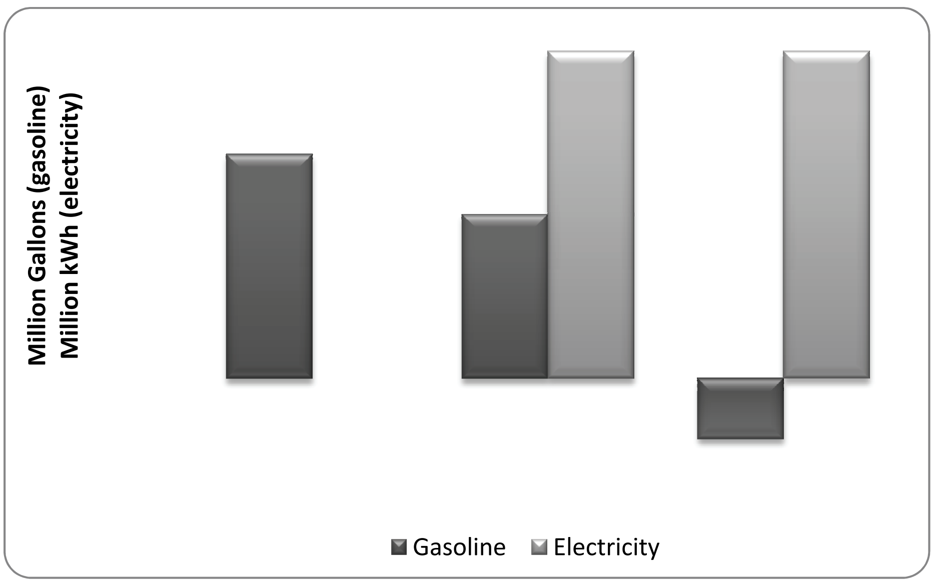

Figure 7-2
Change in Gasoline and Electricity Demand in New York State LDV Fleet (diesel excluded due to small scale)

Valuation of Petroleum and Electricity Expenditures

Changes in transportation fuel demand drive annual fuel costs and savings attributable to PEV use. To value changes in fuel demand, we use New York State annual average retail price data from the U.S. DOE Energy Information Administration (EIA) and NYSERDA for electricity, gasoline and diesel for the year 2008 [4-6]. Considering a range in energy prices allows us to examine a range of possible economic impacts due to PEV-related fuel effects. Therefore we also conduct sensitivity analyses on these prices, exploring historical average, and high and low energy price cases. In all cases we use residential electricity rates to ensure a conservative estimate of fuel expenditure savings. The cases, shown in Table 7-5 and Figure 7-3, are as follows (all prices are in 2008$):

- Case I – In this case we assume 2008 state average electricity ($0.185/kWh) [25], gasoline ($3.44/gallon)[26], and diesel ($3.99/gallon) prices [27, 28]
- Case II – In this case we assume ten-year statewide averages for electricity[8] ($0.159/kWh) [29], gasoline ($2.50/gallon)[28], and diesel ($2.50/gallon) [27]
- Case III – In this case we employ EIA 2030 low energy price projections [30] to derive forecasts for low New York energy prices in the future.[9] EIA's "Low Oil Price" scenario projects gasoline prices (2008$) to be 36% lower than in 2008, and electricity prices are projected to be 2.2% lower than in 2008. Assuming a uniform percentage change in energy prices, we adjust 2008 New York State energy prices accordingly to derive low 2030 estimates—$0.181/kWh, $2.19/gal gasoline, and $2.26/gal diesel
- Case IV – In this case we employ EIA 2030 "High Oil Price" projections [31] to derive New York -specific prices as described above for case III. The High Oil Price scenario projects gasoline prices to be 68% higher than 2008 average prices (in 2008$). Residential electricity price is projected to be 3% higher than in 2008. We adjust 2008 New York State energy prices to derive high 2030 estimates—$0.191/kWh, $5.77/gal gasoline, and $6.05/gal diesel.

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[8] Electricity ten year averages represent the years 1998-2008 (the latest year for which EIA NYS electricity price data was available); gasoline and diesel ten-year averages represent 2000-2009.

[9] We opt to use year 2030 price projections as this is a more realistic timeframe for large-scale PHEV implementation, and so analyzing these price scenarios may lend insight into potential future impacts.

Table 7-5
New York State Average Energy Prices, Cases I - IV (2008$)

Case	Fuel Prices			Cost/Mile Equivalent	
	Gasoline ($/gallon)	Diesel ($/gallon)	Electricity ($/kWh)	Gasoline ($/mile)[10]	Electricity ($/mile)[11]
Case I 2008 Prices	$3.44	$3.99	$0.185	$0.143	$0.060
Case II 10-Year Avg.	$2.50	$2.50	$0.159	$0.104	$0.051
Case III EIA 2030 Low	$2.19	$2.26	$0.181	$0.091	$0.058
Case IV EIA 2030 High	$5.77	$6.05	$0.191	$0.239	$0.062

Source: [19-26]

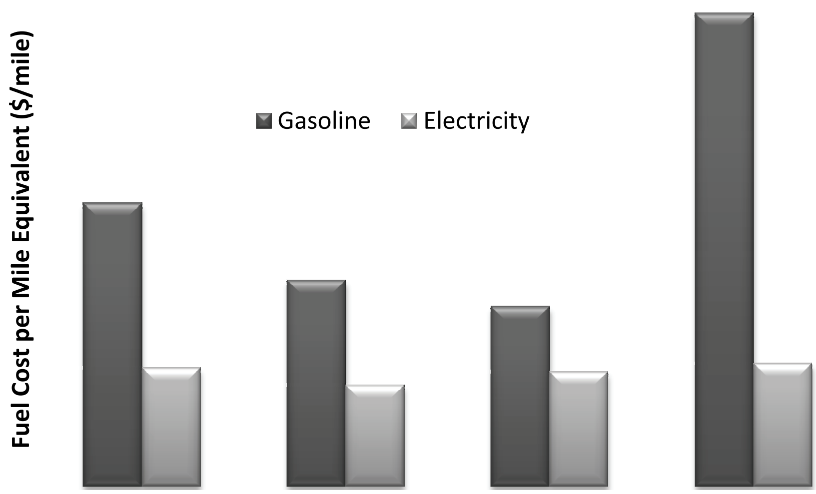

Figure 7-3
Statewide Fuel Cost per Mile Equivalent Cases I - IV, Gasoline and Electricity (2008$)

It is important to note that we use statewide average energy prices as this is a statewide analysis. Prices in local regions of New York State may differ considerably from these averages; for instance 2008 electricity prices in Rochester and Buffalo service areas were about 40% lower

[10] Assuming gasoline passenger vehicle with fuel economy of 24.1 miles/gallon
[11] Assuming PHEV in all-electric mode with a fuel economy 3.1 miles/kWh

than electricity prices in New York City [32]. Therefore local effects of fuel switching may be different than suggested here. Local analyses of individual regions are reserved for future work.

The changes in total energy expenditures give us the annual net household savings. As discussed in the following section, the changes in fuel demand and household savings are employed in our regional input-output models to determine the overall impact on the New York State economy.

Regional Input-Output Analysis

Input-Output Analysis Basics

We apply input-output (I-O) analysis to determine the regional economic impact of PEV penetration and related fuel shifts in New York State. There is a long history of the use of I-O [33, 34]. Some of this literature is particularly aimed at the energy sector [35-37]; and some work has applied I-O analysis to understand the economic impacts of alternative fuel vehicle use [38-40], including work by NYSERDA and others to explore the impacts of development of a state alternative fuel industry [19, 20]. This section provides a brief overview of I-O analysis and explains how it is used in this particular study.

I-O analysis allows the tracking of economic impacts (such as employment and output) from shifts in economic activity within a regional or national economy. Relying on statistical data from the U.S. national accounting system, I-O analysis captures the many production-consumption linkages within the economy. For example, the production of electricity is no simple task—there are fuel purchases, equipment purchases, labor purchases, maintenance services, etc. that are involved in this production. I-O analysis allows one to assess the changes in demand for these production inputs due to a change in demand for the final product. I-O analyses are valuable not only because they capture the *direct* impacts of such shifts (for example, a shift of consumer spending from gasoline to electricity), but also because the *indirect* effects of these direct impacts are captured. For instance, an increase in final demand for electricity will create an increase in fuel purchases at the power plant, which in turn trigger increases in the inputs associated with fuel production such as mining services, fuel delivery, and fuel extraction equipment, as shown in Figure 7-4. These impacts are all considered “indirect” impacts in I-O analysis.

Additionally, I-O captures “induced” economic effects. With any shift in final demand (and related shifts in production inputs) there will be shifts in employment and therefore household income. For example, increasing electricity demand may lead to increased labor requirements at the power plant, which implies additional dollars in take-home pay for new or existing electric utility employees. These employees will have increased household income and will spend it accordingly, thereby inducing higher economic activity within the regional economy. Along with the indirect effects mentioned above, these induced effects are included in our analysis.

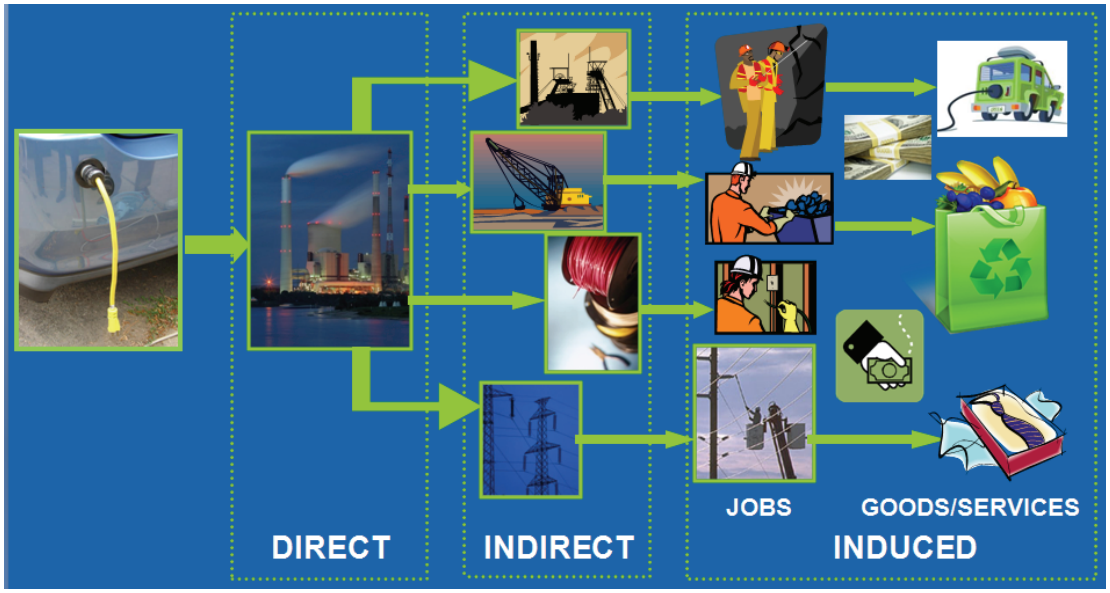

Figure 7-4
Schematic of Direct, Indirect and Induced Impacts of Electricity Purchases

Regional I-O Analysis

RIO analysis is I-O analysis conducted on a particular region. In order to conduct these analyses, national accounting data tables must be restructured to account for the economic activity and production function attributes that occur *within the region under study*. We rely on economic activity data specific to New York State.

To assist in the RIO analysis, we use the IMPLAN (IMpact Analysis for PLANning) Professional software analysis tool (Version 3.0) [41]. We obtained the most recent economic structural matrices and county data files (representing the year 2008) for New York State to construct our model. From our RIO analysis, we can determine statewide economic impacts of the following two key parameters:

- ***Output***, which is measured in $/year and represents the value of economic activity in the State (by industry and in total) [16]
- ***Employment***, which is measured in jobs on an annualized basis, reflects the number of part time and full time positions involved in an industry. Employment includes wage and salary employees, and self-employed jobs.

Structuring the RIO Model

Overview

The main challenge of RIO analysis is translating a particular event or activity (e.g., increased PEV market penetration) into changes in final demand for products, services, or investments. Petroleum displacement from PEVs implies a real shift of spending patterns in the state. In particular, New York State consumers will spend less on gasoline and diesel and more on electricity in a future that involves large numbers of PEVs. Since operating a vehicle on electricity is less expensive than operating it on gasoline (per mile basis), PEV consumers will also save money, freeing up resources for other purchases.

We use our model to calculate *employment* (jobs) and *economic output* ($billion/year) impacts, based on assessments of the following:

- Statewide economic impacts from a *decrease* in petroleum demand
- Statewide economic impacts of an *increase* in electricity demand
- Statewide economic impacts of an *increase* in household income (in response to decreased fuel expenses).

Each of these impacts is discussed in more detail below.

Decrease in Petroleum Demand

RIO analysis assumes that a decrease in demand for a good (output) also decreases demand for all industries contributing to the good production (inputs). Therefore, reductions in retail gasoline demand at a local level would also affect all the "upstream" inputs needed to meet that demand, including gasoline stations, transportation of fuel, wholesale trade, and petroleum processing and refining. In modeling reductions in petroleum demand, the value of decreased petroleum purchases in New York State is calculated, which reduces demand for all supporting input industries. Case-specific dollar values for decreases in petroleum are shown in Table 5 of the results section.

Increase in Electricity Demand

To model impacts of increased electricity demanded in New York State, we calculate the value of increased electricity and distribution purchases by households due to PEV use. Case-specific dollar values for increases in electricity demand are shown in Table 5.

Increase in Household Income

Overall household transportation fuel cost savings are calculated by subtracting increased electricity expenditures from petroleum cost savings. Household savings are modeled as increases in income, using an income-weighted approach that allocates savings across nine household income brackets according to each bracket's respective portion of petroleum consumption in New York State. Appendix A shows petroleum consumption figures by household income bracket. Case-specific increases in household income are shown in Table 5.

Addressing Incremental Costs of PEVs and EDVs

PEVs are currently (and will likely remain) more expensive than an "equivalent" internal combustion counterpart. This represents an *incremental capital cost* associated with the purchase of a PEV. Incremental costs of PEVs to the manufacturer are estimated at $5,500 - $18,000 per vehicle in the near term (depending on range), reducing to $3,000 to $11,000 by 2030 [5, 42, 43]. Handling such costs is an important consideration in RIO modeling.

We choose to ignore incremental capital cost impacts in this study for the following reasons. Recent literature suggests that consumers do not make choices between directly comparable alternative fueled and conventional vehicles, but rather choose across many vehicle types based on a complex analysis of vehicle attributes and the consumer's budget for vehicle purchase. If a consumer has a fixed budget for a vehicle, he/she looks to maximize or satisfy preferences for various vehicle attributes within that budget [44, 45]. In fact, HEV consumers have been found to choose between SUVs or sports cars and HEVs, rather than comparing HEVs with conventional counterparts [45-47]. Moreover, HEVs and PEVs possess additional attributes not available in conventional vehicles that are valued by consumers: HEVs and PHEVs are symbolic of environmental stewardship, reduced emissions, petroleum displacement, fuel cost savings, and high-technology to consumers; these attributes are cited as the central factors in purchase decisions [44, 47]. Thus, there may not exist what is traditionally termed an "incremental cost", as the consumer is spending no more than what he/she intended to spend – it is only that the package of attributes purchased for that amount may differ across vehicle types.

Results

Direct Fuel Spending Impacts

Table 7-6 and Figure 7-5 show the direct changes in household transportation fuel expenditures for each case. Large-scale implementation of PEVs implies a large shift of spending patterns for New York State households. Household consumers will spend less on petroleum, will spend more on electricity, and will realize considerable annual fuel expenditure savings, referred to here as "increased household income".

In this analysis, petroleum expenditures by New York State households would decrease by between \$3.86 and \$10.19 billion/year. Electricity expenditures would increase by between \$1.46 and \$1.83 billion/year. Shifts in fuel spending shown here are attributable only to the reduced cost of fuel per mile (electricity compared to gasoline). These fuel spending estimates do not incorporate estimated changes in baseline demand for petroleum in response to changes in petroleum prices. Nor do these estimates incorporate any 'rebound' effect (increased VMT) due to decreased fuel prices per mile. That is, baseline petroleum consumption and change in demand for petroleum and electricity (as shown in Table 7-4) are assumed to remain constant for all price cases, with a constant quantity of electricity displacing a constant quantity of gasoline.

Also shown in Table 7-6, the net change in household income due to fuel shifts, ranging from \$2.1 billion/year in Case III to nearly \$8.4 billion/yr in Case IV. These cases represent between \$540 to \$1,050 average annual household savings.12 These savings can be spent on any number of alternative goods and services, increasing GSP and creating jobs.

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[12] In 2008, there were 7,977,286 households in New York State according to the U.S. Census Bureau (www.census.gov).

Table 7-6
Direct Changes in Fuel Expenditures and Household Savings in New York PEV Scenario ($million/year, 2008$)

	Case I 2008	Case II 10-Year	Case III 2030 Low	Case IV 2030 High
Direct Impact				
Reduced Petroleum Demand ($M/yr)	-$6,070	-$4,120	-$3,860	-$10,190
Increased Electricity Demand ($M/yr)	$1,770	$1,460	$1,730	$1,830
Increased Household Income ($M/yr)	**$4,300**	**$2,900**	**$2,130**	**$8,360**
Increased Income per Household ($/yr)	$540	$360	$270	$1,050

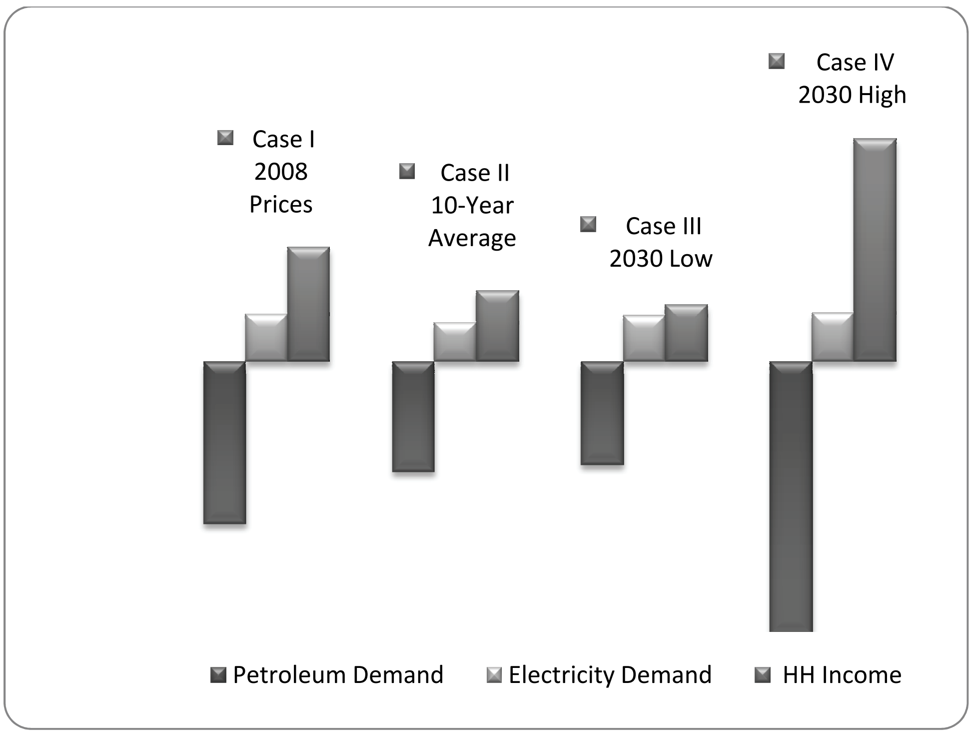

Figure 7-5
Estimated Direct Changes in Fuel Expenditures in New York PEV Scenario ($billion/year, 2008$)

Regional Input-Output Analysis Results

Table 7-7, Figure 7-6, and Figure 7-7 show economic output results for Cases I through IV. The impacts of shifts in transportation fuel expenditures are positive without exception, though results vary depending on energy prices.

Results show that across all cases, impacts range from $4.45 billion to $10.73 billion/year for increased output (GSP), and 19,770 to 59,810 job-years for employment. Employment estimates include direct, indirect and induced job impacts, and represent both full-time and part time positions. Induced employment represents the greatest share of employment impacts, comprising ~85% - 95% of jobs in each case, while direct jobs comprise roughly 3-10% of employment impacts.

Table 7-7
PEV Scenario Fuel-Driven Economic Impacts in New York State, Cases I – IV (2008$)

Case	Impact	Output ($Millions)	Employment (Jobs)
Case I 2008 Prices	*Decrease Petroleum*	-$240	-480
	Increase Electricity	$2,340	5,360
	Increase HH Income	$3,710	23,480
	Total	**$5,820**	**28,370**
Case II 10-Year Average Prices	*Decrease Petroleum*	-$240	-480
	Increase Electricity	$2,340	5,360
	Increase HH Income	$2,990	19,030
	Total	**$5,100**	**22,920**
Case III 2030 Low Prices	*Decrease Petroleum*	-$240	-480
	Increase Electricity	$2,340	5,360
	Increase HH Income	$2,340	14,890
	Total	**$4,450**	**19,770**
Case IV 2030 High Prices	*Decrease Petroleum*	-$240	-480
	Increase Electricity	$2,340	5,360
	Increase HH Income	$8,620	54,920
	Total	**$10,730**	**59,810**

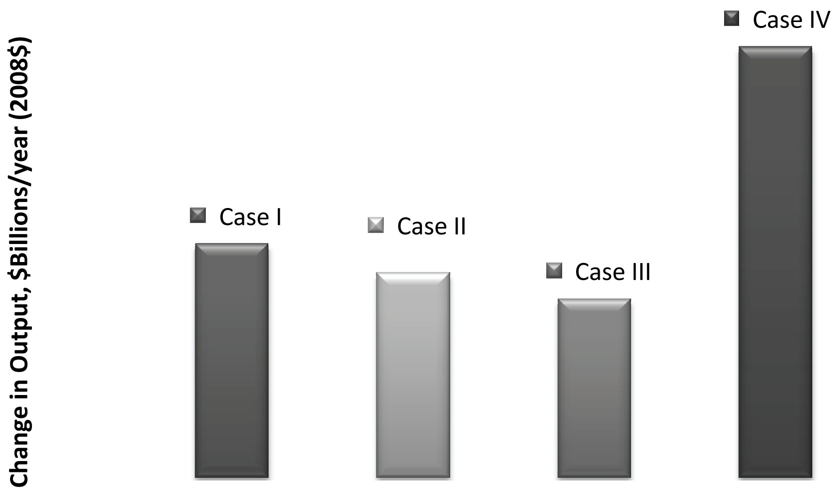

Figure 7-6
PEV Scenario Fuel-Driven Increase in New York Gross State Product across all Cases, Billions/Year (2008$)

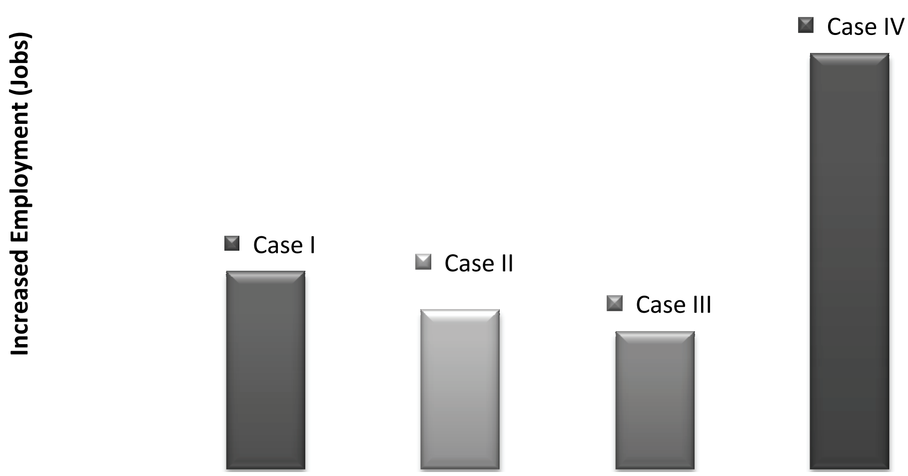

Figure 7-7
PEV Scenario Fuel-Driven Total Employment Impacts in New York across all Cases, Measured in Jobs

Table 7-7, Figure 7-8, and Figure 7-9 show the economic and employment impacts associated with increased and decreased household expenditures within the State economy for Case I (2008 prices). Petroleum displacement decreases output by $237 million and employment by 479 jobs. The relatively small impacts of reduced petroleum demand might be expected, as in 2008 New York State produced an amount of petroleum equal to only 1.4% of total state petroleum demand [48].

Increased electricity demand increases output by $2.34 billion/year and employment by 5,360 jobs. In contrast to petroleum, the majority of electricity purchased in New York is supplied by New York State producers [41, 48, 49].

Household income savings have an enormous impact, demonstrating the importance of household income being spent on goods and services in New York State rather than being funneled outside of the State economy and outside of the United States. The "multiplier effects" of increased household income increase output by $3.7 billion/year and increase employment by 23,480 jobs.

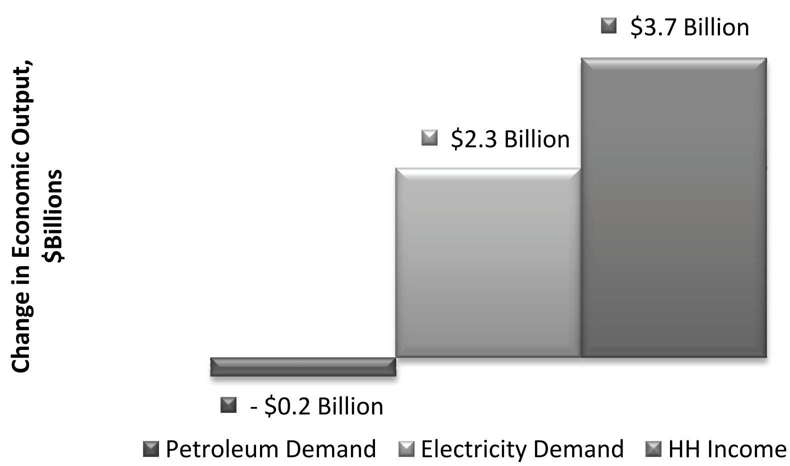

Figure 7-8
Gross State Product Impacts of Individual PEV Scenario Fuel Shifts and Household Income Changes, Case I (billions, 2008$)

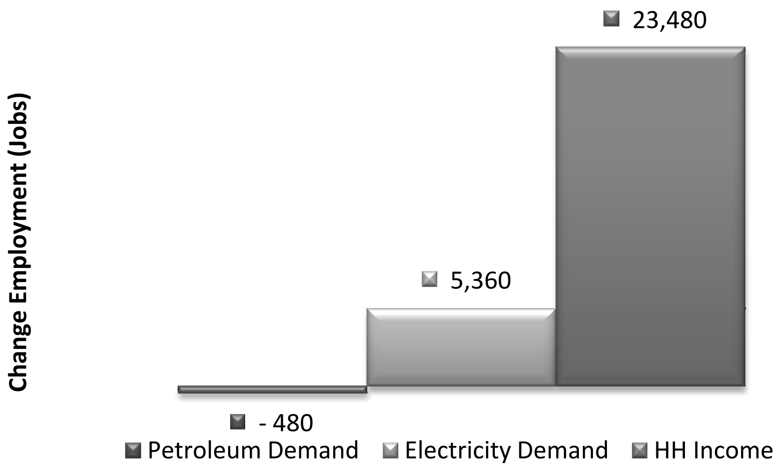

Figure 7-9
Employment Impacts of Individual PEV Scenario Fuel Shifts and Household Income Changes, Case I (jobs)

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8 EMISSION IMPACTS OF PEVS IN NEW YORK

Executive Summary

Plug-in Electric Vehicles (PEVs) have the ability to use electricity as a transportation fuel, which can drastically reduce the amount of gasoline used by the vehicle. Petroleum reduction alone is a significant benefit, but this shift also enables a reduction in carbon dioxide (CO2) emissions and an improvement in air quality, since electricity generation for transportation usually has lower emissions than using gasoline as a transportation fuel. This report describes an analysis of the impact of a high penetration of PEVs in New York State by looking at the tradeoff between emissions from New York electricity generators used to charge electric vehicles and the reduction in gasoline use.

