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# Consumer Adoption and Grid Impact Models for Plug-in Hybrid Electric Vehicles in Wisconsin

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**16. Abstract**

This proposed study focuses on assessing the demand for plug-in hybrid electric vehicles (PHEV) in Wisconsin and its economic impacts on the State's energy market and the electric grid. PHEVs are expected to provide a range of about 40 miles per drive cycle using plug-in recharging from the electric grid, in addition to the virtually unlimited range offered by conventional and hybrid vehicles. Given the concern over global warming and the need for reducing America's dependence on foreign oil, PHEVs are among the emerging 'green' alternatives to conventional fossil-fuel vehicles. Although they are recognized to have the potential to play a key role in climate change and energy security strategies, projected levels of market adoption, charging patterns, and impacts on electricity market and infrastructure supply are uncertain.

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## Note on This Document

This document contains two parts that together make up the final report for CFIRE project 03-01: *Consumer Adoption and Grid Impact Models for Plug-in Hybrid Electric Vehicles in Wisconsin*.

- Part A: Consumer Adoption Models (60 pages)
- Part B: Grid Impact Studies (175 pages)

**State of Wisconsin**
**Department of Administration**
**Division of Energy**


# Environmental Research Program


**Final Report**
May 2010


## *Consumer Adoption and Grid Impact Models for Plug-in Hybrid Electric Vehicles in Wisconsin*
*Part A: Consumer Adoption Models*


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# EXECUTIVE SUMMARY

This study focuses on assessing the demand for plug-in hybrid electric vehicles (PHEV) in Wisconsin and provides near term recommendations to manage its impacts on the State's electric grid.

This study has two main objectives:

- Enhance the understanding of consumers' perception of and demand for PHEVs, thereby informing policy development for wider PHEV deployment.
- Assess the market potential of PHEVs in Wisconsin and estimate the associated vehicle charging patterns, electricity consumption, and infrastructure needs.

In view of the time frame for the study, our analyses were limited to the Greater Madison area. As such, the project serves as a demonstration of research methodology as well as a preliminary study for future expansion to analyzing the PHEV impacts to the entire state of Wisconsin.

The objectives have been accomplished through three major research components: infrastructure readiness assessment, consumer preference analysis and grid impact studies.

## *Infrastructure Readiness Assessment*

A PHEV readiness analysis at the community level using parcel level has been completed using Tax Assessment data for the City of Madison, WI. Nearly 70% of all residential parcels in Madison are found to be PHEV ready. That is, these parcels are occupied by single detached homes with either attached or detached garages. Based on results on the readiness analysis, a scenario analysis of electrical grid impact due to varying levels of PHEV adoption is also described. Compared to past studies of PHEV readiness that typically utilize aggregate data provided for census geographies, our parcel-level analysis provides much higher spatial accuracy regarding where the PHEV-ready households are. Both analyses serve to demonstrate the benefits and the need for parcel-level analysis to support utility planning and PHEV market promotion at a refined geographic scale. The methods allow electrical utilities to analyze their distribution network under scenarios of maximum near-term PHEV load.

However, recharging capability (at home or elsewhere) being a necessary but not a sufficient condition for early PHEV adoption, the likelihood of a household becoming an early adopter depends on a suite of factors ranging from infrastructure availability, charging methods, vehicle and fueling costs, vehicle performance characteristics, to household's income, life style, and attitudes towards environmental issues. Future studies are needed to better understand the relationship between PHEV preference and PHEV readiness, between the true market and the potential market pool.

In the long run, the possibility for recharging PHEV at commercial sites or public stations will not only change market behavior but also load distribution across the utility network. This aspect of PHEV is not covered herein, but to do so in the future would require an analysis of commercial/industrial geographic areas where such opportunities are more likely to be installed. It is hoped that our work presented here would assist with those expanded efforts.

Additionally, agencies that wish to adopt policies encouraging denser built environments with goals of fewer road miles may reveal a contradiction with PHEV home charging. If single unit personal garages remain the universal primary charging locations, the inclusion of those garages will use more land. Further, residents who choose to live in denser urban environments may be served well by PHEV if they must own personal vehicles, yet may not have adequate access to PHEV charging opportunities. It is anticipated that our geospatial approach would be extended to assist in these future assessments.

### Consumer Preference Analysis

An in-depth consumer survey was conducted among consumers in the Madison area using a specifically designed survey instrument to study the impact of consumer preference on PHEV adoption.

Out of the 61% respondents that are interested in purchasing a vehicle in the next five years, 80.59% are willing to consider purchasing an alternative vehicle. This equates to 49% of the sample being willing to consider purchasing an alternative vehicle in the next five years. Applying this proportion to the population gives an estimated 70,000 households as the PHEV willing households in the Madison area in the five-year timeframe.