The air quality impacts of PEVs were analyzed by comparing the power plant emissions increases due to increased generation relative to the vehicle and fuel system fuel emissions reductions due to decreased gasoline use. These relative emissions were then simulated in an air quality model to determine resulting levels of ozone, 2.5 micrometer and smaller particulates (PM2.5), and 10 micrometer and smaller particulates (PM10). The use of PEVs:

- Decreases ozone levels, and has a high impact on populated areas
- Leads to a reduction in PM2.5 across New York State and the surrounding areas, especially around New York City
- Leads to a reduction in PM10 across New York State and the surrounding areas

Overall, the relative magnitude of changes is small even for large penetrations of PHEVs.

Overview

Plug-in Electric Vehicles (PEVs) have the ability to use electricity as a transportation fuel, which can drastically reduce the amount of gasoline used by the vehicle. Petroleum reduction alone is a significant benefit, but this shift also enables a reduction in carbon dioxide (CO2) emissions and an improvement in air quality, since electricity generation for transportation usually has lower emissions than using gasoline as a transportation fuel. This report describes an analysis of the impact of a high penetration of PEVs in New York State by looking at the tradeoff between emissions from New York electricity generators used to charge electric vehicles and the reduction in gasoline use. This work is based substantially on EPRI reports 1015325 and 1015326, Environmental Assessment of Plug-In Hybrid Electric Vehicles Volumes 1 and 2 (called the EPRI-NRDC analysis below). This report will summarize the assumptions used to calculation emissions changes; detailed information about the economic and emissions assumptions can be found in these two reports, which are publicly available at no cost.

In order to perform this analysis, two scenarios are examined: a scenario with no PEVs and a scenario with aggressive PEV adoption. The relative impact of PEVs is analyzed by looking at the difference between CO2 emissions and air quality measurements in these two scenarios.

Plug-in Hybrid Electric Vehicle Deployment Model

Two PEV deployment scenarios are used: a Base case without PEVs, and a PEV case with aggressive PEV deployment, which uses the 'Medium' scenario from the EPRI-NRDC analysis. Both scenarios assume an aggressive move to efficiency, with a high penetration of Hybrid Electric Vehicles (HEVs) in both cases. In the Base, a high level of HEVs is present; in the PEV case, a large number of PEVs are present, replacing HEVs. In both cases, it takes a long time for new vehicles to be deployed across the entire fleet. Figure 8-1 and Figure 8-2 show new vehicle sales and Figure 8-3 and Figure 8-4 show the fleet shares for the two cases. Figure 8-5 shows the new vehicle share and fleet share for only PEVs in the PEV case to illustrate the time lag for deployment.

It should be noted that this comparison is a relatively conservative one: PEVs are not matched against conventional vehicles, but against already-efficient hybrid vehicles. In actuality, if PEVs were not available, some vehicle sales would likely go to conventional vehicles instead of to HEVs, since there are a variety of vehicle uses and consumers for which HEVs are not the best replacement for PEVs. Since no data on this split is available, though, this analysis compares the most conservative option.

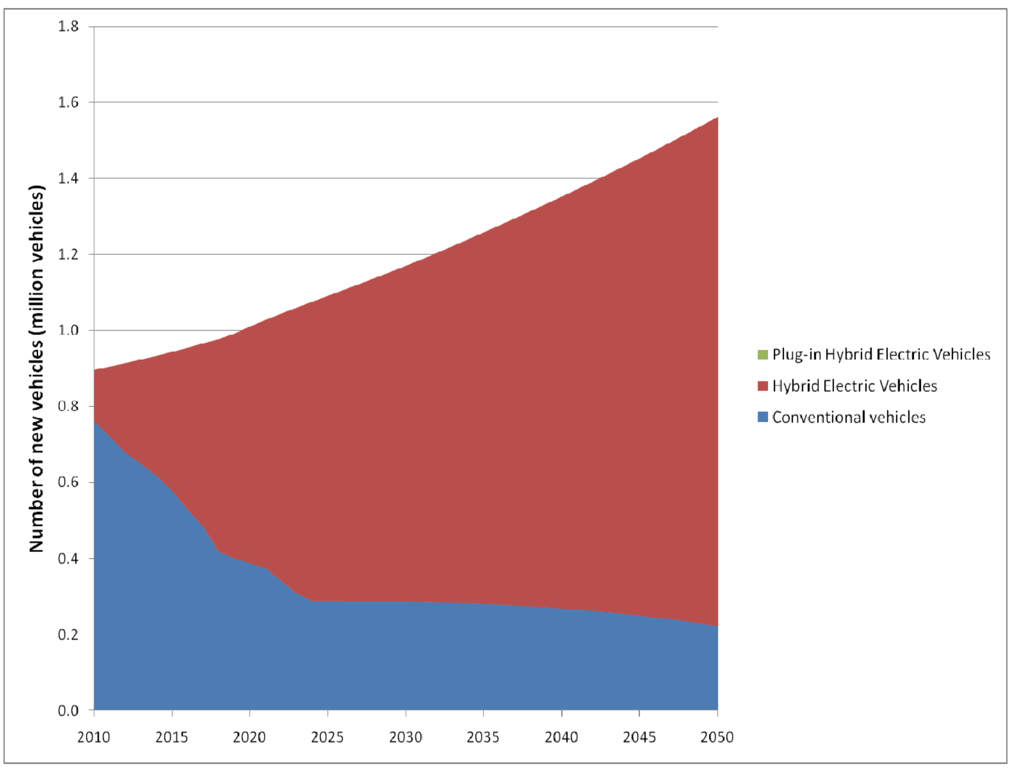


Figure 8-1
New Vehicle Sales in Base Case

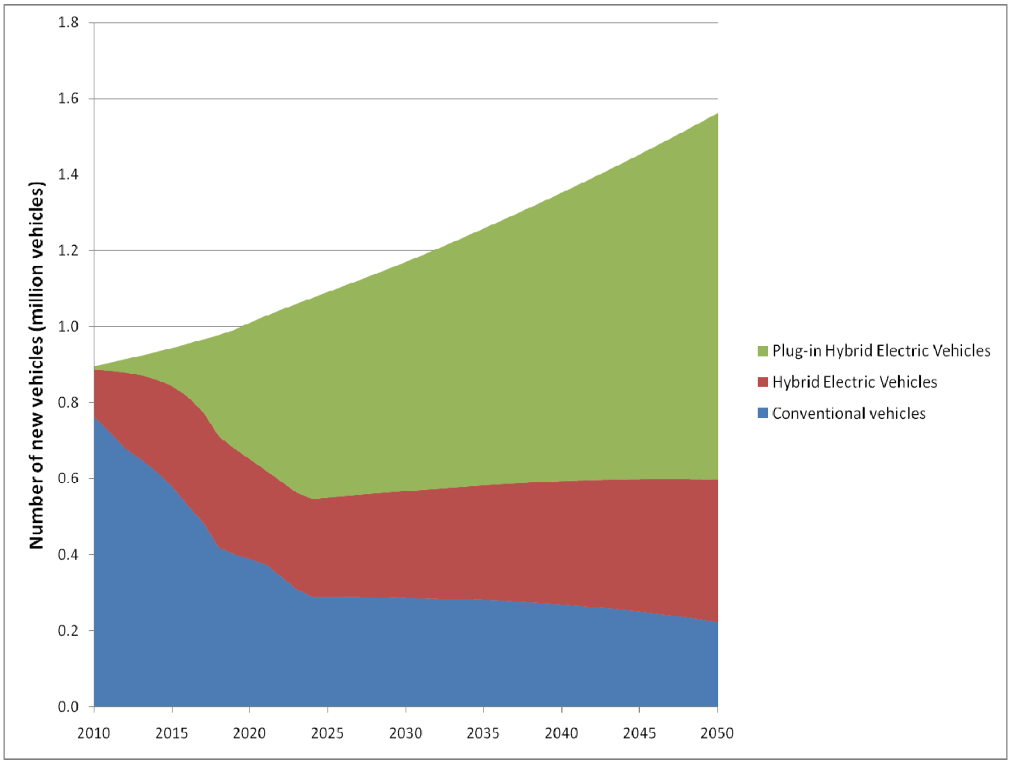


Figure 8-2
New Vehicle Sales in PEV Case

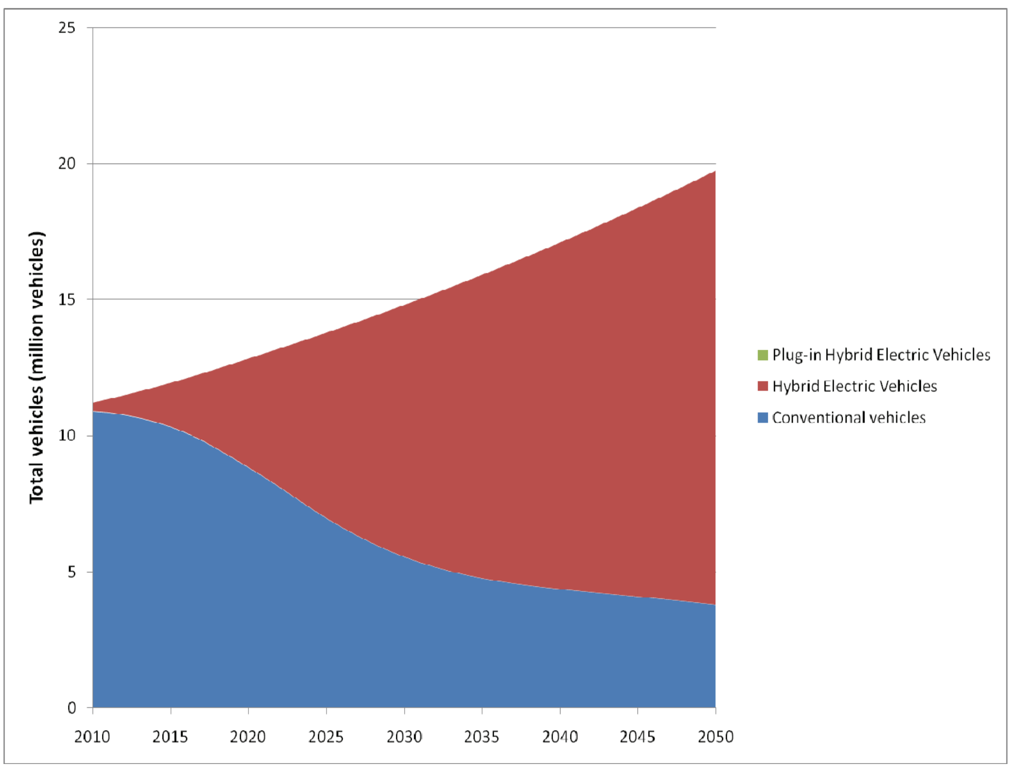


Figure 8-3
Fleet Shares for Base Case

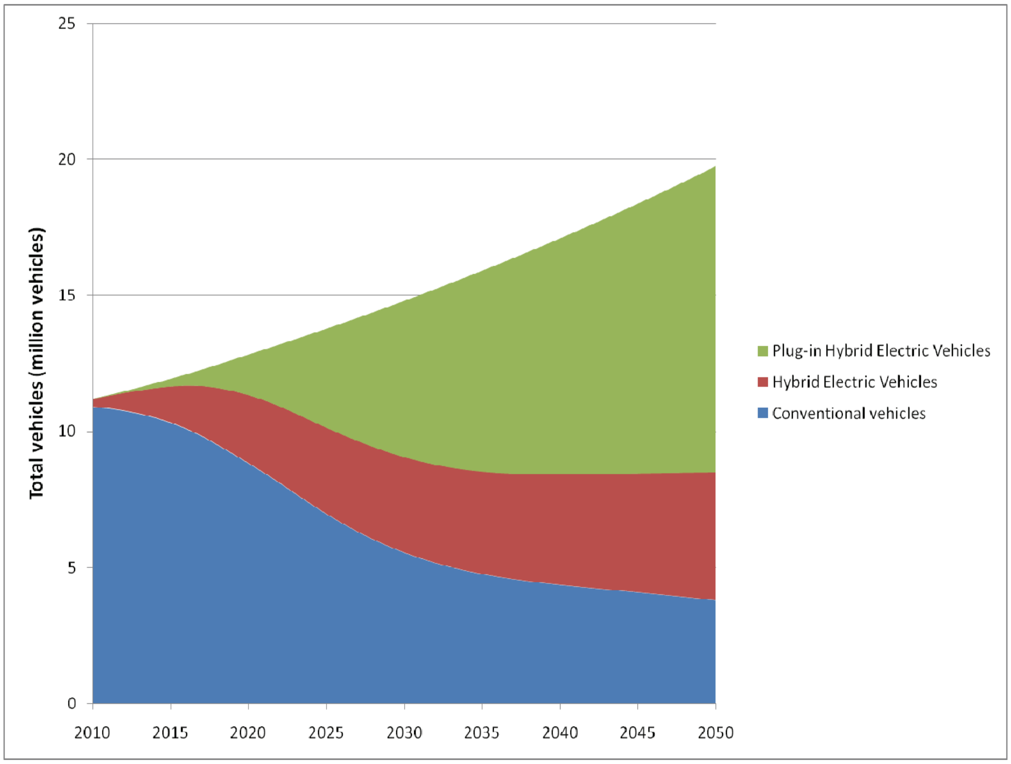


Figure 8-4
Fleet Shares for PEV Case

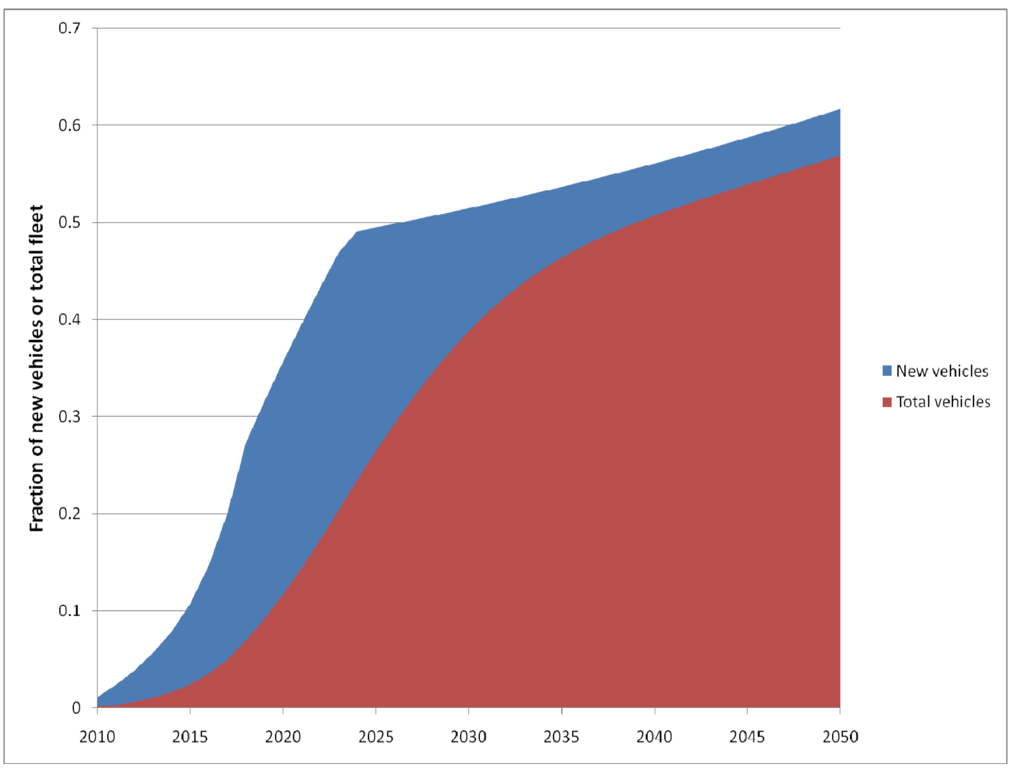


Figure 8-5
Penetration Lag of PEVs in PEV Case

Air Quality Analysis

The air quality impacts of PEVs were analyzed by comparing the power plant emissions increases due to increased generation relative to the vehicle and fuel system fuel emissions reductions due to decreased gasoline use. These relative emissions were then simulated in an air quality model to determine resulting levels of:

- Ozone
- Particulates
- Deposition of sulfate, nitrate and total nitrogen

Volume 2 of the EPRI-NRDC report describes the methodology used in this analysis in detail. The emissions levels and air quality impacts are simulated for the year 2030, after a substantial penetration of PEVs, but within the time horizon during which emissions can be reasonably modeled. The results from New York are presented and discussed below. Each set of results is presented as a chart of the emission in the Base case, and a chart of the percentage change between the Base case and the PEV case. Negative percentages represent reductions; positive percentages represent increases due to PEVs.

In general, PEVs lead to improvements in air quality in New York State and surrounding areas based on a wide array of measures. Although the modeling finds some limited negative impacts, these are greatly offset by improvements, and should be considered areas for increased investigation rather than 'showstoppers.'

Ozone impacts of PEVs

Figure 8-6 and Figure 8-7 show a measure of the ozone level for the Base case and the PEV case for the year 2030. The National Ambient Air Quality Standard (NAAQS) for ozone (O_3) is based on the 99^{th} percentile of the highest daily 8-hour average of ozone concentrations, or simply the fourth highest daily 8-hour ozone average. This basis is referred to as the "design value" of the standard. The current level of the standard not to be exceeded by the design value is 75 ppbv (parts per billion per volume). This corresponds to regions in Figure 8-6 shown in orange-to-red colors. The figures show that although the improvement in lowering ozone concentration is modest, it does tend to occur in areas with higher ozone concentrations. Figure 8-8 and Figure 8-9 show a modified measure which weights exposure based on population. These figures show that use of PEVs can lead to reduced exposure to ozone in highly populated areas. In summary, although there are many challenges to lowering ozone concentrations even in 2030, PEVs do not exacerbate the problem and at the penetration rates modeled can provide some modest benefits.

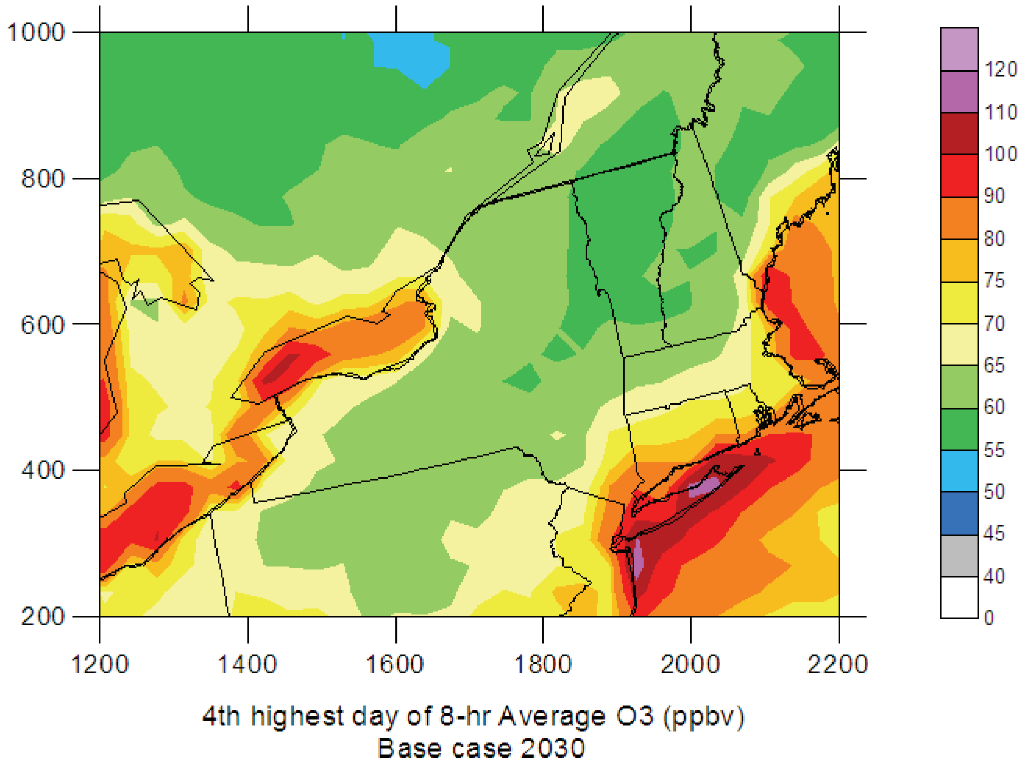


Figure 8-6
Annual 4th Highest 8-Hour Ozone (ppb) for Base case

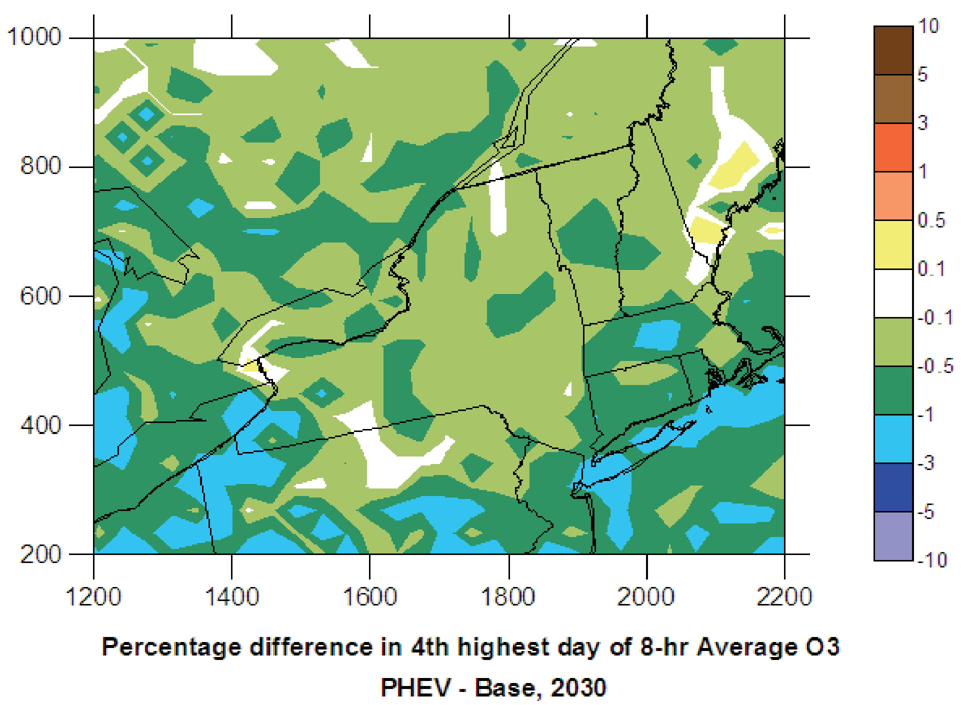
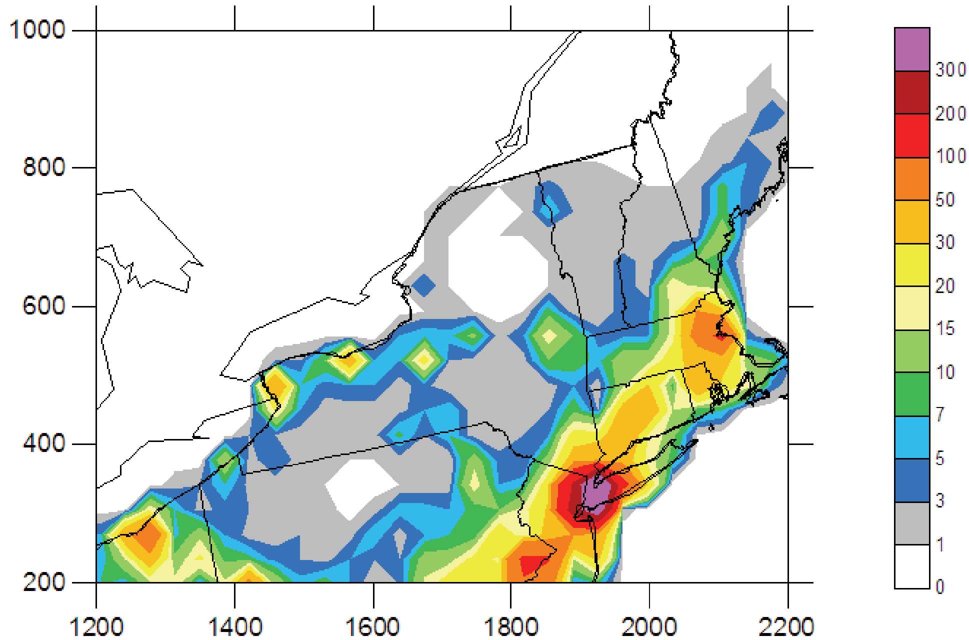


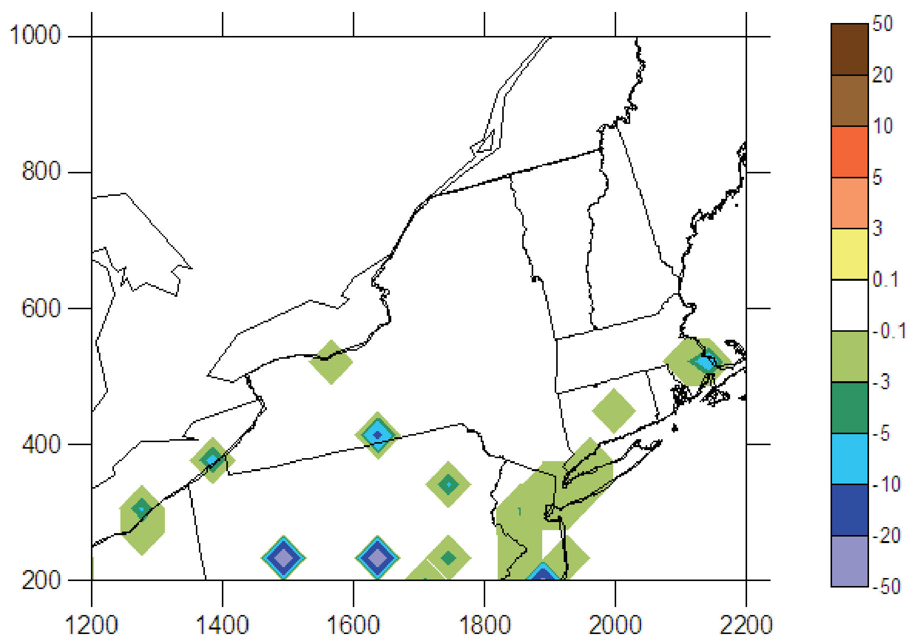
Figure 8-7
Percentage Difference in 4th Highest 8-Hour Ozone Level between Base Case and PEV Case



Ozone design value exposure based on 4th high 8-hr ozone [ppb x 10^6 persons]

Base case 2030

Figure 8-8
Ozone Design-Value Exposure Based on 4th Highest 8-Hour Average Ozone (000,000 ppb x person) for Base Case



Percentage difference in design value exposure based on 4th high 8-hr ozone

PHEV - Base, 2030

Figure 8-9
Percentage Difference in Ozone Design Value Exposure between Base Case and PEV Case

Particulate Matter Impacts of PEVs

Particulate matter in the atmosphere is a result of direct emissions from sources such as power plants and vehicles and is also formed in the atmosphere due to reactions between gaseous pollutants. Air quality models simulate both the emissions of primary particulate matter and the formation of secondary particulate matter in the atmosphere. Over the past years, a high degree of emphasis has been placed on fine particulate matter (PM2.5) due to its association with a variety of adverse health impacts. There are currently two design values for PM2.5, one based on the 98th percentile of 24-hour (daily) averages and one based on annual averages. The current level of the daily standard is 35 $\mu g/m^3$ and the current level of the annual standard is 15 $\mu g/m^3$. Figure 8-10 and Figure 8-11 show the peak concentrations of PM2.5 in the Base case and as a percentage change from the base case for the daily average PM2.5 design value in 2030. Increased use of PEVs leads to a reduction in PM2.5 across New York State and the surrounding areas including areas that may still be in non-attainment within the New York City Metropolitan Area.

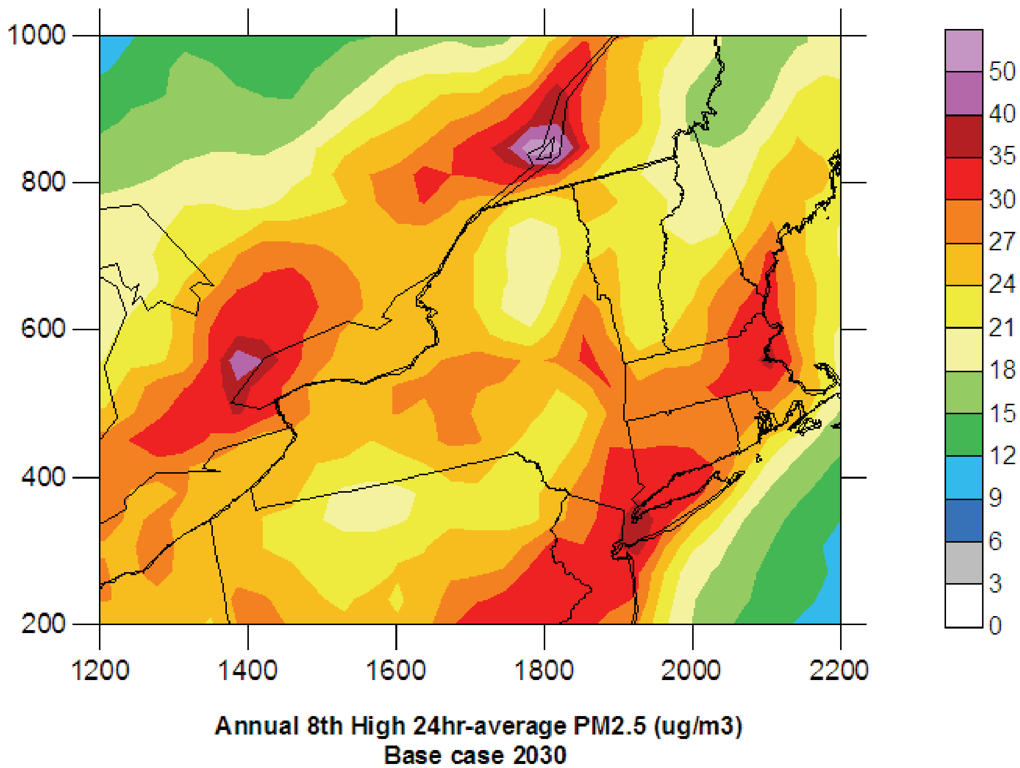


Figure 8-10
Annual 8th Highest 24-Hour Average Concentrations (μg m-3) of PM2.5 for Base case

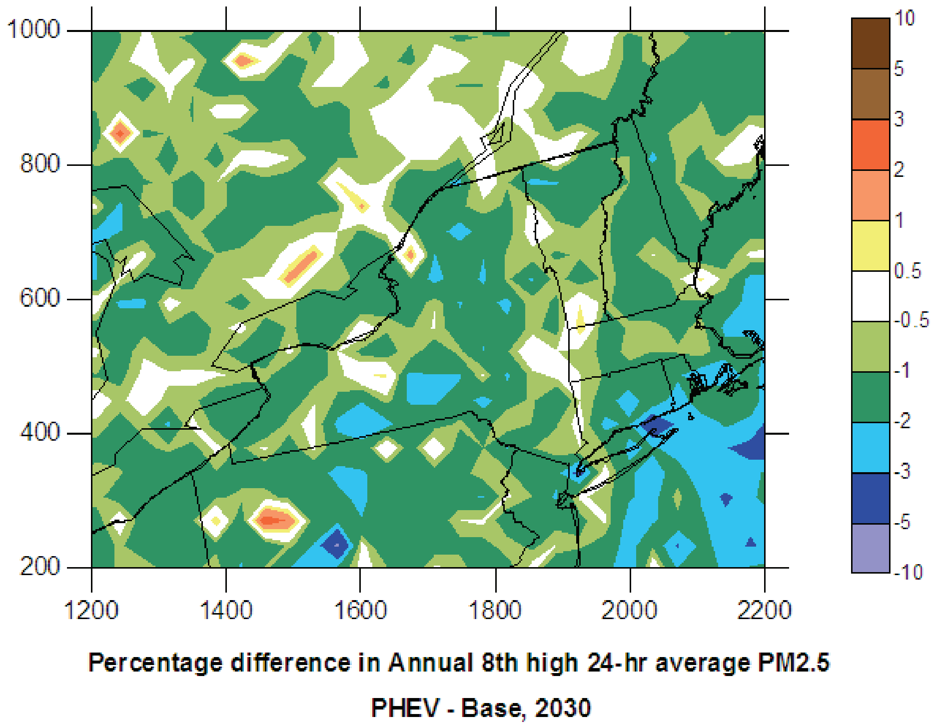


Figure 8-11
Percentage Difference in Annual 8th Highest 24-Hour Average Concentrations of PM2.5 between the Base Case and the PEV Case

Figure 8-12 and Figure 8-13 show the average concentrations for PM2.5 for the year 2030. These maps integrate model predictions of PM2.5 over the entire year as opposed to the daily standard that focuses on the eighth highest 24-hour average. As a result, the values are lower and the spatial distribution is also different, reflecting the contribution from various sources and different meteorological and chemical regimes. PEVs lead to a general reduction in annual concentrations of PM2.5 in New York State and surrounding areas. There is an apparent increase in concentration in particulate matter in New Hampshire due to PEVs, but this is more likely due to a modeling artifact than an expected effect. It is likely that a number of older power plants were already concentrated in this area, and new power plants added to this area increased local pollution. In reality, it is likely that area-specific siting considerations, such as New Source Review (NSR) and Prevention of Significant Deterioration (PSD), would ensure that this type of concentration of emissions would not take place.

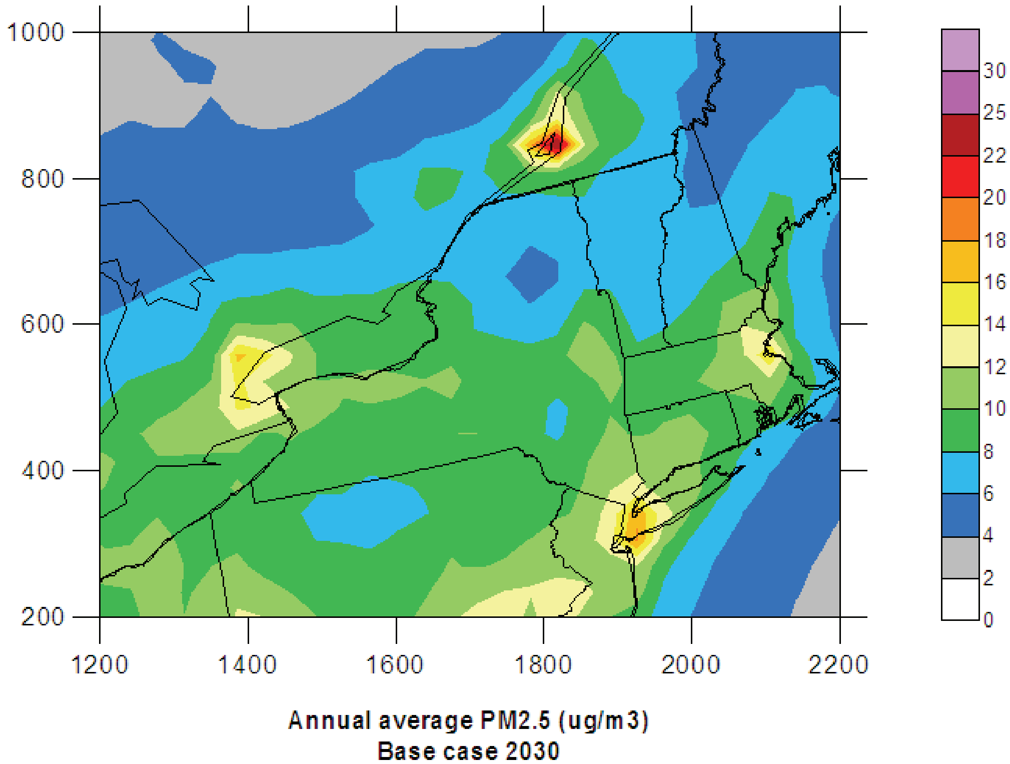


Figure 8-12
Annual Average Concentrations (µg m-3) of PM2.5 for Base Case

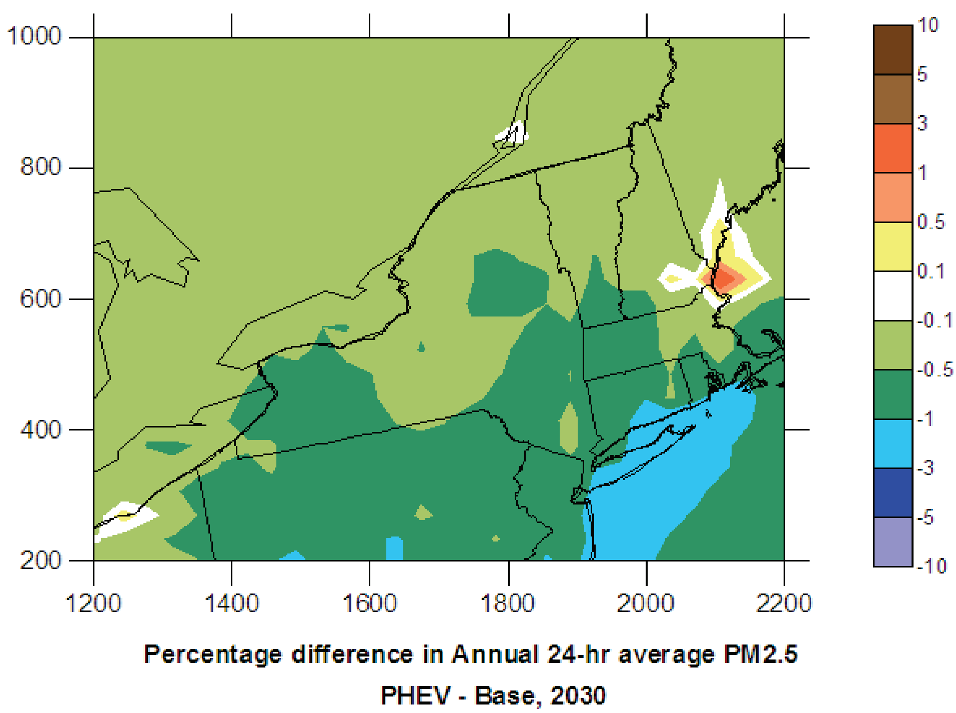


Figure 8-13
Percentage Difference in Annual Average Concentration of PM2.5 between Base Case and PEV Case

Figure 8-14 and Figure 8-15 show the population-weighted peak exposure to PM2.5 for the Base case and the percentage difference between the Base case and PEV case. Introduction of PEVs leads to a substantial improvement in population-weighted peak exposure to particulate matter in New York State and the surrounding areas, with reductions in exposure prevailing in the main transportation corridors, which could lead to significant public health improvements.

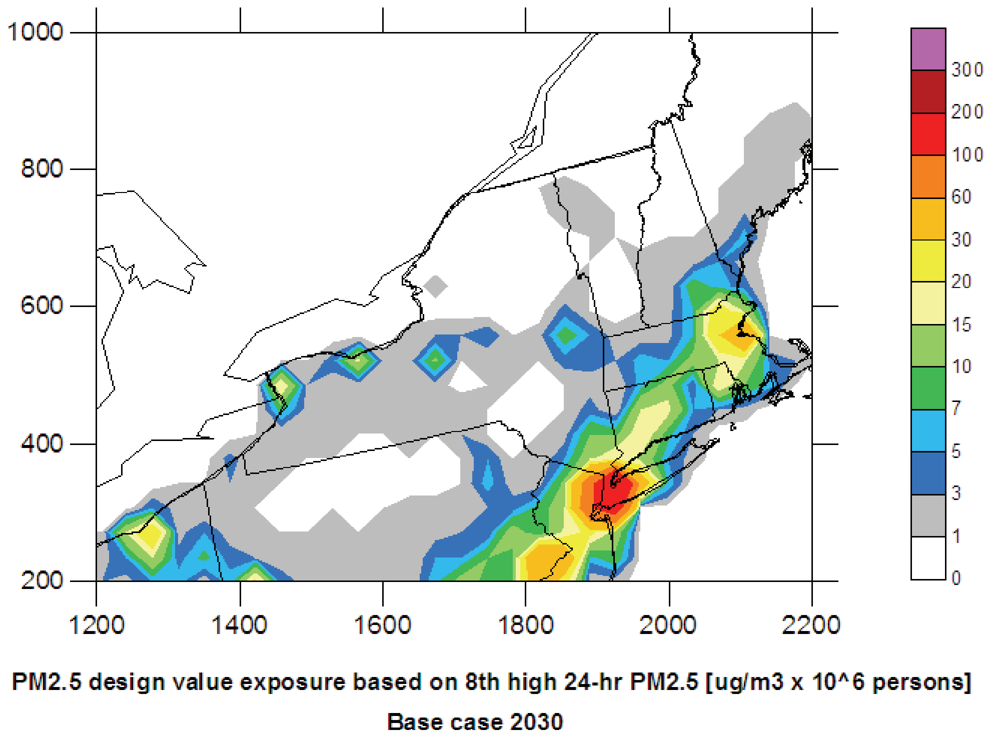


Figure 8-14
Daily PM2.5 Design-Value Exposure based on the 8th Highest 24-Hour-Average PM2.5 Concentration (000,000 µg m-3 × person) for Base Case

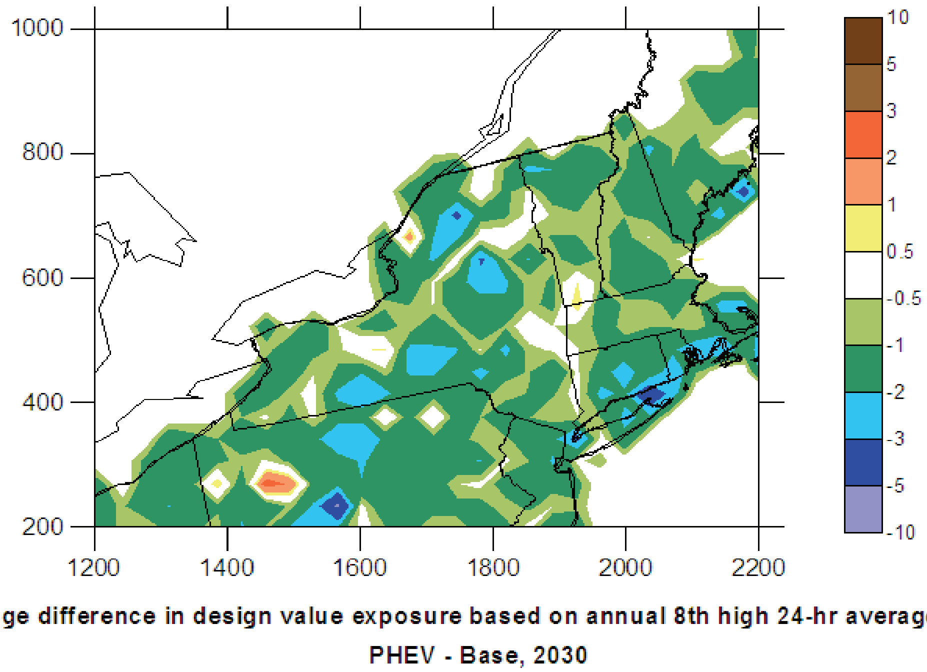


Figure 8-15
Percentage Difference in Daily PM2.5 Design Value Exposure between the Base Case and the PEV Case

Sulfate, Nitrate and Total Nitrogen Deposition

Figure 8-16 and Figure 8-17 show the annual deposition of sulfate in the Base case, and the percentage difference between the Base case and the PEV case. Although this analysis appears to suggest that PEVs lead to an increase in sulfate deposition in most of New York State, in reality sulfate deposition has reached very low levels due emissions reductions under the Clean Air Interstate Rule (CAIR) and other regulations included in the air quality modeling. After this analysis was performed, the courts remanded CAIR and EPA has proposed an alternative Clean Air Transport Rule (CATR). As CAIR was remanded and not vacated, CAIR Phase I reductions are currently taking place. Assuming that CATR supersedes CAIR, its approach to emissions caps will be adopted instead of the second phase of CAIR. However, this should not affect the main result which is a reduction in emissions and ensuing deposition from electric generating units. In addition, it should be noted that EPA is expected to issue further transport rules (which are developed to minimize the impact of interstate transport of pollution) when NAAQS standards are modified for ozone and PM in the future.

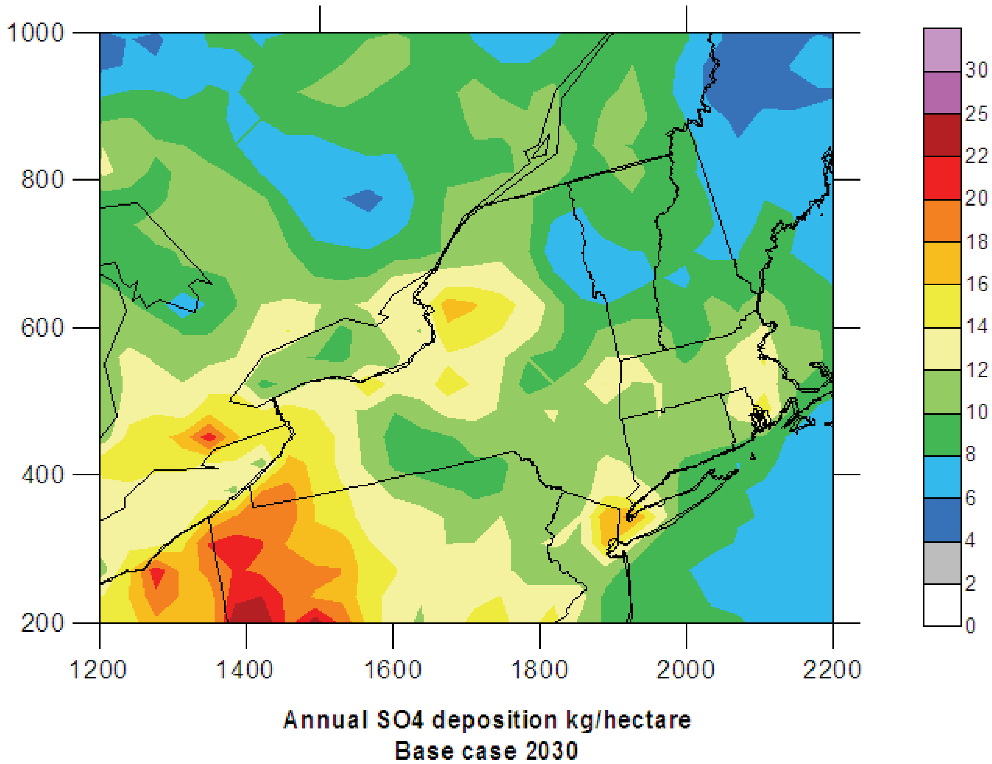


Figure 8-16
Annual Deposition (kg Ha^{-1}) of Sulfate in Base Case

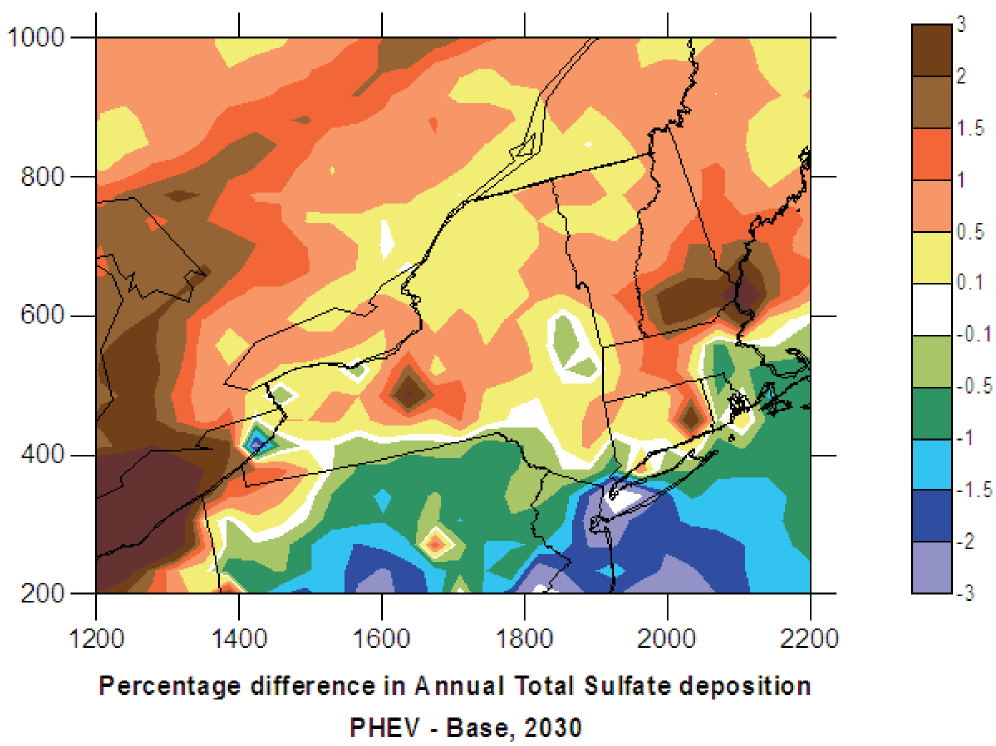


Figure 8-17
Percentage Difference in Annual Sulfate Deposition between Base Case and PEV Case

Figure 8-18 and Figure 8-19 show the annual deposition of nitrate in the Base case and the percentage difference between the Base case and the PEV case. Figure 8-20 and Figure 8-21 show the annual deposition of total nitrogen in the Base case and the percentage difference between the Base case and the PEV case. PEVs lead to a substantial decrease in the deposition levels for both pollutants in New York State. There are some negative impacts in total nitrogen deposition in New Hampshire. As described above, this is likely due more to a modeling artifact than a likely impact.

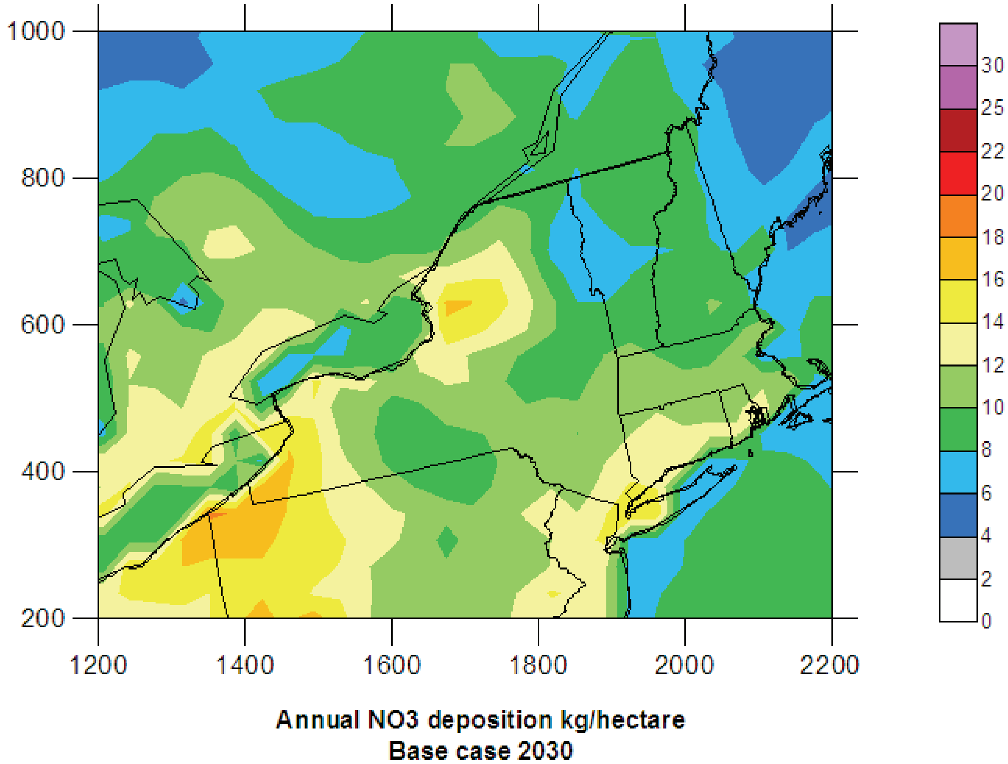


Figure 8-18
Annual Deposition (kg Ha^{-1}) of Nitrate for Base Case

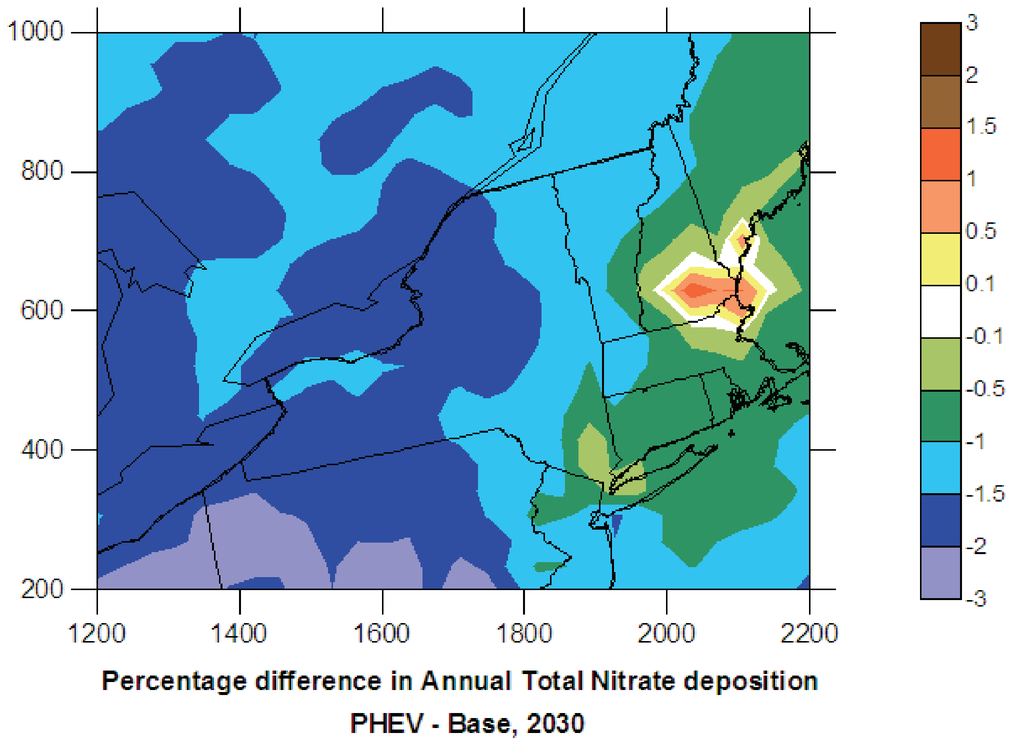


Figure 8-19
Percentage Difference in Annual Nitrate Exposition between Base Case and PEV Case

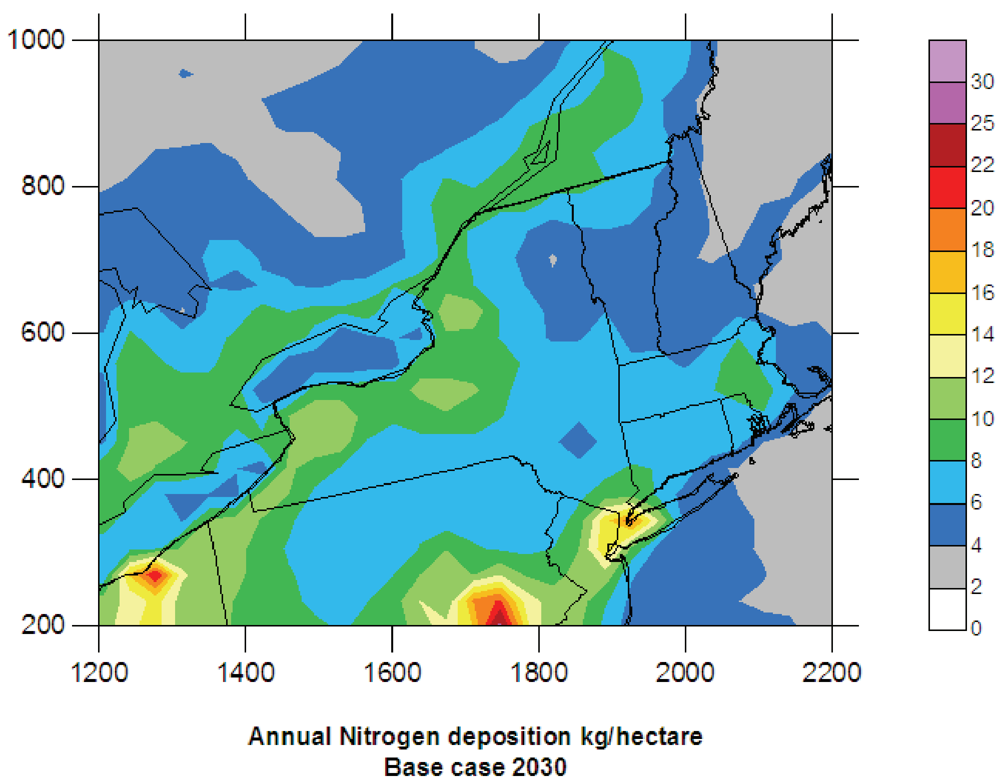


Figure 8-20
Annual Deposition (kg N Ha^{-1}) of Total Nitrogen for Base Case

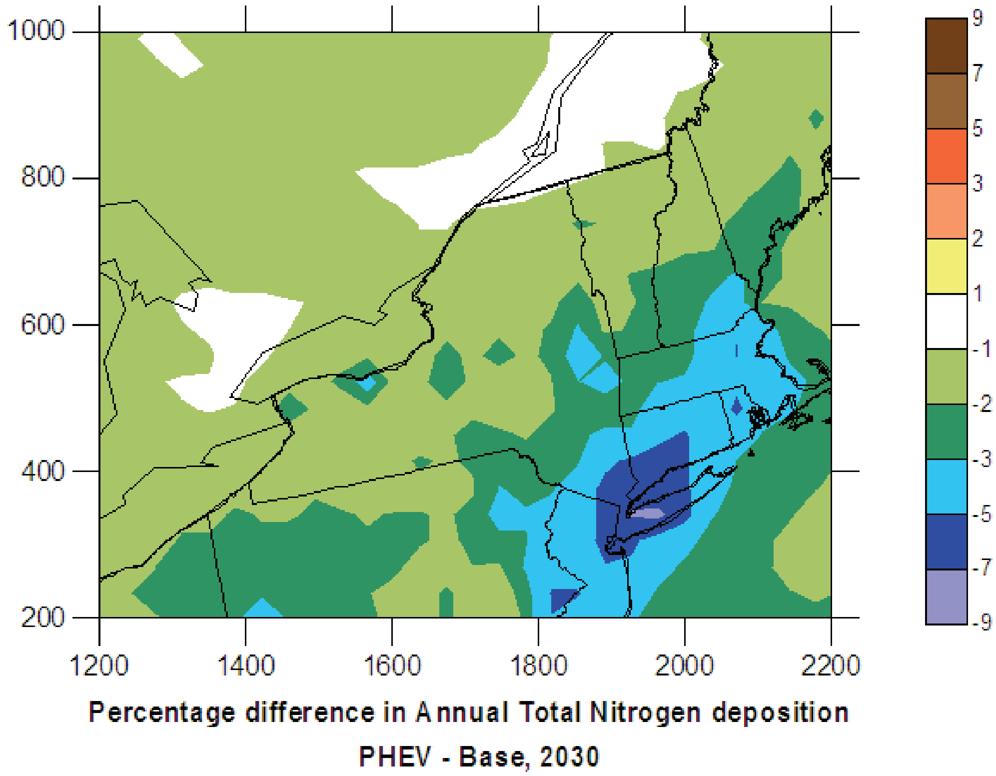


Figure 8-21
Percentage Difference in Annual Deposition of Total Nitrogen between Base Case and PEV Case

Greenhouse Gas Analysis

Use of PEVs will increase emissions due to generation, but they will decrease emissions due to gasoline consumption. It is important to analyze the tradeoff between these sources of emissions as the grid and the transportation fleet change.

9 IMPLICATIONS OF PEV AS A DISTRIBUTED RESOURCE

Executive Summary

This report summarizes studies and demonstrations of the use of demand-side resources, in particular plug-in vehicles (PEVs), to provide services to the grid and smooth the output of renewable generation such as solar photovoltaic (PV). PEVs include plug-in-hybrid (PHEV) and battery electric vehicle (EV) technologies. The vehicles represent a controllable load whose charging may be curtailed, and in addition the vehicle may provide energy back to the grid to act as a source of mobile energy storage. This is commonly called vehicle-to-grid (V2G), and would require the capability for bi-directional power flow when the vehicle plugs into the grid. The economic value and the value of the PEV as a source of energy depend on the storage capacity of the battery system, the capacity of electrical supply where the vehicle is plugged in, and the service the vehicle is providing.

Several studies have assessed possible economic benefits from PEVs providing grid services such as frequency regulation. The results of these studies suggest that the storage on board PEVs may be used for a variety of services in the power grid and merit further research as vehicles are introduced into the mass market. Depending on the local market conditions and other infrastructure development such as advanced metering infrastructure (AMI) or increased penetration of renewables it may be worthwhile to explore the topics herein in further detail.

As an example, the V2G program at the University of Delaware (UD) has assessed the economic potential for advanced vehicle technologies providing ancillary services in various independent system operator/regional transmission operator (ISO/RTO) markets [1- 3]. The annual net revenue for a single vehicle was assessed considering PEV, EV and fuel cell vehicles, and ranged from $290 to $2,554 depending on the type of vehicle and the service being provided. Another report found that the net revenue achievable for a vehicle providing frequency regulation is three to four times as much as providing spinning reserve depending on the market [2]. Fleet applications have also been considered with a resulting $200 to $800 per vehicle in some applications [3].

The objective of this work was to determine the state of distributed storage and V2G research and demonstration. The material will interest energy providers who are considering the impacts of PEVs in their service territories. In addition the examples of valuation of the economic benefits of providing grid services will be of interest to vehicle owners when considering participation in enhanced demand response and V2G programs in the future.

The results and applications discussed in this study may be extended to any form of modular energy storage that may be used to improve bulk grid reliability, or in combination with distributed intermittent renewable generation sources. As smart grid infrastructure including two-way communications associated with AMI becomes more widespread and as ISO/RTO markets evolve to better accommodate participation of smaller capacity resources the topics discussed will become more relevant. In addition, current vehicles being released in the near-term will not be equipped for bi-directional energy supply associated with V2G; therefore substantial work in

the area of hardware, software, and control technologies will be needed for large-scale application of these ideas.

The work being done at EPRI with vehicle and power system modeling will aid in the assessment of what forms of vehicle supply will be feasible and what their impacts will be on grid operations. EPRI is actively involved in standards development of automated demand response, smart grid, AMI and PEV technologies, and therefore is in touch with the needs of stakeholders throughout the V2G value chain. The needs of power grid, grid operators, and vehicle owners must all be considered when exploring the use of PEV as distributed energy storage.

The results presented herein will allow users to identify possible benefits associated with increasing penetration of PEV and provide examples of the value streams that vehicle owners might realize by allowing their vehicles to be used for V2G applications. The material was gathered through a thorough review of current academic and industry literature.

Study of Electric Vehicle Storage as a Distributed Resource

Given typical driving patterns, about 85-90% of the total vehicles are expected to be in a “parked” state at any given point throughout the day. Furthermore, it is expected that electric vehicles will constitute a significant portion of total automobiles in service by the end of the next decade. One could then foresee a significant quantity of electric vehicles that will be connected to the electric grid and available for dispatch if called upon. The available idle energy associated with such a large aggregate source represents a potential resource from which to support utility system operations.

Grid operators use a variety of tools commonly referred to as “ancillary services” to reliably operate the electrical system. The Federal Energy Regulatory Commission (FERC) defines ancillary services as “those services necessary to support the transmission of electric power from seller to purchaser, given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system.” [23] Load following, for example, is the balancing of generation to normal time-varying changes in load. Another ancillary service is operating reserves in the form of spinning and non-spinning reserves that are called into service to provide system reliability in the event of a major grid disturbance such as the loss of a generator or transmission line. In all, it is estimated that ancillary services accounts for 5-10% of the total cost of electricity, which in the U.S. alone equates to approximately $12 billion per year [24].

A significant driver in examining the vehicle-to-grid (V2G) operation as a potentially ancillary service is the ability to vary output quickly. Power plant generator ramp rates are typically quantified in terms of minutes due to the mechanical nature of these sources. Electric vehicles on the other hand are interfaced to the system via power electronics and can therefore be dispatched and ramped up in very short spans of time, as fast as a few seconds. This fast response time would have no problem following fast changing load fluctuations or even quick changes in generation associated with renewable sources such as wind and photovoltaic solar panels. Additionally, charging controls could be augmented to provide localized frequency support that responds instantaneously to large frequency deviations. This control would potentially emulate the generator governor controls that respond to deviations occurring at a faster rate than the automatic generation control signals can respond to. While response time is an attractive feature, availability of sufficient energy resources of an aggregated source is a concern. Vehicle-to-grid operation represents a distributed resource interconnected at distribution system level but supplying ancillary services to both distribution and transmission systems. As such, V2G represents an aggregated bottom-up resource that is in stark contrast to traditional generator supplied ancillary support. Given the intermittent nature of vehicular interconnection and state of charge, it will be necessary to identify under what conditions an aggregated V2G operation would be considered a reliable ancillary service provider.

The natural question then is: "does V2G offer a competitive alternative to conventional generation systems used today to provide ancillary services?" Additionally, is there viable potential for V2G to provide additional system services typically associated with other distributed sources such as peak demand shaving and at home backup power. Brief descriptions of potential ancillary and support services for V2G implementations are subsequently examined.

V2G: Ancillary resource – Load Following

Stable and reliable grid operation requires assuring real time matching of total generation with the total load. The United States power system consists of three sub-grids, the Eastern Interconnect, Western Interconnect, and Texas Interconnect, which are tied together with high-voltage DC transmission lines. Each system is in itself an AC transmission system consisting of sub-regions and smaller control areas. System operators act within each control area to ensure that demand is met and that scheduled power flow with adjacent control areas, termed tie-line power flow, is maintained. The system operates nominally at 60 Hertz when load and generation are perfectly balanced, however the frequency fluctuates around 60 Hertz in response to changes in system load throughout the day. There are several levels of balancing provided by grid operators ranging from day ahead scheduling of generation to accommodate general loading trends to dispatch of automatic generation control (AGC) to match minute-to-minute load fluctuation.

Load following or frequency regulation is used to balance generation and load in the power grid on a minute-to-minute basis and to ensure that scheduled tie-line power flow is maintained with adjacent control areas. There are two types of regulation, primary and secondary. Primary frequency regulation is provided by generators with speed governors and acts automatically to mitigate frequency deviations within the system. Primary regulation alone can arrest frequency deviations, however a steady-state frequency error will result, i.e., the frequency will not return on its own to 60 Hz. Therefore a second level of regulation is necessary to return the frequency to 60 Hz and account for deviations from scheduled tie-line power flow. The area control error (ACE) is computed to determine the required change in generator output to correct the frequency and tie-line flow deviations. Based on the ACE a control signal is sent to generators participating in automatic generation control (AGC) every four seconds telling them to either increase or decrease their output to provide regulation up or regulation down respectively. In simple terms, when load exceeds generation, system frequency will drop and generators will be asked to provide regulation up to meet system load, and vice versa for regulation down. Some ISO/RTO regulation markets combine regulation up and down such that both have the same clearing prices (e.g., NYISO and PJM) while other markets have separate clearing prices for regulation up and down (e.g., CAISO and ERCOT).

Individual control of a multitude of intermittently connected vehicles across the control area is a task grid operators are not equipped to handle. Instead, a controller is necessary, which can aggregate each available resource in such a way that they can be treated as a single resource by the grid operator. Each connected vehicle will therefore be required to communicate to the aggregate controller its operation parameters and charging requirements. This information will be compiled by controller and correlated to the grid operator command to determine each vehicle's demand and/or generation dispatch.

In an electric vehicle, regulation can be purchased just as it is done today for conventional generation resources. Payments for regulation are based on two components: (a) a contract payment for availability (in US$/MWh) plus (b) an energy payment per kWh when power is produced. Yearly revenue from regulation up or down can be calculated from the plug-in time, capacity price, market selling price, and the power available in the vehicle's battery. The cost to produce regulation up is calculated as the cost to produce each kWh times the number of kWh produced per year.

A vehicle supplying regulation down is expected to increase charging, therefore there is no cost for a vehicle supplying regulation down. On the other hand, a vehicle supplying regulation up may equate to either decreased demand or battery discharge. It is important to note that decreasing the existing load by curtailing existing vehicle charging demands effectively acts as regulation up. As such, it is not always necessary for V2G to inject power into the system in order to provide both up and down regulation. Nevertheless, if discharging occurs, the cost for the energy stored in the battery must be considered. The battery degradation costs must also be factored in. It is important to remember that in regulation the battery degradation is different when compared to transportation mode as a result of the shallow type of cycling for regulation rather than deep charge/discharge cycling in the transportation mode.

An initial approach to implementing V2G could be to focus on regulation services that can be performed with the plug-in vehicle operating exclusively as a dispatched load rather than a source. This possibility is examined by Brooks [25]. The approach has many advantages for the initial rollout of V2G: it eliminates the interconnect issues around feeding power back to the grid; battery wear due to bi-directional power cycling is not well understood, and could have a cost impact greater than the benefit produced. Finally, storing energy in a battery and then discharging it back into the grid results in energy losses due to the conversion of AC to DC in the charger, throughput losses in the battery, and then DC from the battery back to AC. Nevertheless, the application of this approach may be limited by the hourly charging demand behaviors. If it is assumed that most of the charging occurs during the night, curtailment of the day time controllable demand may not provide sufficient regulation.

Preliminary analysis has indicated that a positive revenue stream is achievable through the use of V2G to provide frequency regulation [26]. In general, larger profits come from providing V2G power for regulation up and down but providing regulation down only can be more attractive option for certain vehicles and/or A/S markets. It is necessary to evaluate the use of electric vehicles in a specific market, looking at supplying regulation down alone and both regulation up and down. Variability in market prices should also be taken into account to get a complete picture of V2G value.

V2G: Ancillary resource – Spinning Reserve

Spinning reserves are provided by additional generating capacity that is synchronized to the system. A generating station that is operating at part capacity could sell spinning reserves for its unused capacity. Spinning reserves must respond immediately and must be available within ten minutes of a request from the dispatcher. Spinning reserves are paid for by the amount of power, times the time they are available and ready. If the spinning reserve is called, the generator is paid an additional amount for the energy that is actually delivered, based on the market clearing price at that time. Note that this pricing arrangement is potentially favorable for electric vehicles, since they are paid as "spinning" for many hours, just for being plugged in, while they incur relatively short periods of generating power. This is true for battery electric vehicles (which will typically be plugged in, anyway), as well as hybrid or fuel cell vehicles, which can easily start generating within the 10-minute requirement. Both spinning reserve and frequency regulation require fast response and need to be under direct utility control. Regulation is called on more frequently than spinning reserve, up to several hundred times a day compared to a few times a year.

The electrical power capacity available for V2G for use in regulation is determined by two factors: (a) the capabilities of the battery charging system and the stored energy in the battery, and (b) the physical properties of the electrical network at the point of interconnection. The limit imposed on the electrical power capacity for V2G by the vehicle is a function of the energy stored onboard (i.e., in the batteries), the available dispatch period, and charging system power limits. Still, more importantly for spinning reserve applications, moving large amounts of power upstream through the distribution system to be delivered elsewhere on the network will incur a relatively high amount of losses. Therefore, efficient operation requires that the injected power be made use of on a more local level. Consequently, the effectiveness of V2G as a spinning reserve ancillary service also requires examination of the geographical and spatial diversity of potentially controlled vehicles across the grid.

Peak Power Resource

Independent System Operators and Regional Transmission Operators (ISO/RTOs) manage markets for ancillary services and determine the market clear price for these services based on the bids submitted and based on constraints in the transmission system. Typically these markets will have both a day ahead and real-time option (hourly or five minute) for resources that wish to participate. The market clearing price represents the maximum social welfare achievable considering the bids submitted for that time period, or the point where the supply and the demand curves meet. As a result, any resources cleared in the market will be paid a capacity price for being available to provide the ancillary service over the term of the contract, as well as the market clearing price for any energy provided if they are called during that period.

Peak power is generated or purchased at times of day during which high levels of power consumption are expected—for example, on a summer afternoon predicted to be especially warm. Since peak power is typically needed only a few hundred hours per year, it is economically sensible to draw on generators that are low in capital cost, even if they are more expensive per kWh generated. Or, to put it another way, these power plants are very expensive per kWh generated, because they have fewer kWhs over which to amortize the investment. As a result, peak demand is the most expensive power to provide in a system. Therefore, peak shaving through large scale V2G operation may be economically viable option.

Vehicle-to-Home Backup

Another potential service application is the use of the vehicle charging system to provide emergency backup power to the point of interconnection. The typical point of interconnection expected for most vehicles is the residence, so this application is termed vehicle-to-home or V2H. During an outage the vehicle charging system can be controlled to back feed into the home wiring in order to provide power to essential home loads such as lighting and refrigeration. Implementation of this service must take into account issues such as electric codes, protection coordination, and system islanding.

Literature Survey

Vehicle-to-Grid – Overview

There is currently work being done to bring plug-in vehicles (PEVs) to mass market and install public charging stations throughout the nation. Significant work will be needed to understand the system impacts of vehicle charging. Although there may be adequate generation capacity in the evening, and on average there may be sufficient grid capacity for charging, it will likely be necessary to control charging to take advantage of excess generation and minimize localized stress on distribution system circuits. In addition to simply controlling charging, PEVs represent a mobile form of energy storage. As a storage asset the PEVs would charge from the grid and discharge energy back to the grid, which is commonly termed vehicle-to-grid (V2G).

Distributed energy storage systems (DESS) is expected to play an important role as penetration of variable solar resources increase. Energy storage is receiving increasing attention by utility engineers and regulators alike for its potential to solve a wide number of technical challenges due to high penetration of intermittent resources. Storage can proactively reduce the active power variations and time-shift peak PV production to align with peak load demand and alleviate key utility operational challenges created by demand peaks and non-dispatchable renewable resources. Still, widespread use of storage will require the coordinated effort of technology developers and utilities to ensure that systems are designed to adequately address utility needs. Utilities need to understand the technical attributes of the various technologies being advanced by the developers.

Storage may also be used to defer distribution system upgrades by providing peak shaving and aiding in voltage support. From a transmission level, storage may be used as a capacity or reliability asset by providing power and energy to support grid operations. The following sections discuss work that has been done relating to V2G in terms of impacts and services, modeling and control, and its use in combination with load control and distributed PV.

A first step in studying vehicle-to-grid (V2G) is to develop a better understanding of how the PEVs will impact current grid operations. Vehicle usage and charging patterns have been studied in several countries [4-6]. In general, vehicles are parked a majority of the day and, in the U.S., driven less than 40 miles per day. It is assumed that vehicles will be parked at varying locations throughout the day as people go to work and run errands and that public charging will be available in addition to charging at home.

Evans et al. studied the impacts of distributed storage and plug-in electric vehicles (PEVs) acting as distributed storage on electric delivery systems through simulation [7]. The focus is on distribution system impacts and capacity limitations with random placement of PEVs and strategic placement of distributed storage. In both cases the storage is dispatched by the system operator to optimize system performance. The authors used AEMPFAST™ and Positive Sequence Load Flow (PSLF) to optimally dispatch demand-side assets in the system and calculate the power flow in the network. The system consisted of nearly 100,000 buses with a peak load of about 1,300 MW and additional capacitors and demand response resources were included in the base model.

The first case assessed the impacts of varying penetrations of PEVs, from 1,400 up to 35,112 vehicles capable of V2G that are placed randomly throughout the system. The vehicles were modeled with an on-peak discharge capacity of 25 kW with the ability to discharge at this rate for at least an hour, and an off-peak charge rate of 16 kW. It was assumed that this would fit an electric vehicle with a storage capacity of about 65 kWh. The vehicle penetrations represent about 3 % to about 75 % of the 46,000 distribution transformers serving the customers in the system. With 3 % penetration (35 kW of discharge capacity) the V2G increased the minimum bus voltage in the test system and decreased power losses on-peak, and conversely decreased the minimum voltage and increased losses when charging off-peak. Overall the established minimum off-peak voltage of 0.95 PU was maintained. Similar results were found with 22 % penetration with greater decreases in losses on-peak and remaining above the minimum off-peak voltage. With 75 % penetration and random placement of the vehicles the system could not be solved due to voltage collapse. To determine the effects of distributed storage placed at optimal points in the system, and again dispatched by the system operator, incremental amounts of storage were placed throughout the system where the on-peak benefit minus the off-peak dis-benefit was maximized. An optimal storage increment of 70 MW was determined for the system based on the off-peak minimum voltage level; multiple storage elements may be placed at a single location if the minimum voltage requirement is maintained. The storage elements will discharge at rated capacity for at least an hour and then charge off-peak at 1.25 times the rated charge capacity. Placing 500 storage units throughout system to get 35 kW total (same as first case of 3 % V2G), resulted in greater loss reduction than with random V2G placement.

Vehicle-to-Grid Opportunities

A number of organizations have done work to determine what services could be provided through V2G based on the capabilities of Li-Ion battery systems and the mobile nature of PEVs as a storage resource.

An overview of hybrid-electric and fuel cell vehicles in terms of their drive systems and capabilities for vehicle propulsion has been provided by Kramer et al [8]. The services that vehicles could provide through V2G are briefly explained. An overview of the components necessary for implementation of vehicle-to-grid are presented along with discussion of the power electronics used in AC Propulsion’s tzero™ drive system [9] as a specific example. Testing for compliance with IEEE 1547 [10] is discussed.

Frauke et al. discuss possible architectures for charge control and vehicle-to-grid [11]. They present a combinatorial optimization algorithm that is used to schedule vehicle charging and discharging based on the price for electricity while maintaining the SOC within a given band. Possible metering scenarios are discussed to accommodate public charging and charging in multiple service territories. A controller located on-board the vehicle is proposed to schedule and control vehicle charging/discharging.

PEVs may be used to provide any number of services to the grid, including services included in Independent System Operators and Regional Transmission Operators (ISO/RTO) markets. The ISO/RTO Council (IRC) assessed the integration of PEV with their existing markets [12]. The report provides an overview of driving characteristics based on key factors such as where standard Prius hybrid-electric vehicles have been adopted and the goal of one million PEVs on the road within five years. It is assumed that an aggregator will act as an intermediary between a group of PEVs and the ISO/RTO market systems. This is to avoid having to possibly dispatch to large numbers of PEV assets, and to meet minimum capacity requirements for markets that are typically on the order of 1 MW. The case where vehicles are able to modulate charging and where only on/off charging control is available are both considered. Limitations of bidding into ISO/RTO markets are discussed, including the case where PEVs could bid for two or more services in a co-optimized market and the ISO/RTO would decide which one was most conducive. Overall, a key point is that if a vehicle chooses to provide more than one service at a time, for instance regulation and emergency load curtailment (ELC), the PEVs must have reserves for ELC in addition to the reserves set aside for regulation.

A summary of traditional services is provided in the report [12] detailing the requirements for PEVs participating in each market. Overall it is likely that existing services would need to be modified to accommodate PEV participation. In addition the communications requirements are outlined where the latency for communications from the PEV to the aggregator and the aggregator to the ISO/RTO in general would need to be less than six seconds, and the latency from the aggregator to the PEV in general would need to be less than two seconds [12].

A number of near-term opportunities for PEVs were identified as follows [12]:

- Emergency curtailment
- Dynamic pricing
- Enhanced aggregation
- Regulation
- Reserves

The use of PEVs as energy or capacity resources was considered a longer term objective [12] that may require further control and market evolution.

The University of Delaware (UD) has a V2G program that has studied the use of both plug-in hybrid electric vehicles (PHEV) and full electric vehicles (EV) for V2G including evaluation of the economics of PEVs providing various market services.

As a basis for future work, equations to study the economics of vehicle-to-grid (V2G) provided by fuel cell, hybrid electric, and battery electric vehicles were developed [1]. For vehicles participating in markets, it is important to get high value to compensate for wear-and-tear on batteries. The paper discusses general services that could be supplied by vehicles in terms of duration of service and frequency of need. In terms of energy and capacity need may be daily on the order of hours, which may not be ideal for vehicle supply, and also has a lower market value.

Both spinning reserve and frequency regulation require fast response and need to be under direct utility control. Regulation is called on more frequently than spinning reserve, up to several hundred times a day compared to a few times a year.

The power supplied by the vehicle may be limited by the capacity of the vehicle's system or by the wiring supplying the vehicle, and equations are included to calculate both. In addition, equations are provided for revenue from providing various market services and the cost to supply [1]. The cost is broken down into cost for purchased energy, battery wear, and capital costs associated with equipment necessary for the vehicle to provide V2G.

The cycling resulting from V2G is discussed due to the limited cycle life of current battery technologies. Providing longer duration services such as peak load or spinning reserve will require deeper cycles, whereas the duty cycle of providing frequency regulation will require shallower cycling. The effects of frequency regulation will mimic the use of the battery while driving, particularly in an urban setting [1].

The revenue and cost associated with an EV providing frequency regulation were calculated using a RAV4 EV as an example [1]. The vehicle draws $4,928 per year in revenue, with $2,374 per year in costs for purchased energy, wear and capital costs of V2G equipment, and upgrades. The resulting net profit is $2,554 per year for the single EV. A fuel cell vehicle providing spinning reserve was also considered with a net annual profit of $525. The same fuel cell vehicle providing peak power has a net annual profit of $290. In all cases it was assumed that premise wiring was upgraded to provide 15 kW of charging capacity for the vehicles. This is likely higher than what will be available for residential charging where a Level 1 (max 1.44 kW) or Level 2 (max 7.68 kW) charging system will probably more common. Therefore, the net profit would be less.

More recently, UD worked with PJM to study the use of a single car providing real-time frequency regulation for the PJM system [2]. The study compared the ten-year present value of revenue for vehicles providing spinning reserve versus frequency regulation. The results showed that a vehicle providing regulation could obtain between $4,000 and $29,000 compared to between $1,000 and $8,000 for providing spinning reserve. The revenue varies based on the charging power for the vehicle where power levels of 2 kW, 6 kW, 10 kW, and 15 kW were evaluated. The parameters and methodology for the connection of the eBox for PJM regulation were given as a specific example [2].

UD has also done an economic evaluation of the use of an EV fleet for frequency regulation in four U.S. ISO/RTO markets [3]. Fleets are a convenient starting point for vehicle-to-grid services because they provide a convenient aggregation that will likely be located in a common location while charging, and they will have more predictable behavior in terms of usage and charging habits. A vehicle must have capability for two-way power flow and must have capability to be dispatched by system operator in real-time in order to be eligible to supply frequency regulation.

Similarly to [1] the revenue from and costs associated with the electric vehicles supplying frequency regulation were calculated for the fleets. A vehicle supplying regulation down is expected to increase charging, therefore there is no cost for a vehicle supplying regulation down. On the other hand a vehicle supplying regulation up may equate to battery discharge therefore the cost for the energy stored in the battery must be considered. Including all of the hardware necessary for V2G (bidirectional power flow, flow metering, and communications) the annualized capital cost was found to be $90 per year, per vehicle. For a vehicle providing only regulation down this annualized cost is reduced to $25 per year, per vehicle.

The economic evaluation was performed for two fleets, a fleet of 100 Th!nk City cars managed by NYPA and a fleet of 252 Toyota RAV4 EDVs managed by an investor-owned utility. For both vehicle types the maximum depth of discharge was 80%.

The annual net profits for the Th!nk City fleet evaluated in four markets (PJM, ERCOT, CAISO, and NYISO) providing both regulation up and down based on market prices for the years 2000-2004 may be as high as several hundred thousand dollars (charge power of 6.2 kW). The maximum is achieved in CAISO. The same evaluation was performed for the vehicles providing regulation down only, with annual net profits varying from around $20,000 to almost $80,000.

The results for the two fleets vary substantially based on the market being considered and the range of services. The NYPA fleet is more profitable providing regulation only. This is partly because in its home market, NYISO, regulation up and regulation down have the same price. In CAISO regulation up and down are priced separately and in some years payments for regulation up were 2-3 times higher than those for regulation down (2000 and 2001), therefore the RAV4 fleet could have been more profitable providing both regulation up and down versus down only.

Including analyses of the value of regulation in ERCOT and PJM it becomes clear that it is necessary to evaluate the use of EDVs in a specific market looking at supplying regulation down alone and both regulation up and down. Variability in market prices should also be taken into account to get a complete picture of V2G value [3].

Work is also being done outside of the U.S. For example, the use of EV for storage compared to the use of pumped-hydro storage in Great Britain was studied by Zhong et. al [13]. Discussion of balancing services specifically frequency response (MFR) and short term operating reserve (STOR) both of which provide a capacity payment for resource availability and energy payment for providing services if and when needed. Equations for revenue from both types of services are presented, and they also look at costs in terms of per unit energy and power costs. Only the energy cost per unit is included for battery vehicles, and compared to the costs for pumped hydro battery vehicles cost less to provide energy to the grid.

The study assumes the use of a regional aggregator to act as larger resource (required 3 MW minimum) and to manage communications [13]. An example of 120 EVs is presented where the vehicles provide MFR while parked at home in the evening, while parked at work in the morning, and a combination of work and home. In each of three cases vehicles are available to provide service for an hour, and the vehicles providing frequency response for a half hour at work and then later a half hour at home provides the highest net profits.

The study also found value for the 120 vehicles providing STOR and again the net profits were highest for the vehicles providing at home and at work [13]. In both cases the cost to provide energy were the same, however the value of the short term balancing services are higher therefore more profit was derived from vehicles providing STOR.

Oak Ridge National Laboratory has looked at issues related to loads providing ancillary services concentrating on loads as spinning reserve [14]. The focus was on contingency reserves because they are not needed on a regular (daily) basis, they are only needed for short duration, and they have high value service. NERC allows non-generation resources to provide spinning reserves, contingent on rules and regulations of regional councils and ISO/RTOs. Some form of aggregation is ideal for responsive loads such that intermediate handling of communications and monitoring, and to provide an aggregate view of larger size resource for system operators [14].

The report recommends that loads that have some built-in control/communications capabilities are well suited for service as it may be cost prohibitive to retrofit existing loads with these capabilities [14]. Fast response of load curtailment is an advantage compared to central generation resources that ramp up over a period of up to 10 minutes. This is ideal for curtailing vehicle charging or engaging discharging of vehicles to restore vehicle battery to pre-event state.

The report also identified the following monitoring requirements for loads providing contingency reserves [14]:

1. Failure to respond: necessary for large generators, not as critical for responsive loads since non-response of a few loads will not significantly impact size of aggregate resource.
2. Resource availability: to provide operators with knowledge of available contingency reserves. Response from thousands of small loads may take a while, therefore forecasting will be valuable for this purpose.
3. Performance monitoring: to ensure that resources signed up to supply are in fact responding and not free loading.

A repository for smart grid use cases is being managed by EPRI and includes several V2G use cases [15]. The use cases describe the interactions between the various stakeholders and business units to carry out V2G transactions that may be common in the future.

Vehicle-to-Grid – Optimization, Simulation, and Demonstration

Several studies have been done developing optimization for scheduling of vehicle charging and simulation of V2G. This section describes some of that work and ends with a discussion of a V2G demonstration project.

A group at Missouri University of Science and Technology developed a real-time model of vehicle fleets using a real-time digital simulator (RTDS) platform to simulate scheduling of charging PEV [16]. The vehicles are simulated in groups with a small transmission line between the parking lots, where vehicles are connected through 208 V/22.9 kV inverters with a two-level topology. In the first case two groups of four vehicles are simulated and a binary particle swarm optimization algorithm is used to schedule vehicle charging and discharging to maximize revenue for the vehicle. Vehicles must maintain minimum state-of-charge and buying/selling is scheduled to maximize profit when a vehicle participates in the real-time CAISO energy market. First charging is scheduled based on real-time pricing from CAISO's, and then a 10 cycle three phase fault is simulated in the system. During the fault the power drawn by individual vehicles spikes to several hundred kW, depending on the location of the fault. A second case is considered with simulation of hundreds of vehicles in the parking lots. A binary particle swarm optimization algorithm is used to schedule vehicle charging/discharging within the parking lots [16]. Vehicles park in lots throughout the day and have variable states-of-charge upon arrival, therefore the vehicles develop unique buy and sell strategies. Based on the fault simulations the conclusion is that adequate controls and protection must be provided to mitigate damage to inverters and vehicles in case of faults.

Han et al. present an optimization algorithm that may be used in parking lots where an aggregator controls vehicle charging for all vehicles signed up to provide regulation in such a way as to maximize the aggregate revenue for the group of vehicles [17]. While a vehicle is recharging its battery it is considered to be unavailable for regulation service, and is simply considered a load. Strategy for parsing regulation among vehicles is to do so in proportion to each vehicle's available capacity. Charge control is handled differently at upper and lower state-of-charge limits for each vehicle. It is assumed that the owner will input the time when the vehicle is expected to be used next and the vehicle's SOC will be at least equal to that when it initially parked.

Dynamic programming is used to determine when to charge or discharge while staying within limits on SOC. Maximum charge and discharge rates will be used whenever the vehicle is engaged for charging/discharging. An objective function is developed incorporating these features with a weighting factor used for the desired final SOC, and the resulting equations for the system are discretized [17]. Prices from PJM are used to determine the effectiveness of the system. It is assumed a vehicle with a 20 kWh battery is allowed to charge/discharge at a rate of 2 kW. The study found that on vehicle plug-in the optimal control decisions can be mapped out based on the SOC and the duration of plug time.

Pacific Gas and Electric (PG&E) and Tesla Motors have partnered to evaluate the use of V2G for regulation supply [18]. A ratio is presented to be used to get a feel for the average charging power and the duration of regulation supply of a vehicle over a period of time. First approach is to use vehicles as a controllable load without feeding power back to the grid.

Solar PV Integration and Storage

Storage may provide a means for smoothing or shifting solar peak generation that is not lined up with system peak. Several organizations have been studying the integration of storage and PV for residential and commercial applications [19-21]. The Solar Energy Grid Integration Systems (SEGIS) program [19] is an industry-led initiative to facilitate increasing penetration of residential and commercial PV systems through development of advanced inverters, controllers, and energy management systems. The concept is to tie together distributed PV generation, load control functions through advanced control algorithms. This includes development of appropriate protocols for communications and interconnection of the components. The integrated system would optimize energy consumption by controlling loads based on the needs of the local system and the output of the PV installation to maximize value and decrease system impacts. Several system architectures with varying complexity are presented where energy storage and adaptive control functions may be integrated and multiple levels of communications capabilities are considered.

The economics of solar PV integration and storage are critical. Factors such as tax credits, incentives, and pricing structures will affect value associated with distributed PV. The disparity in NPV of PV and PV plus storage systems was studied by Hoff et al [20]. Adding storage to premise-level PV installations provided added value for residential and commercial PV. Two specific locations were studied; San Jose, CA and Long Island, NY. In all cases more value was achievable in CA due to higher buy-down incentives, summer energy and demand rates in San Jose. The communications, hardware and software necessary to integrate distributed PV, storage, and load control systems will add cost, but also add value, allowing better use of the assets and higher financial payback.

The SEGIS – Energy Storage (SEGIS-ES) program extends the initial SEGIS work to include energy storage as part of the integrated system [21]. Ton et al suggest the following applications for energy storage integrated with distributed PV: peak shaving, load shifting, demand response, outage protection, grid power quality control, and microgrids. Options for storage technologies are discussed and several areas where further development is needed are identified, including storage cycle life, decreasing charge-discharge cycle times, and reducing costs. Several of the additional features that must be included with a storage system are an integrated inverter, charge controller, and safety mechanisms. This is convenient if PEVs are considered as the storage element since a base PEV battery system incorporates many of these features and the addition of V2G would cover it all.

Integrated Vehicle-to-Grid Methodology[13]

Several approaches have been proposed for control and aggregation of vehicles providing V2G. Due to the typical size and charging needs of typical Lithium-Ion PEV battery systems the vehicles could be used individually as a premise level supply or as an aggregate for system level services. With large numbers of PEVs, and the communications and sensing associated with the smart grid, the batteries can be used to provide energy and ancillary services for the grid. Frequency regulation is an ideal service for PEVs because the duration of supply is short (on the order of minutes) and it is the highest price ancillary service on the market offering greater financial returns.

Development of a control framework for plug-in electric vehicles (PEVs) acting as distributed storage providing frequency regulation for the power system, was developed as part of this work. Large central generators traditionally supply frequency regulation through two mechanisms:

1. Large generators are equipped with speed governors for primary response to frequency deviations with load/generation imbalance in the power system, and
2. Generators providing automatic generation control (AGC) receive control signals to increase/decrease their power output to balance load and generation on a minute-to-minute basis.

Drawbacks of central generators providing regulation include the wear-and-tear on large machines from ramping up and down and the slow response, on the order of minutes.

The Li-Ion battery technology being developed for PEVs would allow vehicles to provide regulation with a nearly immediate response compared to large-scale generators. Vehicles can supply regulation up by either increasing discharge rate or decreasing charge rate; conversely they can supply regulation down by decreasing discharge rate or increasing the charge rate. Current projections of battery cycle life do not allow a lot of room for additional cycling outside

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[13] S. Mullen, "Plug-in hybrid electric vehicles as a source of distributed frequency regulation," Ph.D. dissertation, Dept. of Elec. and Comp. Eng., Univ. of Minnesota, Twin Cities, 2009.

of what's needed for driving; however, as technologies continue to improve, this will likely change.

To facilitate PEV participation in ISO/RTO regulation markets some form of aggregator will be necessary to group the vehicles into a larger asset size. There are various approaches being studied, including allowing the aggregator to make charging decisions for the vehicles [17] and having only a controller on-board the vehicle [11]. Due to the differing needs at each level of the system some combination of the two (with intelligence in the aggregator and in the vehicle) were also studied. While the aggregator will have access to local operation information and pricing data it is necessary to have a vehicle controller make the final charge/discharge decision. There are several reasons for this, first being that the primary purpose of a PEV is to act as a mode of transportation for its owner, therefore it should be charged according to the needs of its owners. In addition, if multiple PEV and EV designs make it to market, there will be many types of battery systems and charging profiles required by manufacturers and it is not feasible to expect an aggregator to manage various types of vehicles according to their physical charging limitations and the needs of the vehicle owner. A hierarchical control architecture was proposed to address these issues, which include the following components:

- Local vehicle controllers to make ultimate supply decision based on battery state and owner preferences
- PEV coordinator that monitors system frequency, determines supply recommendation for local vehicles, acts as an aggregator for local vehicles, and provides communications between grid/market operator and vehicles
- PEV coordinator located at high side of distribution substation transformer where measurement of system frequency is more reliable

Initial Evaluation of Demand Alteration Technology

Initial generations of electric vehicles will function simply as additional system demand. Still, assuming sufficient control structures are in place during later generations, the additional PEV demand can be dramatically altered. For example, the electric battery contained within each PEV represents idle energy storage whose charging could conceptually be curtailed or even reversed to provide support to the electrical grid; this is commonly referred to as vehicle-to-grid operation or V2G. Furthermore, PEV system demand as viewed at the meter can also be altered via other demand altering devices, such as stand-alone energy storage or photovoltaic (PV) generation.

A few simple example cases illustrating the general change in customer level demands in light of these technologies are examined. In each examined case, a detailed distribution system model is represented in OpenDSS and the system response to various technologies is evaluated. In particular, cases were selected to illustrate changes given:

- additional PEV demands
- stand alone energy storage in reducing peak demand increases due to PEV charging
- stand alone energy storage to store energy generated by residential photovoltaic generation for later use of night time PEV charging
- PEV vehicle-to-grid operation designed to shave the peak load.

Base Model Assumptions:

The demand side benefits of each case are expressed at the service transformer level. Circuit data representing an existing distribution feeder in the United States was used as the starting point for the model evaluations. A single-phase 100 kVA transformer serving a total of 14 customers was selected at the target study; with an individual service line connecting each customer load to the common transformer. For each modeled scenario, the technologies are applied on an individual customer basis, and the resulting change in aggregate demand at the transformer (the common point of interconnection) is observed. In Figure 9-1, the circle indicates the location of the distribution transformer on the feeder where all the assumed resources are supplied.

The assumed hourly load variation seen at the 100 kVA study transformer before the distributed resources are considered is provided in Figure 2. The particular set of hourly demands was taken from the summer peak day demands from the source circuit. As shown, the total aggregate demand of the 14 customers peaks at 42.65kW at 4:00 PM and it drops to 17.84kW in the early morning. Note that the 24 hour period is modeled starting at noon (hour 12). The selection keeps the sequential nature of the charge/discharge profiles, which can extend past midnight, from being divided in the figure, and is used in all figures in this section.

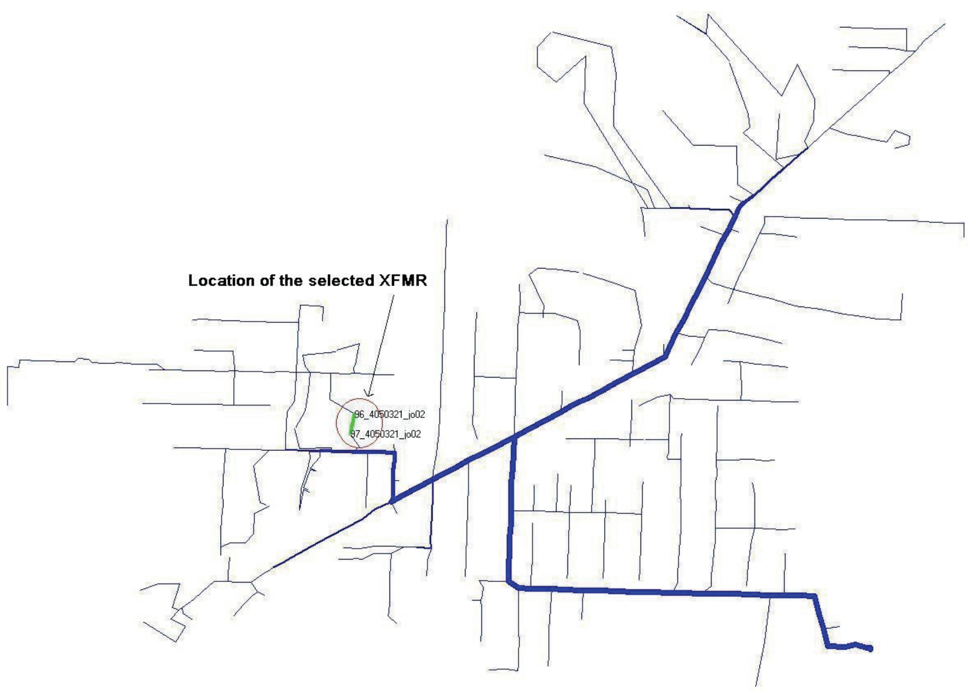

Figure 9-1
One-Line Feeder Diagram

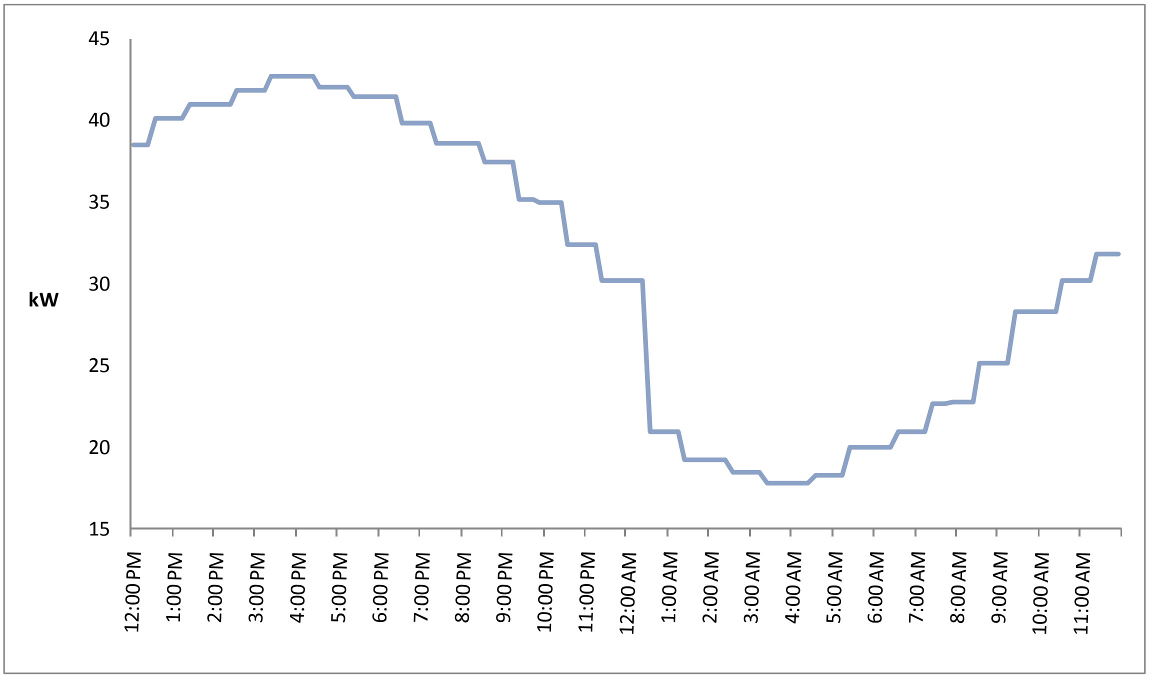

Figure 9-2
Transformer Hourly Base Load

Variable Demand/Generation

It is not necessarily likely that every customer would adopt all of the technologies considered. To that end, a fixed amount of each device is assumed to be distributed among the modeled customers. The assumed distribution and operating characteristics for each device are detailed as follows:

PEV

Plug-in electric vehicles are assumed in the model as having a charging rate of 7.2 kW and durations sufficient to provide a full battery charge. A total of six PEVs (four with 8 kWh and two with 24 kWh battery capacities) are distributed among the fourteen customer loads. In most cases, all six PEV demands are modeled as starting at 5:20 PM and continue to charge until their respective battery is fully charged. This time was chosen simply to represent a strong additional demand during some of the highest demand hours as seen in Figure 9-2. The respective demand profiles are provided in Figure 9-3.

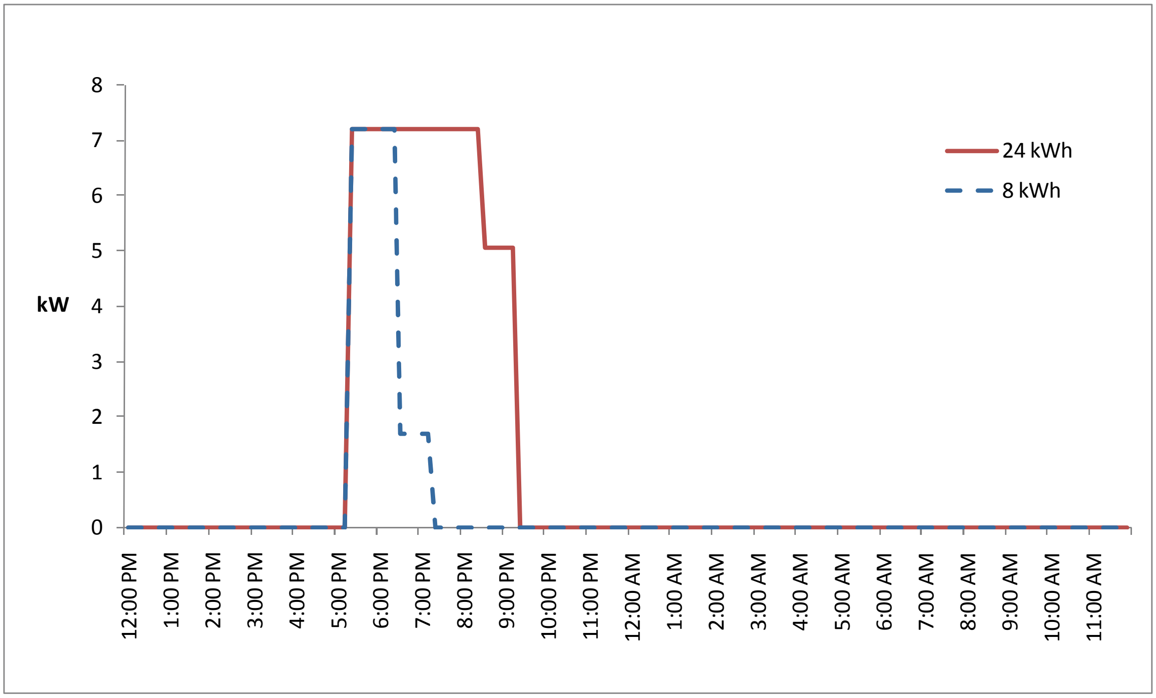

Figure 9-3
PEV Charging Profiles

Still, for the V2G scenarios, the larger 24 kWh battery PEVs are considered as participants in V2G operations while the 8 kWh PEV retain their simple load status. As such, the 24 kWh PEVs are set to provide peak shaving during the peak hour (note the negative demands during this period) then begin a full charge starting at 12:40 AM. Furthermore, during their charging cycles the 24 kWh battery chargers are constrained to half their normal charging rate, or 3.6 kW. These selections were chosen to emulate a possible control that seeks to flatten the profile not only through peak shaving but shifting of the additional demand to typically low demand periods as well.

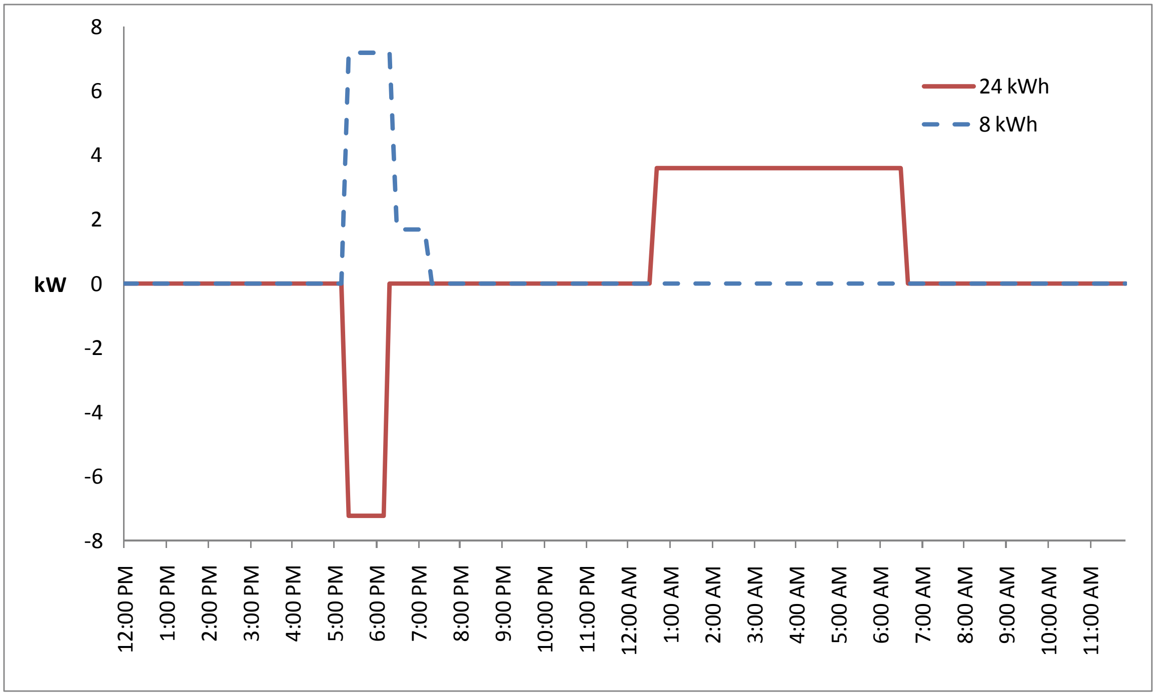

Figure 9-4
PEV Charge Profiles under V2G Operation

<u>Energy Storage</u>

In the analysis, three stand-alone energy storage devices are assumed. A 24 kW rate and 72 kWh capacity is assumed for each energy storage device based on projected characteristics for residential applications. The charging and discharging is detailed with the particular examined scenario via the assumed control scheme.

<u>Photovoltaic Generation</u>

A total of four photovoltaic (PV) sources are assumed to be distributed among the fourteen customer loads. Each generator is represented as a negative load; the profile or variation in the PV generation is based on actual PV output measurements and is assumed to have a maximum output of 7.56 kW.

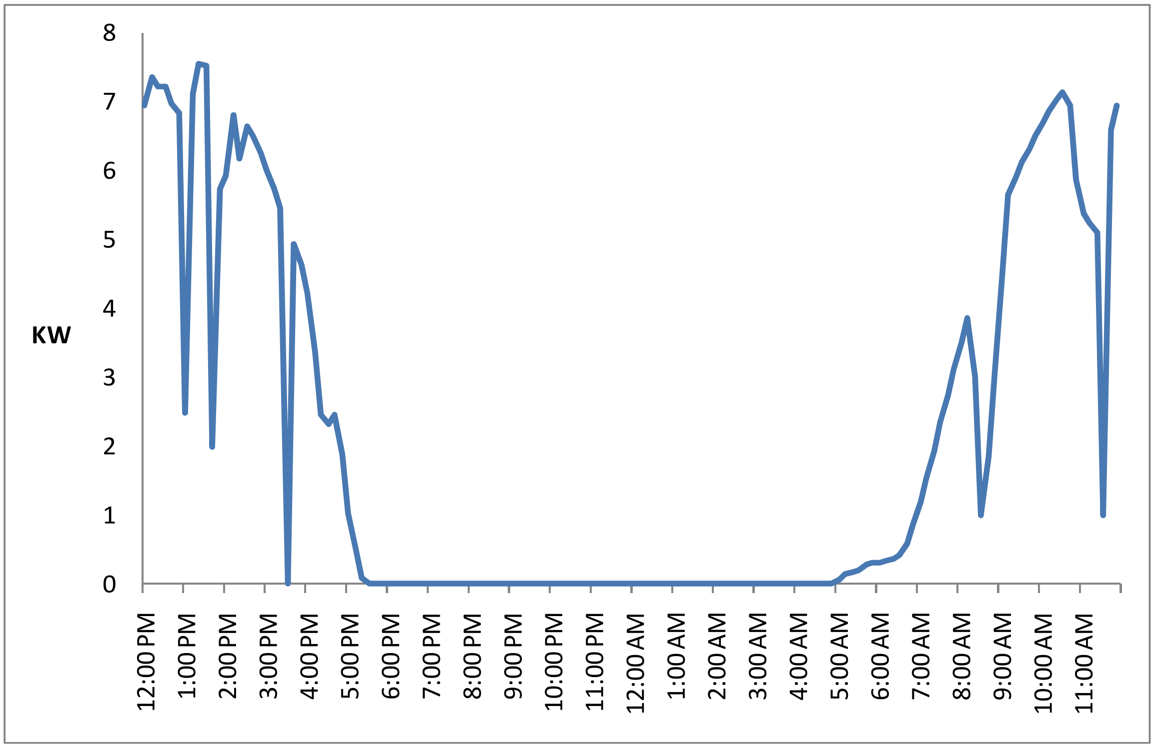

Figure 9-5 Individual Photovoltaic Generation Variation

Study Cases

Case 1: PEV Charging

In this case, all six PEV are assumed to be charged from the grid starting at 5:20 PM until fully charged. As shown in Figure 9-6, this scenario results in a doubling of the peak demand as seen by this transformer. The additional demand, however, quickly tapers off after the first few hours as the 8 kWh PEVs' demand drops off. This fundamental difference between the different PEV battery sizes is captured in Figure 9-3.

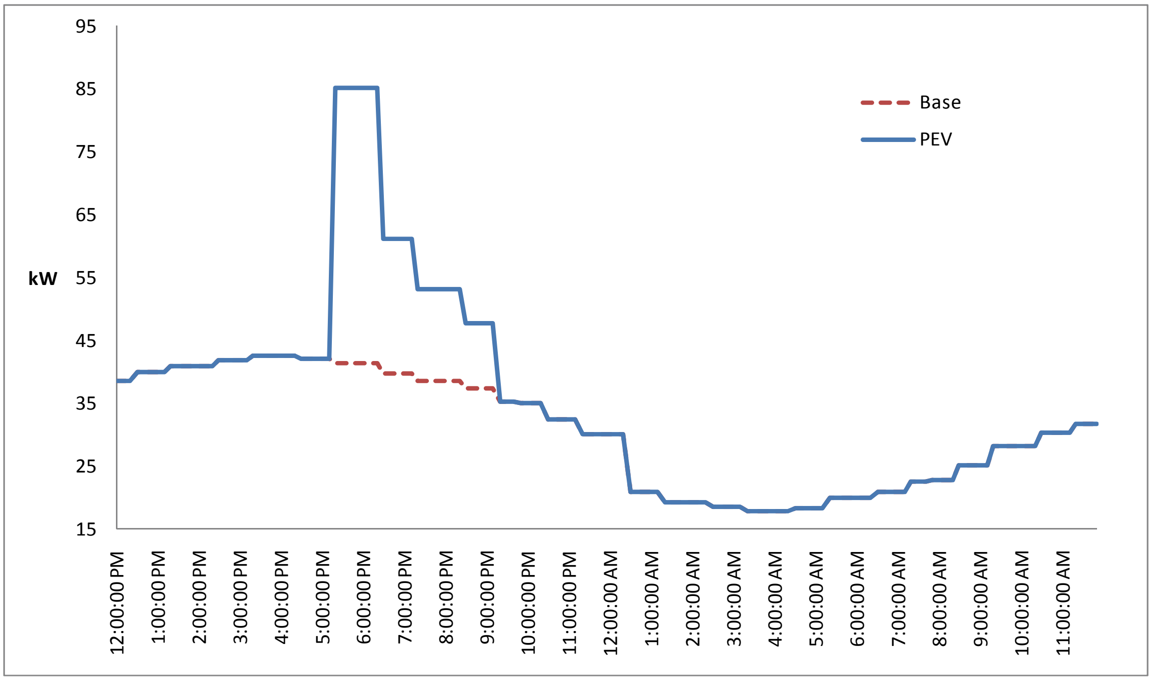

Figure 9-6
Transformer Loading with Standard PEV Charging

Case 2: PEV + Energy Storage

In this example case the potential use of stand-alone storage in counteracting the increased demand from PEV is presented. In general, the desired result is to shift the additional demand from the PEV to hours where the demand is not as high. To this extent, the energy storage devices are set to discharge when kW on the monitored transformer is higher than a given set point. Conversely, the storage is set to charge itself when the transformer loading is sufficiently low. As shown in Figure 9-7, the net demand of the transformer is significantly reduced at the peak hour compared to the previous case. Furthermore, the additional demand is shifted to the early morning hours essentially "flattening" the load profile. Nevertheless, the same general impact to net demand could also be achieved through controlled or dispatched PEV charging.

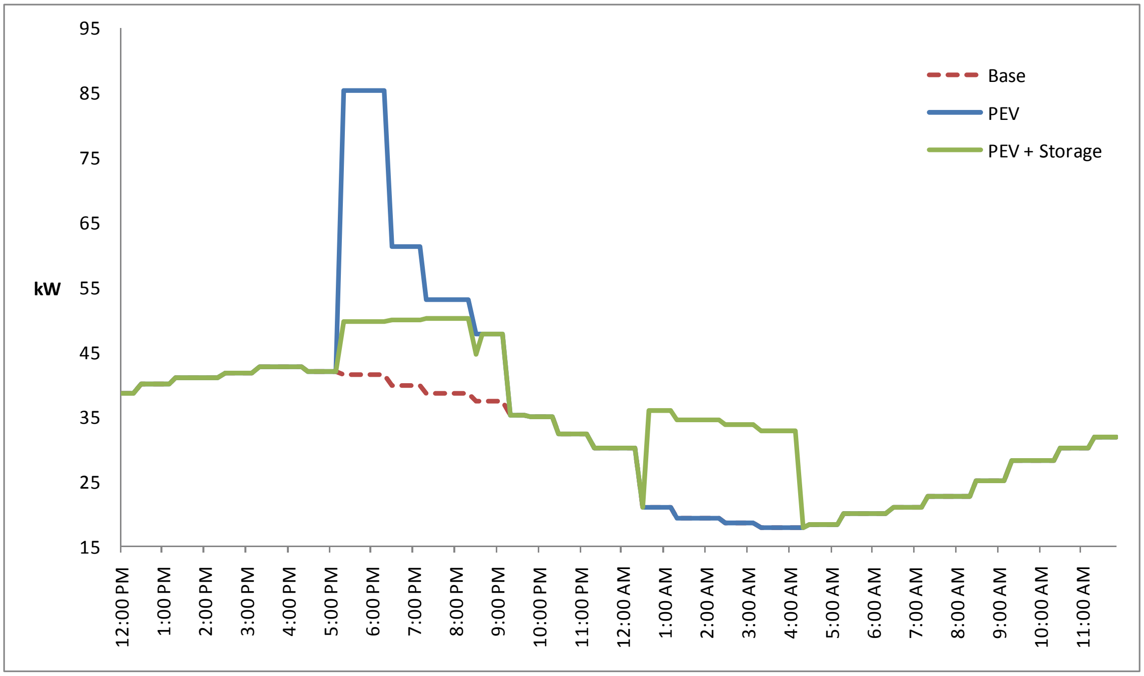

Figure 9-7
Transformer Loading when PEV and Storage are Connected

Case 3: PEV + Photovoltaic Generation + Energy Storage

In this case, localized PVs are assumed to be installed at four of the 14 customers. The impact on total demand, when considering the PV alone, is shown in Figure 9-8. Given this particular combination of generation and load, the PV effectively reduces the aggregate demand during many of the daylight hours.

The PV generation, however, is an uncontrolled source that cannot always be counted upon to provide reliable peak shaving or other system operations; note in Figure 9-8 the peak demand is not reduced for the entire hour. One possibility is to use storage in conjunction with PV to provide some measure of controllability. A host of various control options could be considered with this paring; from peak shaving to reducing the variation in PV output. Evaluating the effectiveness and benefits of these control schemes is beyond the scope of this effort. Instead, we look here at the possible use of storage to act as a bridge between PV generation and PEV charging.

PV and PEV charging are expected to have opposite diurnal patterns. Simply stated, PV generation occurs only during the daylight hours, and PEV charging will mainly occur in the later evening hours. Given enough of these devices on the system, the combination can effectively increase the overall variation in system demand, as highlighted in Figure 9-9. Nevertheless, storage could conceptually be used to bridge this gap in time, thereby supplying the energy produced by the PV for use in the electric vehicle. While peak demand is reduced for this particular combination, as shown in Figure 9-9, additional control functions between the different technologies would be needed to smooth the variations introduced by the variable PV generation. Furthermore, additional losses are incurred when using the stand-alone storage.

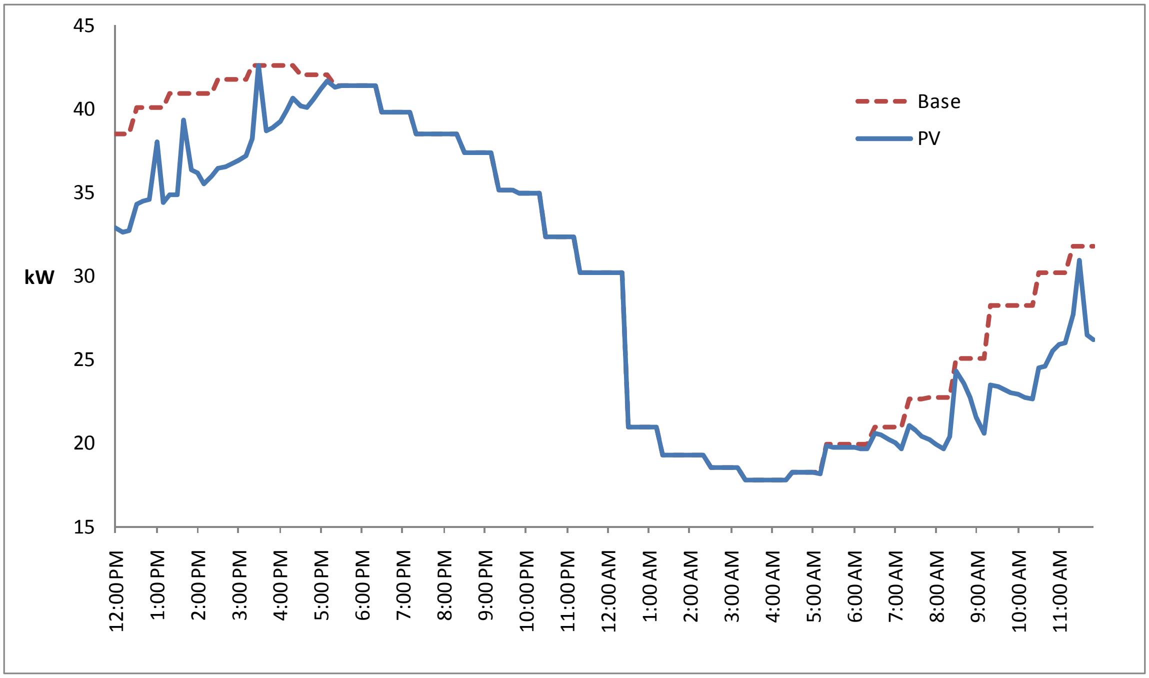

Figure 9-8
Transformer Loading with Photovoltaic Generation

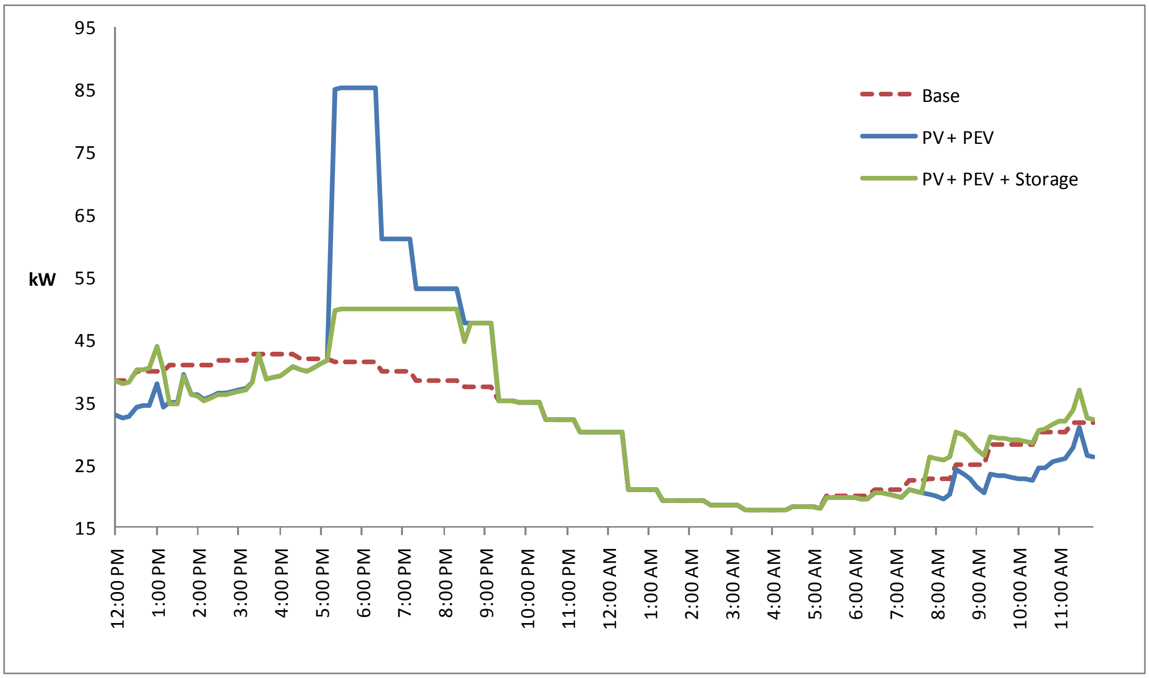

Figure 9-9
Transformer Loading when PV, PEV, and Storages are Connected

Case 4: Vehicle-to-Grid Operation

In this case, the two largest PEVs (24 kWh) served off the transformer are assumed to participate in a V2G program where their respective charge profiles are dictated by a controller. The intent of the emulated control is to use any available energy on the V2G PEV batteries to lower the peak demand as well dispatch the demand for these vehicles to the early morning hours. The resulting demands, with and without V2G operating PEVs, is shown in Figure 9-10.

The actual available energy stored on a V2G PEV at given point in time, however, can vary depending upon vehicle usage and whether the vehicle is even connected to the electric network. In fact, while the V2G operation initial offsets two of the 8 kWh PEVs in this case, the available energy is depleted by 6:00 PM, resulting in a spike in demand, see Figure 9-10. Still, a significant improvement in "flattening" the load is achieved through shifting these demands to the early morning off-peak hours.

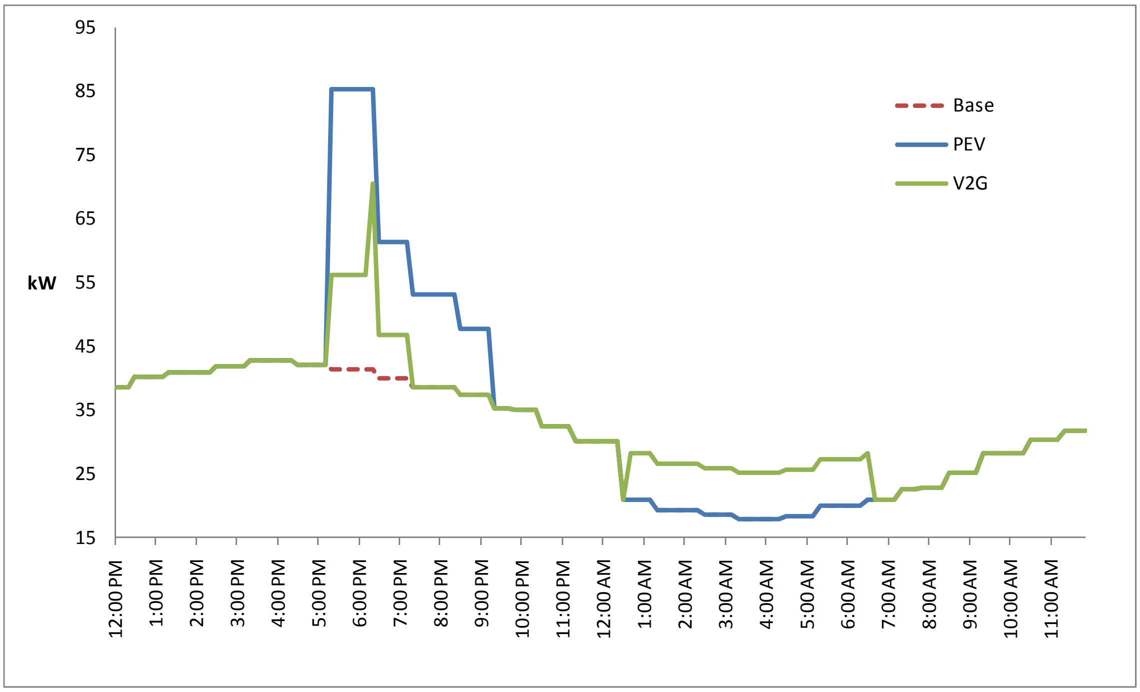

Figure 9-10
Transformer Loading given PEV Vehicle-to-Grid Operation

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10 INVESTIGATION OF ON-BOARD CHARGERS POWER QUALITY IMPACTS THROUGH TESTING & MODELING

As on-board chargers and PEVs continue to evolve and grow in popularity, adverse power quality issues could affect the grid. EPRI has conducted lab tests and collected data on onboard PEV charging systems with the purpose of determining the power quality impacts on the grid. Data collected focuses on charge cycle, distortion, harmonics, power consumption, and power factor. This data and future activities are discussed in depth in later sections. A time domain battery charger model was also developed for a generic 120V – 12A PEV battery charger using electromagnetic transients program (EMTP-RV).

Introduction

Electric utilities and Electric Power Research Institute (EPRI) are evaluating the impacts of PEV chargers, whether on-board or off-board the vehicle, with respect to system loading, transformer life, and power quality. Widespread adoption of plug-in electric vehicle (PEV) charging depends in major part to the reliability of both the electric grid and the PEV charger. To achieve this goal, vehicle and equipment manufacturers along with electric utilities must understand the characteristics of the AC service to which the charger will be connected, as well as the impact chargers can have on service quality.

To address the power quality concerns, the Society of Automotive Engineers (SAE) has created Recommended Practice J2894/1 – "Power Quality Requirements for Plug-In Electric Vehicle Chargers." This chapter addresses the power quality requirements for electric vehicle charging. SAE cites three major reasons driving the need for instituting power quality requirements:

1. Many modern products use microprocessor-based devices and these may be susceptible to power quality issues
2. There is a concern related to the increasing number of non-linear devices in the grid. These can generate harmonic content that is of concern for the grid
3. Modern society is very dependent on the electric grid, increasing the consequences of power outages

Establishing these requirements will help charging system designers develop hardware that will operate properly when connected to the grid, ensure proper operation of the PEV during power quality events such as sags, swells, and transients, and protect the grid from potential adverse power quality effects. The recommended practice has three main sections.

1) Charger PQ Requirements
   a) Power Factor
   b) Power Transfer Efficiency (at maximum power)
   c) Current Total Harmonic Distortion including individual harmonic currents

    d) Inrush Current
2) Characteristics of AC Service
    a) Voltage Range
    b) Voltage Swell
    c) Voltage Surge
    d) Voltage Sag
    e) Voltage Distortion
    f) Definition of Momentary Outage
    g) Frequency Variation
    h) Portable (Self) Generation / Distributed Energy Resources
3) Charging Control
    a) Utility Messaging
    b) Communication
    c) Staggered Restart (Cold Load Pickup)
    d) Load Ramp Rate (Soft Start) Definition

In support of J2894, and to develop an understanding of the impact of present on-board charger designs, EPRI recently collected data on several plug-in electric vehicles. The vehicles evaluated represent of mix of aftermarket conversions and a very limited number of original equipment manufacturer vehicle models. The selection of vehicles was based solely on availability.

Vehicles Tested

EPRI recorded data on three vehicles in the field, one in the lab, and received data on seven other vehicles from other utilities. From the three vehicles in the field, only spot short term measurements were acquired. Full charge cycle was unable to be recorded due to time constraints.

For each of the tests performed, the following data was recorded to analyze the different power quality attributes of the on-board charging system.

1. Voltage and Current
2. Current Harmonic Distrortion (iTHD%), Voltage Harmonic Distortion (vTHD%)
3. Individual harmonic currents and voltages up to 9kHZ
4. Power- Apparent, Real, and Reactive
5. Frequency
6. Power Factor
7. Complete Harmonic Spectrum
8. Voltage and Current Waveforms

By recording and analyzing this data, the effects of the charger on the grid can be determined and analyzed. Identifying potential adverse power quality impacts to the grid will not only inform the J2894 document development but will also provide valuable information to charger manufacturers and utility engineers. Of particular interest are the power factor, the load profile including peak power usage, and any harmonics that may be introduced into the grid.

The basis and starting point for power quality evaluation of the vehicles is the charging system. All the vehicle models tested used an on-board charger. Figure 10-1 shows a typical configuration for a vehicle charger. The input to the charger, at the left of the diagram, is AC voltage, while the output, at the right of the diagram, is DC voltage.

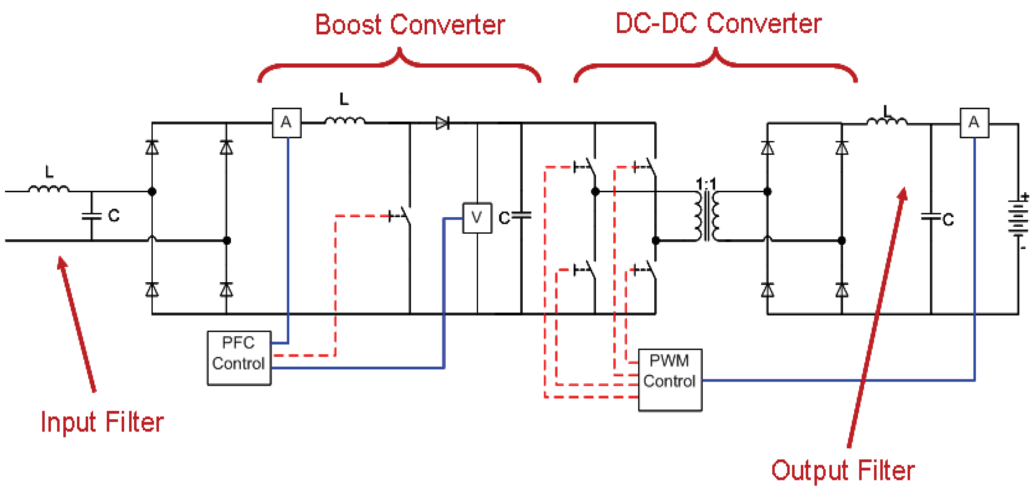

Figure 10-1
Typical Charge System

Regardless of the input voltage, most vehicle chargers use a similar topology to that shown in Figure 10-1. After the AC input voltage is filtered, it is rectified and then converted to DC at a voltage higher than the peak of the AC input voltage using a boost converter topology. At the output, a DC-DC converter is used to provide the appropriate DC output level. This DC output is then filtered and applied to the battery.

Table 10-1 lists the chargers that were evaluated.

Table 10-1
Description of Chargers

Charger Designation	Charger Voltage	Input Power (in kW)
PEV 1	120	1.38
PEV 2	120	1.38
PEV 3	120	3.05
PEV 4	120	1.30
PEV 5	120	0.92
PEV 6	120	1.23
PEV 7	240	3.27
PEV 8	240	1.38
PEV 9	240	3.27
PEV 10	208	7.11
PEV 11a	120	1.39
PEV 11b	240	2.92

Harmonic Current Distortion

The first and probably most important power quality aspect looked at was the harmonic content of the current during charging. Harmonics are caused by non-linear loads that cause frequency variations on an AC power line. Some of the more noticeable side effects are increased current, overheating on transformers, neutral current, and potential motor damage. Harmonics can cause a system to become less efficient because of the increased frequency and non-sinusoidal content of the AC waveform. This provides an indication of the overall harmonic footprint the chargers/PEVs as they are introduced into the grid. Figure 10-2 and Figure 10-3 shows the Total Harmonic Current Distortion (ITHD%)of the different PEVs (as shown in

Table 10-1) based on the input voltage charging system.

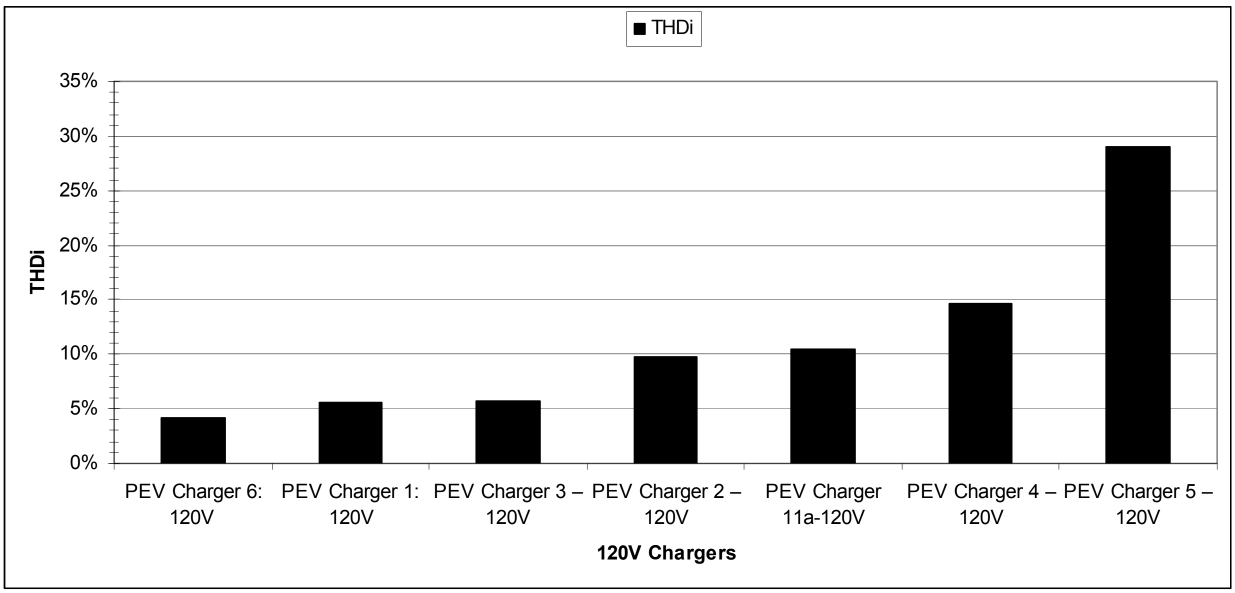

Figure 10-2
120V Chargers ITHD%

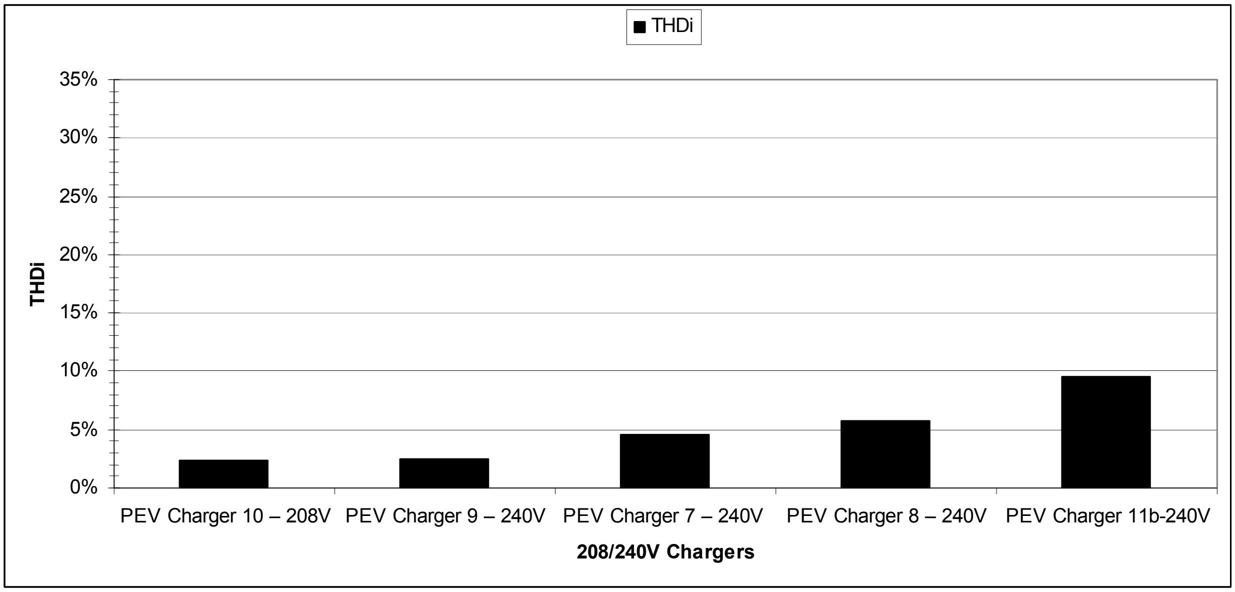

Figure 10-3
208/240V Chargers ITHD%

As indicated by the test results, the current distortion reaches noticeably higher values with the 120V system. With the tested 120V systems, there is a range of 4% to almost 30% ITHD% vs 2% to 9.5% with the 208/240V systems. This tends to indicate that the 240V chargers tested created less distortion on the current waveform then the 120V chargers.

The J2894 recommended practice that is being developed by SAE recommends the ITHD% to be below 10%. Based on this criterion, three of the chargers evaluated would exceed this limit. Improved filtering at the AC input, and better control techniques, could potentially help to minimize these ITHD% values.

Harmonic Current Distortion

The next power quality component looked at was the harmonic content of the various charging schemes. As noticed by the current distortion, it is expected that the 120V chargers will exhibit more harmonic content then the 240V systems. Figure 10-4 and Figure 10-5 show the harmonic spectrum of both systems.

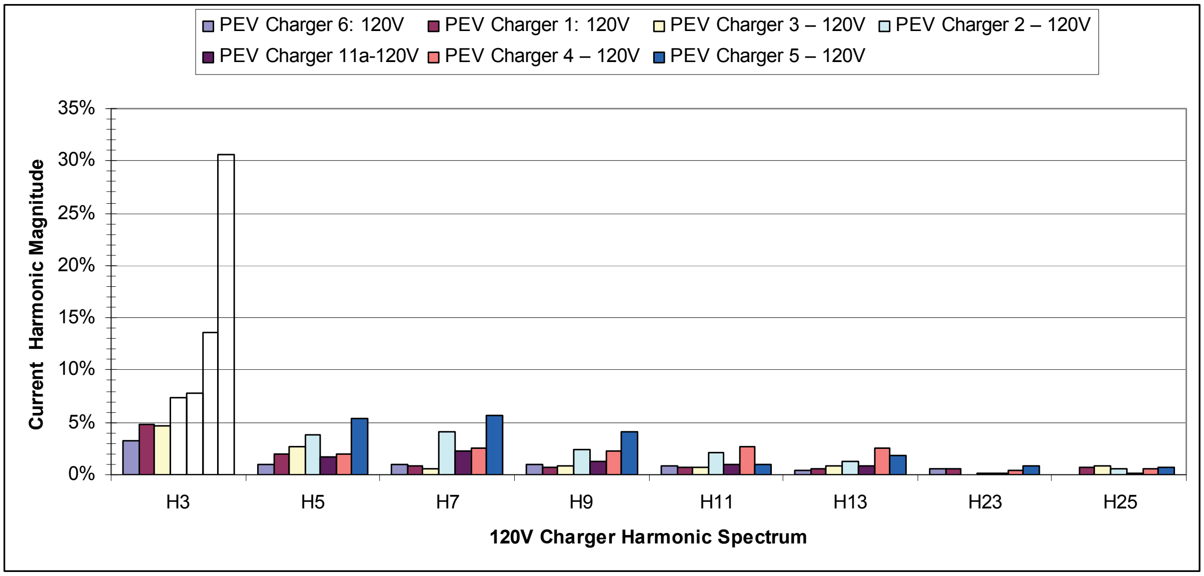

Figure 10-4
Harmonic Spectrum of 120V Chargers

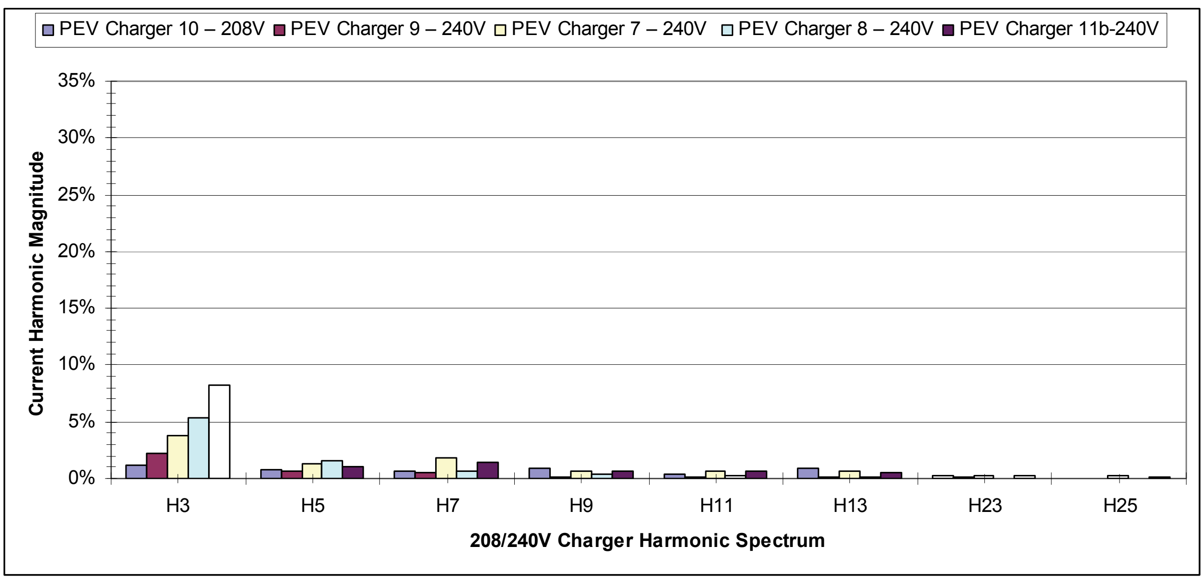

Figure 10-5
Harmonic Spectrum of 208/240V Charger Systems

As indicated by the data, the 208/240V systems produce less harmonic content then the 120V charger systems. The third, fifth, seventh, and even the ninth harmonic show substantial presence on the 120V systems compared to the smaller values on the 208/240V system. In terms of both overall distortion and harmonic content, the 208/240V systems performed at a cleaner quality then the 120V systems.

PEV Charge Cycle Analysis

The next point of consideration is the charge cycle analysis that includes the length of time required for a full charge, and any characteristics of the charging cycle. Figure 10-6 and Figure 10-7 show the charging cycle of two PEVs at 120V, and two at 240V.

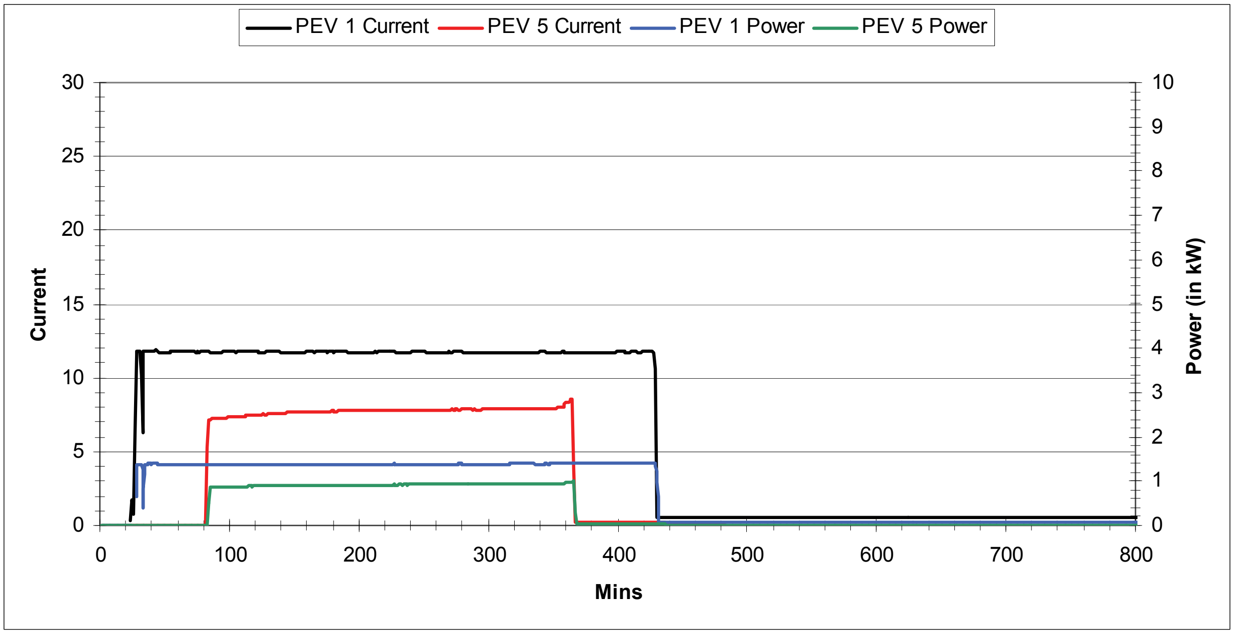

Figure 10-6
120V Charge Cycle

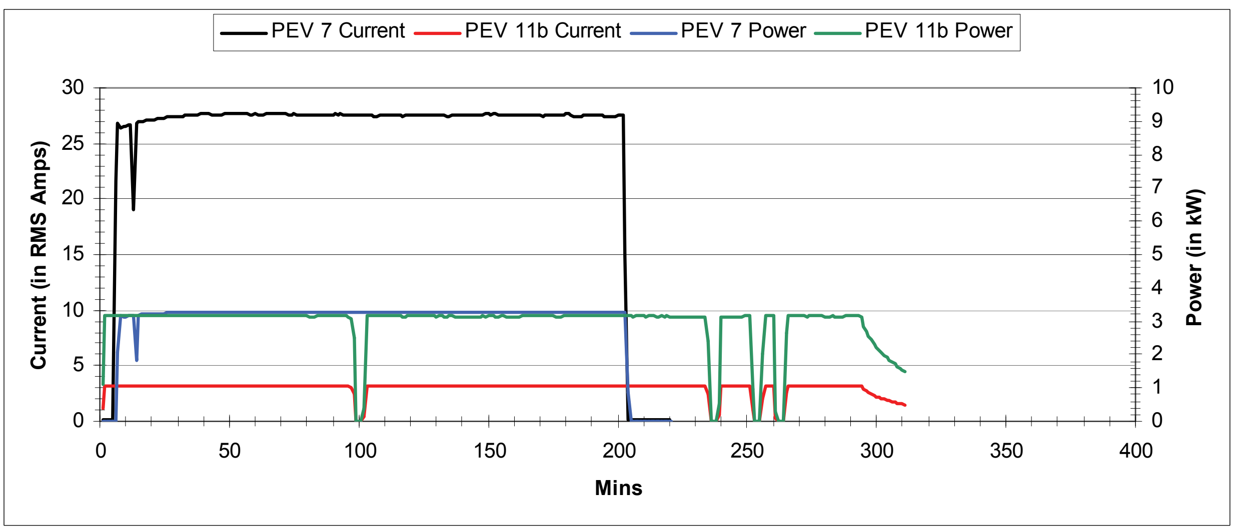

Figure 10-7
240V Charge Cycle

There are also some points during the 240V charge cycle that show a drop in power and current during the cycle. During this point, battery maintenance cycles are occurring. This allows time for the charger to ensure the charge is progressing. While the 240V systems charge at a higher current, they also complete the charge cycle typically in half the time. Figure 10-8 and Figure 10-9 show a breakdown of the power consumption among the different chargers.

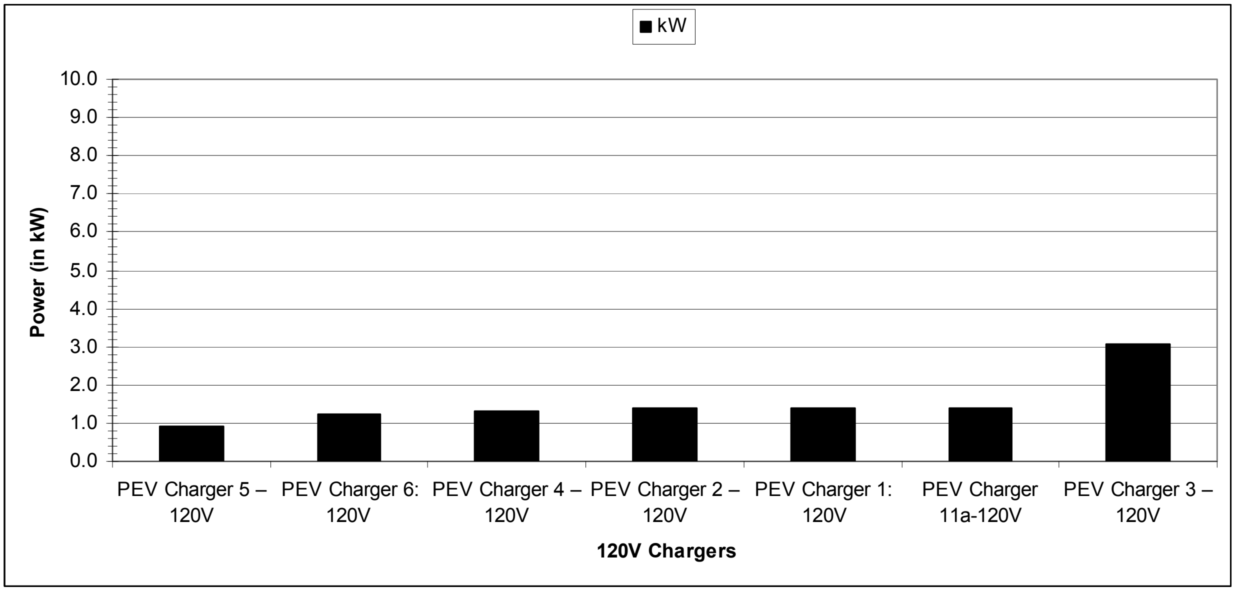

Figure 10-8
120V Chargers Power Usage

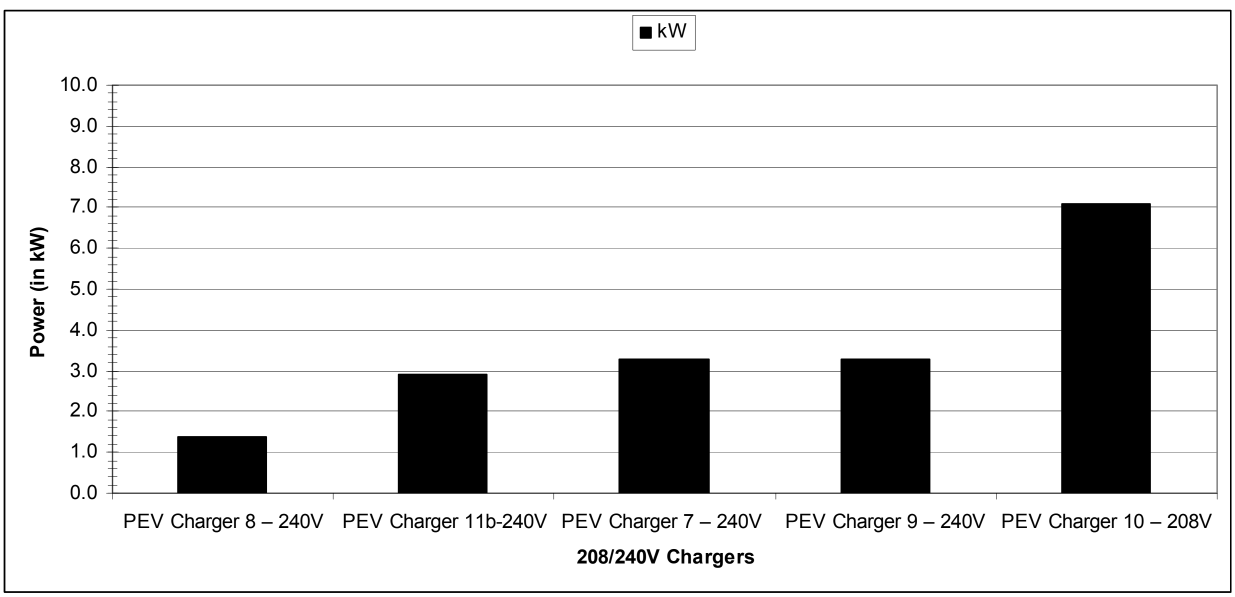

Figure 10-9
208/240V Charger Power Usage

Based on the data, the main difference between the 120V and 240V systems is the increased current for the 240V systems, and the reduced charge time. In most cases, the power is nearly the same across the board.

Power Factor Analysis

The final analysis occurs over the power factor. The power factor is the ratio of real power to apparent power. It is a number between 0 and 1 and can be either positive or negative. Apparent power, or Volt-Amps is the RMS voltage times the RMS Current. This is the basis of system ratings. The closer to one the power factor is, the closer real and apparent power are, and the less current there is in the system. As the power factor deviates from 1, improperly sized wiring can then begin to become overheated. Figure 10-10 and Figure 10-11 show the power factor for the charger systems.

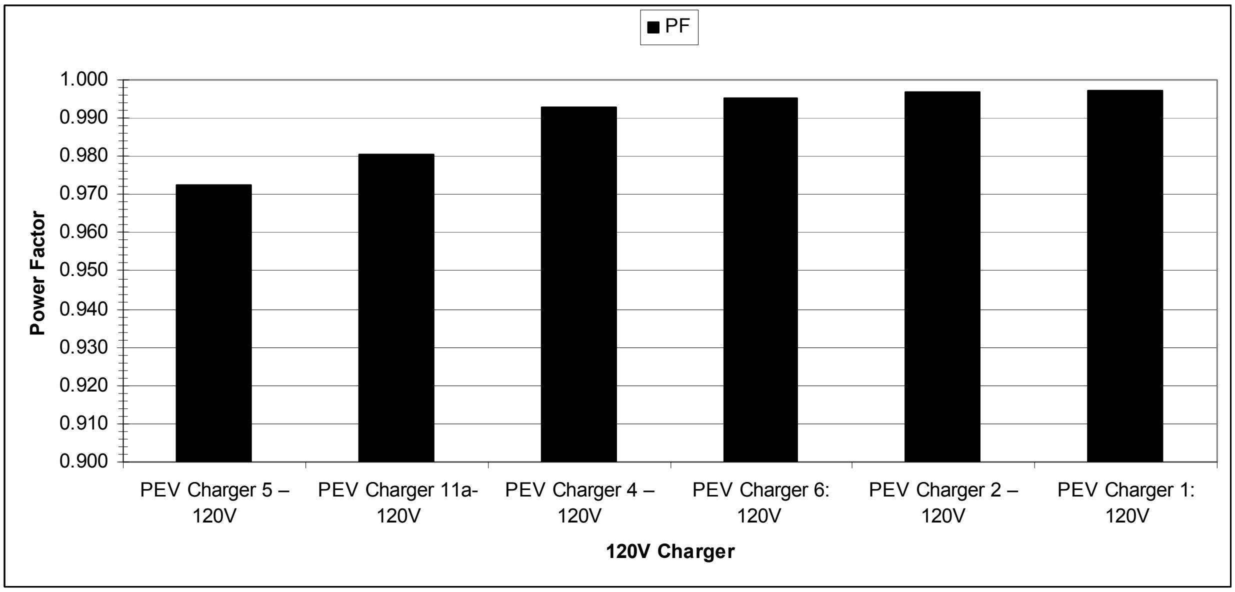

Figure 10-10
120V Charger System Power Factor

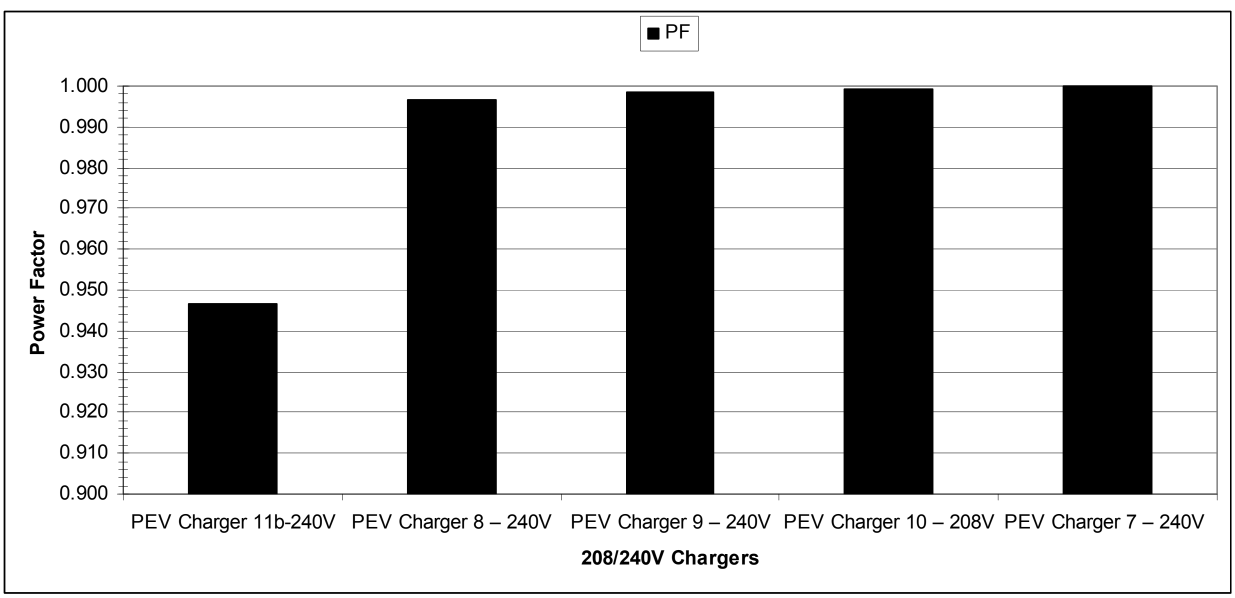

Figure 10-11
208/240V Charger System Power Factor

All of the chargers tested appear to be power factor corrected having a close to unity power factor. Based on the SAE J2894 draft, the power factor is recommended to be above 0.95.

In this case, only one charger would not make the requirement, and that is PEV 11b. It should be noted though that during the charge cycle, the power factor off PEV11b is near unity, however over the entire charge cycle due to battery maintenance, it does reduce the average power factor over time. Figure 10-12 shows the power factor over the entire charge cycle. As shown by the graph, the power factor at any instant point is just below unity.

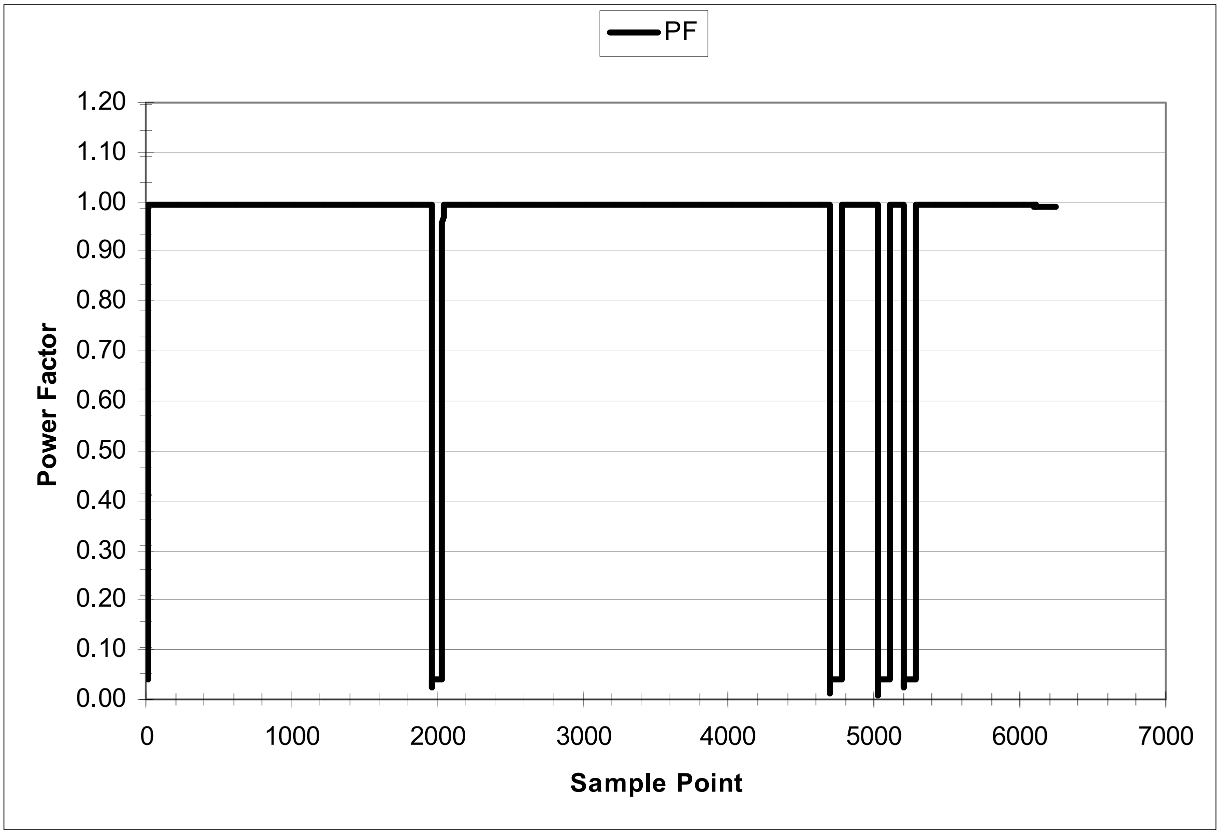

Figure 10-12
PEV 11B Power Factor over Charge Cycle

Future Work on Testing

Future testing should continue to include detailed data capture of the following characteristics that are vital to the successful integration of PEVs to the electric grid.

- Voltage and Current
- iTHD%, vTHD% (the distortion present on voltage waveforms as a result of ITHD%)
  - Individual harmonic currents and voltages up to 9kHZ
- Power- Apparent, Real, and Reactive

- Frequency
- Power Factor
- Complete Harmonic Spectrum
- Voltage and Current Waveforms

The above listed data is required to accurately assess potential charger impacts on the grid. Of those, current harmonic distortion (total as well as individual), and power factor are the most important, and should be included with every set of data captured.

In addition to how the PEV affects the grid, developing an understanding of how common power quality events can affect the charger will be important to ensure reliable vehicle charger performance. When possible, the following test should be included during data collection:

1. Voltage Sags
    a. Sags are quite common and can cause problems such as charge cycle interruption. Typically considered non-destructive testing.
2. Voltage Swells
    a. While not as common as sags, swells can occur during power quality events. The charger should be protected against these events.
3. Sustained under and over voltage conditions
    a. During heavy loading conditions, the voltage may be lower than normal, and this effect needs to be determined on the charger.
4. Reclose Transients
    a. Different reclosers have different clearing schemes. Some of these can turn on and off up to three times in a minute. It is important to determine how chargers can handle this.
5. Cap Switching Transients
    a. These transients are caused when a capacitor bank on the same branch of a distribution system switches on or off. These have been known to cause problems with sensitive electronics.
6. Surges
    a. Surges typically are caused by lightning strikes. Note that these tests should be considered destructive, and have the potential to damage on-board vehicle systems.
7. Variation in Harmonic Current with System Conditions
    a. The harmonic spectrum of the charger may vary with applied voltage level and harmonic content. This effect should be explored.

These data sets will provide a reference point for designers and manufactures of charging systems and PEVs. Testing, monitoring, and recording the interaction of the PEV charger with the grid and common power quality problems that occur on the grid can inform charger designers and auto original equipment manufacturers, allowing them to develop future models and designs that can handle these problems.

Another project to study the impact of the chargers through testing and modeling is also underway. The overall objective of the project is to understand and evaluate the PQ impacts of high-power off-board DC charging systems in real-world operation. EPRI has the following objectives in support of this research:

- Survey the characteristics and features of the Fast Charger systems available commercially and under demonstration. Compare published specifications with standards being developed by SAE and others (IEC/ISO/JARI etc.)
- Establish a test protocol for evaluating the grid compatibility of DC fast chargers
- Acquire and test multiple DC Fast Chargers using the above protocol. Identify and implement any needed adjustments to the test protocol
- Analyze data from the above tests to evaluate important parameters of the DC fast chargers (power quality, efficiency, susceptibility, total harmonic distortion, and power control parameters)
- Develop time-domain models of single and multiple DC fast chargers and use these models to evaluate PQ impacts on the grid
- Perform harmonic penetration analysis of a "typical" distribution system in OpenDSS
- Investigate impact of resulting harmonics on:
  - Transformer loading
  - Background Voltage distortion
  - Harmonic current distortion
  - Elevated neutral-to-earth voltage (NEV) due to 180 Hz current

Battery Charger Model

A time domain battery charger model was developed for a generic 120V – 12A PEV battery charger using the restructured version of the electromagnetic transients program (EMTP-RV). The following is a description of the circuit topology and control schemes that were implemented as part of the model.

A detailed time-domain model of a 120 Vac Level 1 PEV charger was developed in EMTP-RV to investigate the impacts of capacitor bank switching on charger operation. A block diagram of the time-domain model is shown in Figure 10-13.

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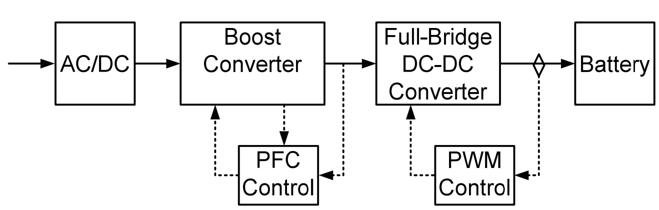

Figure 10-13
Block Diagram of a PEV Battery Charger

The battery charger shown in Figure 10-13 consists of three stages. The first stage is comprised of an EMI input filter and full-bridge rectifier. The second stage is a boost converter with power factor correction (PFC) control, and the third stage is comprised of a full-bridge forward (dc-dc) converter with a low pass filter connected to its output terminals (battery input terminals). This type of PEV charger is referred to as a high frequency two stage converter, and is characterized by low power factor and low ripple output [1]. The following sections describe each stage in detail, as well as the battery model that was used in the simulations.

Full-Bridge Rectifier and PFC Boost Converter

The purpose of the boost converter is to step-up the 120 Vac input voltage to a level that is compatible with modern electric vehicle battery voltages that are typically on the order of 300-400 Vdc. The boost converter uses PFC control to provide power factor correction at the input terminals of the charger. As a result, the charger operates at near unity power factor with minimal low frequency harmonic current content during normal operation. Detailed models of the full-bridge rectifier, boost converter, and input EMI filter are shown in Figure 10-14. Note that the EMI filter can be appropriately modeled using the series/parallel LC circuit shown in Figure 10-14 [2]. The parameters of the circuit elements shown in Figure 10-14 are provided in Table 10-2.

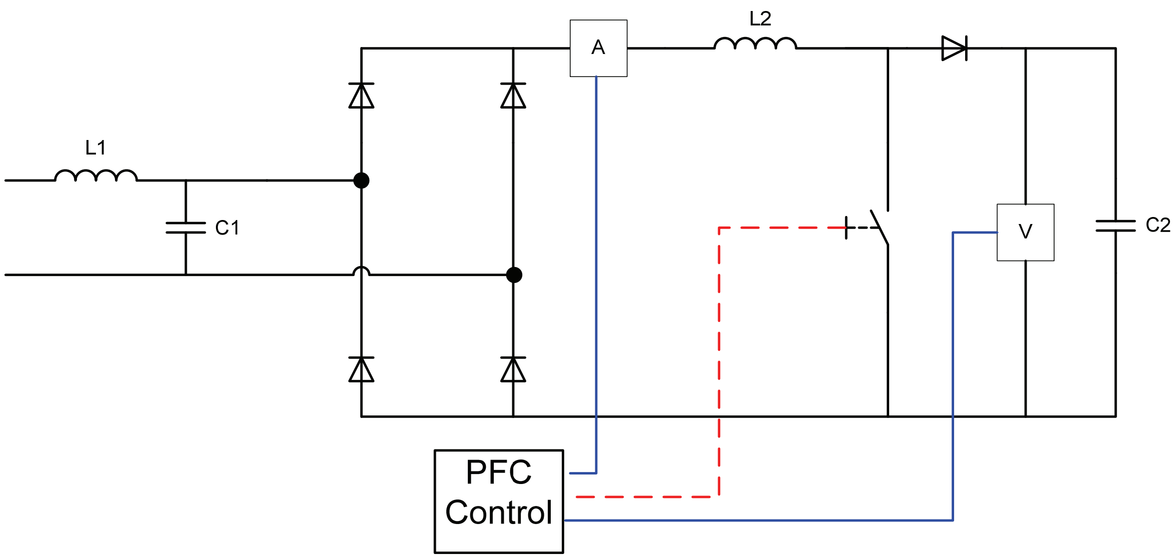

Figure 10-14
Circuit Topology of PFC Boost Converter

Table 10-2
PFC Boost Converter Circuit Parameters

Parameter	Value
L1	0.5 mH
L2	1.8 mH
C1	10 μF
C2	500 μF

It is advantageous for vehicle battery chargers to operate with a very high power factor. One method that is commonly used to provide power factor control (PFC) of a boost converter is PWM control [4]-[5]. When PFC control is employed, the desired shape of the inductor current is that of the fully rectified sine wave (Haversine). When this is accomplished, the boost converter operates at near unity power factor with low harmonic current distortion. The block diagram of the control scheme that is implemented to achieve PFC control is shown in Figure 10-15 [5].

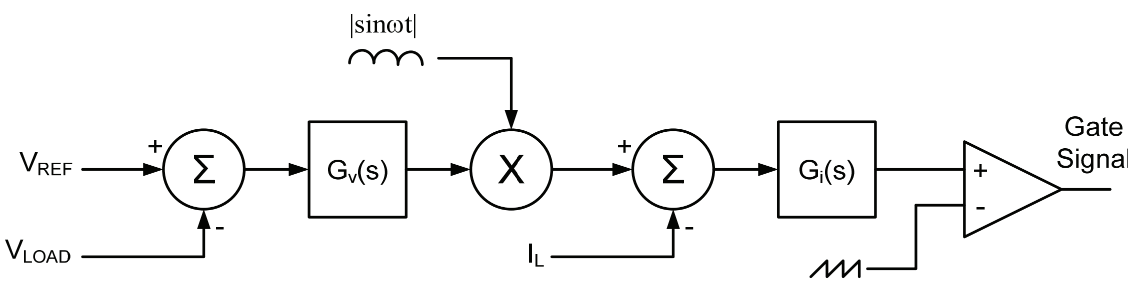

Figure 10-15
Block Diagram of PWM Control of PFC Boost Converter

The current controller, Gi(s) is a lead compensator and is described by (1)

$$G_i(s) = \frac{K_{ii}}{s} \cdot \frac{1 + \frac{s}{\omega_z}}{1 + \frac{s}{\omega_p}} \quad (1)$$

The parameters of the lead compensator described by (1) are provided in Table 10-3.

Table 10-3
PI Controller Parameters for Hysteresis Control

Parameter	Value
K_{ii}	8375.8
ω_z (rad/sec)	16835.7
ω_p (rad/sec)	2.3449×10^5

The voltage controller, G_v(s) is a PI compensator with parameters provided in

Table 10-4. The reference voltage (V_{ref} in Figure 10-15), was chosen to be 370 Vdc.

Table 10-4
PI Controller Parameters for Hysteresis Control

Parameter	Value
K_i	13.17
K_p	0.001

Two protection functions were also modeled in the PFC boost converter, but are not shown in Figure 10-15. The two protection functions are: 1) the input current to the charger (current flowing through L1 in Figure 10-14) is limited to 21.2 Amps peak, and the output voltage of the boost converter (voltage across C2 in Figure 10-14) is limited to 410 Vdc (110% of the reference value). The current limit is necessary to protect the device from overcurrent during situations of low voltage since the charger functions as a constant power load. The overvoltage protection function is to minimize dielectric failure of the various components within the charger. These values (current and voltage) are evaluated at every time step and compared with the corresponding design set-point. If the design set-point is exceeded during the simulation, the gating signal to the boost transistor is discontinued [3].

The methodology behind PFC control of a boost converter is as follows. The difference between the output of the boost converter (voltage across C2 in Figure 10-14), and the reference voltage generates an error signal that is fed into the voltage controller, G_v(s). The output of the voltage controller is then multiplied by the Haversine, and this new error signal is fed into the input of summing junction where a new error signal is formed with the measured current from the boost inductor. This new error signal is then fed into the current controller, G_i(s). The output of the current controller is then compared with a ramp signal (carrier wave) to provide pulse width modulation (PWM) control of the transistor. The result is a boost inductor current that is in phase with the sinusoidal input voltage. The resulting inductor current and reference signal are shown in Figure 10-16. Typical switching frequencies for PWM controllers, such as the one presented here are 50-200 kHz [3]. In order to limit the minimum step size and corresponding simulation time, a switching frequency of 20 kHz was selected.

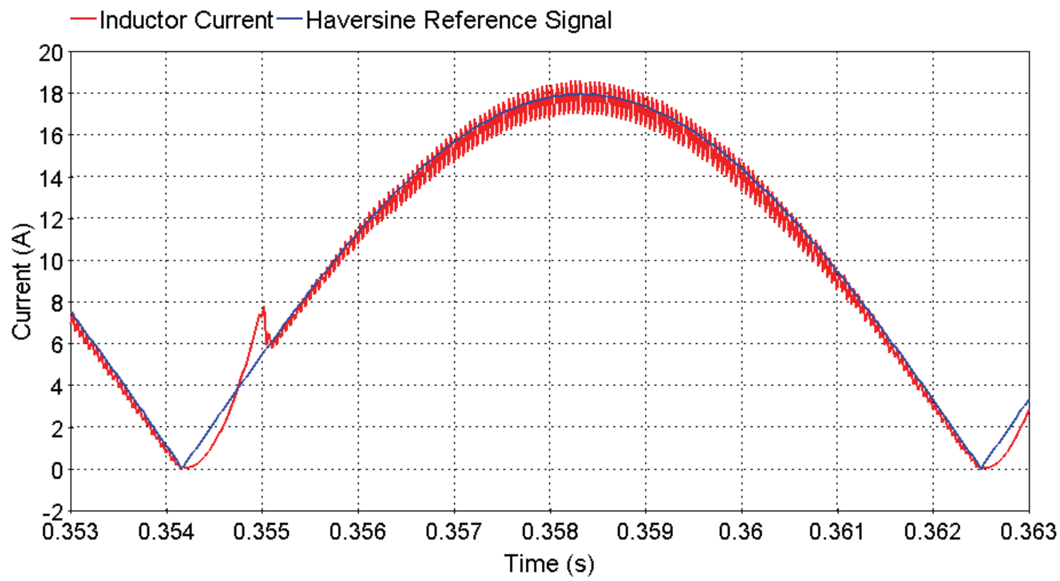

Figure 10-16
Comparison of Inductor Current with Reference Signal

DC-DC Converter Model

A full-bridge forward converter is used to isolate the battery from the PFC converter. A detailed model of this dc-dc converter is shown in Figure 10-17.

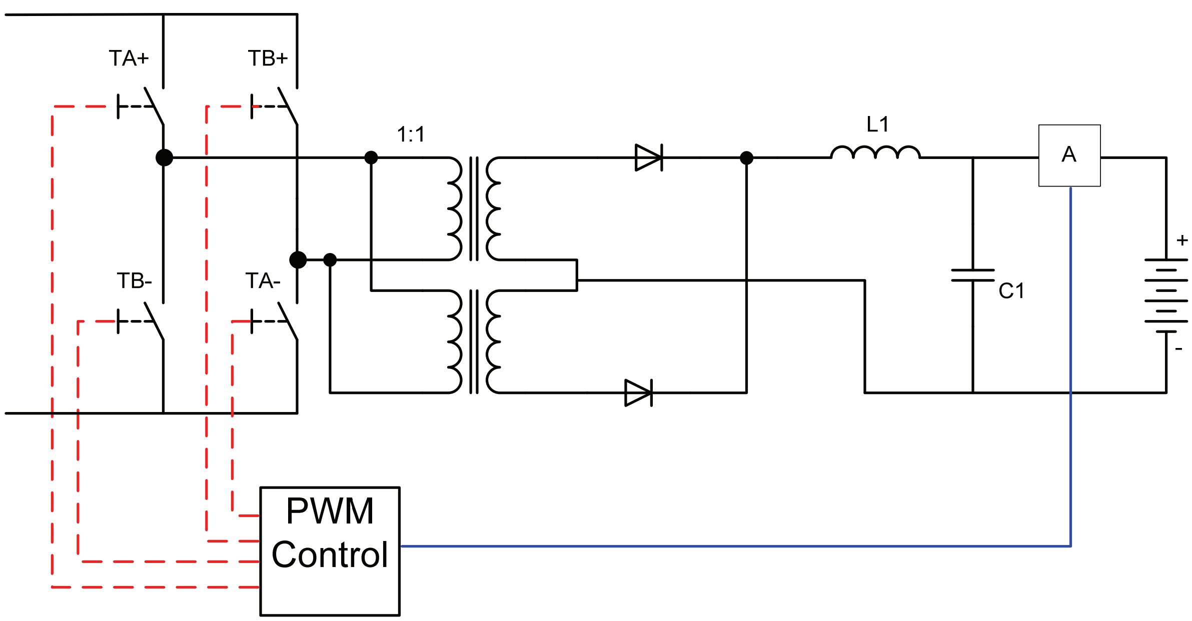

Figure 10-17
Circuit Topology of Full Bridge Forward Converter

The parameters of the output filter shown in Figure 10-17 are provided in Figure 10-2.

Table 10-5
DC-DC Converter Circuit Parameters

Parameter	Value
L1	5 mH
C1	50 μF

A means of controlling the full-bridge dc-dc converters associated with PEV chargers is via pulse width modulation (PWM) [1]. The block diagram used to implement this control scheme is shown in Figure 10-18.

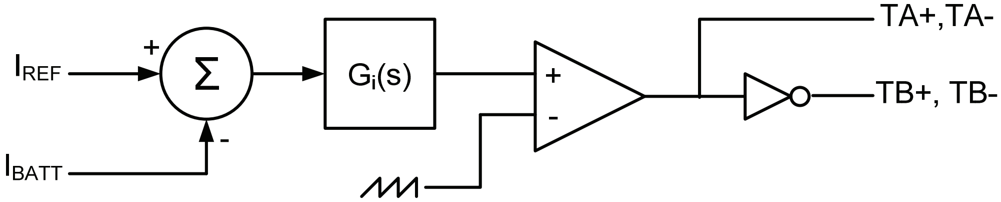

Figure 10-18
Block Diagram of PWM Control of Full-Bridge Forward Converter

The current controller, $G_i(s)$, shown in Figure 10-18 is configured as a PI controller with parameters as provided in Table 10-6. The reference current, I_{ref}, was selected to be 3.65 Amps.

Table 10-6
PI Controller Parameters for PWM Control

Parameter	Value
Ki	100
Kp	1

The methodology behind PWM control of the full bridge forward converter is as follows. The PWM control scheme controls the four transistors shown in Figure 10-17 using bi-polar voltage switching. With this method of switching, diagonally opposite transistors (TA+, TA-) and (TB+, TB-) are switched in pairs. To determine which pair is switched on and off, a 50 kHz ramp signal (carrier wave) is compared to the output of the PI controller, which is a function of the difference between the reference and measured battery current.

Battery Model

The battery was assumed to be a 330 V – 10 kWh (30.3 Ah) Li ion battery. The battery voltage when fully charged was assumed to be 384 V, and it was further assumed that the battery had an internal resistance of 0.1Ω. The time domain battery model that was used in this case was a simple DC voltage behind a series resistance, and is shown in Figure 10-19.

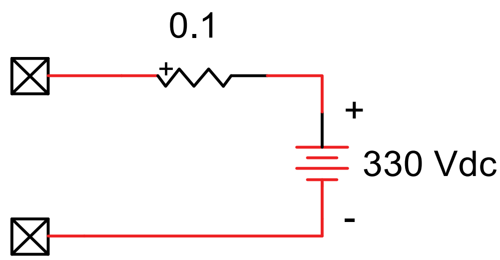

Figure 10-19
Time Domain Battery Model

Although there are more sophisticated time domain battery models available, e.g. [54], these models are not needed for the time period of interest. During the simulations performed as a part of this study, the DC voltage of the battery can be assumed to remain constant throughout the simulation period. The parameters and discharge characteristics for the battery were obtained from [5], and were plotted using Matlab SimPowerSystems toolbox. The discharge characteristic is shown in Figure 10-20.

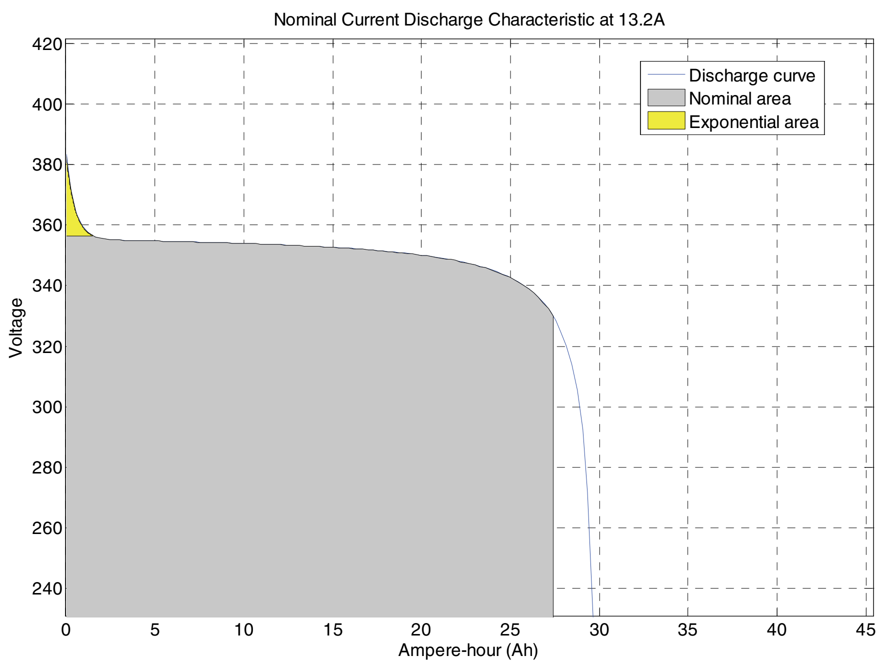

Figure 10-20
Discharge Characteristics of a 330 V, 10 kWh, Li ion Battery

Reduced Order Model

It was later discovered through simulation that, for the purposes of determining the effect of capacitor bank switching transients on charger performance, the full charger model shown in Figure 10-1 is not required. The dc-dc converter and battery can be replaced by an appropriately chosen resistance value which represents the battery load. Figure 10-21 shows a comparison of the resulting boost converter output (voltage across C2) for both the full and reduced charger models during a capacitor bank switching event. A load resistance of 102 Ω was used to represent the dc-dc converter and battery.

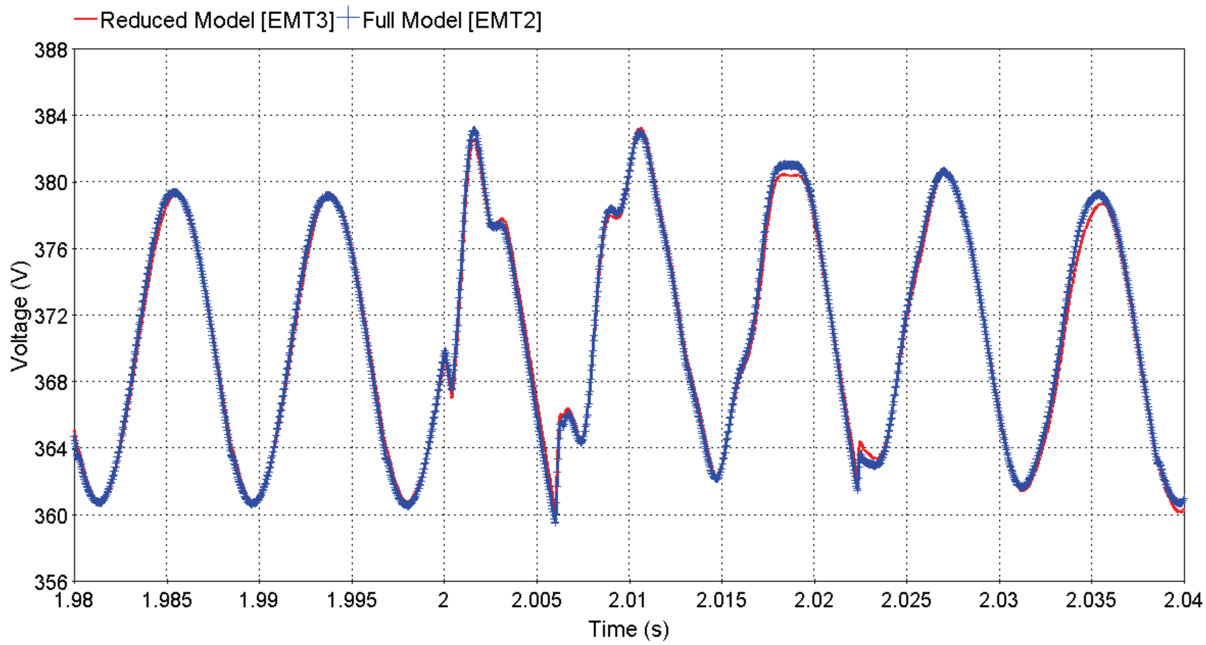

Figure 10-21
Comparison of Full Order and Reduced Order Boost Converter Model

The simulation results in Figure 10-21 clearly show that the reduced order PEV charger adequately represents the behavior of the charger during capacitor bank switching events, and can therefore be used to reduce simulation time and model complexity when needed.

Model Validation

The PEV charger model was validated by comparing simulation data with measurements taken from an actual 120 Vac – Level 1 PEV battery charger. Figure 10-22 shows a comparison of the measured time-domain current waveform and that simulated using the EMTP-RV model described in the previous sections.

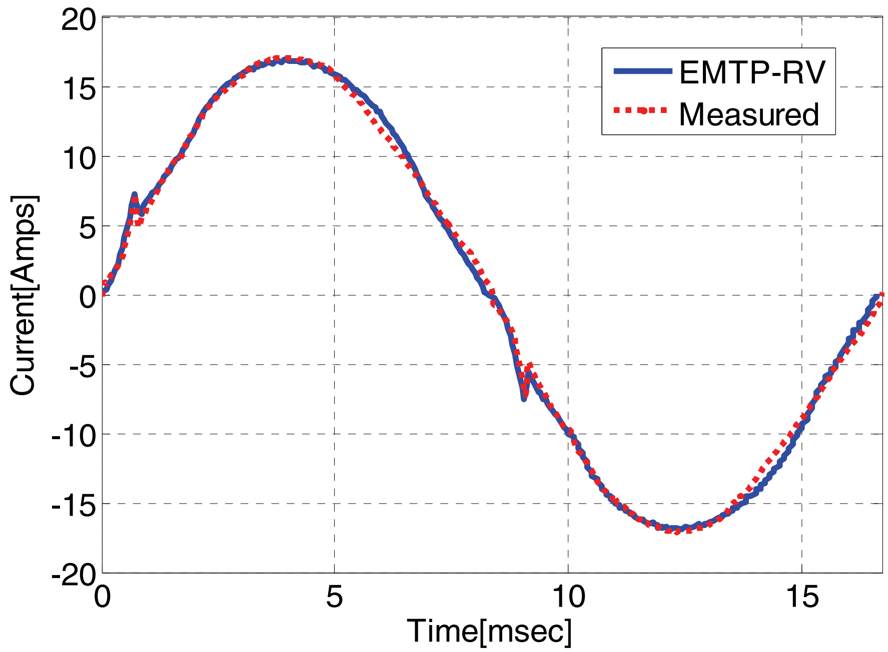

Figure 10-22
Comparison of Measured and Simulated Input Current Waveform

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