However, when one considers the expected price of PHEVs in the range of $30,000 and upwards including subsidies, this translates into an *upper bound* of about 21,000 households that are able *and* willing to purchase PHEVs in the next five years. This would represent an annual increase of about 4.3% of the residential electrical utility customer base of the Madison Gas and Electric. The present level of survey data does not definitively develop the geospatial locations of the households where this growth would occur, particularly in light of the inability in sharing confidential consumer information of the survey respondents for correlation with Madison Gas Electric's customer information database. Thus any extrapolation on the resulting specific grid impact of the near term PHEV adoption by households connected to the distribution grid becomes highly speculative. On the other hand, infrastructure readiness analysis and worst-case transformer loading study results indicates that critical aspects of PHEV adoption that lead to circuit overloading tends to occur in rare occasions at rare locations. Therefore, in light of such uncertainties, it would rather be effective to focus on creative solutions that avert such rare events as opposed to developing guidelines or roadmaps for additional infrastructure investments in the distribution network. Preliminary investigations indicate that existing demand side management approaches may be effectively tailored for this purpose.

### Grid Impact Studies

Demand response is quickly evolving and playing a greater role in the electric industry, particularly with recent promotion of smart grid activities across the nation. PHEV have the potential to provide a significant amount of demand response through a variety of methods. A brief overview of different demand response scenarios from a US-Midwest regional perspective has been studied along with an outline of the different future possibilities of the ways in which PHEV may participate as demand response resources. Furthermore, the case for developing a vision that encourages PHEVs to participate in demand response for their energy storage potential, thus enabling a higher penetration of intermittent and variable generation such as wind and solar energy resources is been put forth.

Specifically, in developing demand response incentives, there should be a clear benefit for PHEV owners who choose to participate in time-of-use programs and charge their vehicles during off-peak hours.  However, if PHEV owners are unable to charge during off-peak hours, participation in time-of-use metering programs is detrimental.  Additional quantitative studies are needed to determine if the potential savings accrued through time-of-use metering and reduction is gasoline consumption is sufficient to recoup the purchase premium of a PHEV over a hybrid electric vehicle or a conventional vehicle. In addition, if the usable storage capacity of a battery is allowed to time shift household residential electricity usage to off-peak hours, it is likely that the required levels of subsidy may change or even become unnecessary. In such a case, a temporary subsidy would be sufficient to encourage residential customers to participate in time-of-use metering programs.

Continuing comprehensive modeling and analytical studies are necessary to determine the necessary magnitude of these subsidies in order to enable PHEV owners to achieve cost recovery on the purchase premium of a PHEV over the life of the vehicle.

Part A of the report concerns with Consumer Adoption Models, and Part B of the report concerns with Grid Impact Studies.

# ACKNOWLEDGMENTS

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# 1
# INTRODUCTION

## Background

This study focuses on assessing the demand for plug-in hybrid electric vehicles (PHEV) in Wisconsin and provides near term recommendations to manage its impacts on the State's electric grid.

PHEVs are expected to provide a range of about 40 miles per drive cycle using plug-in recharging from the electric grid, in addition to the virtually unlimited range offered by conventional and hybrid vehicles. Given the concern over global warming and the need for reducing America's dependence on foreign oil, PHEV are among the emerging 'green' alternatives to conventional fossil-fuel vehicles. Although they are recognized to have the potential to play a key role in climate change and energy security strategies, projected levels of market adoption, charging patterns, and impacts on electricity market and infrastructure supply are uncertain.

Consumers have responded in a dramatic manner to the introduction of hybrid electric vehicles (HEV) in the last decade. The sales of such vehicles have grown as much as 80 percent annually, a particularly striking figure in the face of declining or flat sales trends in most categories of conventional vehicles. PHEVs take that dedication to "clean" alternative fuels to the next level. Not only are they the next step in the emergence of energy-efficient, pollution-reducing technologies designed to stem the growth of transportation-related greenhouse gas emissions, they could be recharged quite literally in the owner's backyard. But there are other considerations before U.S. consumers can adopt PHEVs as the nation's primary personal transportation. An increase in PHEV use will impact the patterns of electricity use, driving habits and the economics and operation of the electricity grid, which could mean more use of coal-powered energy plants to produce enough electricity. This study outlines whether PHEVs could become that primary transportation option and how such adoption would affect the U.S. electricity grid.

The discovery and use of a sustainable fuel is as important to Wisconsin as it is to the United States. Other than the fraction of vehicles represented by ethanol, the majority of energy used for personal transportation in Wisconsin is imported from outside the state. On the other hand, 80 percent of Wisconsin's electricity demand is obtained through in-state generation. Depending on the adoption and growth of PHEVs in Wisconsin, the mix of in-state and out-of-state resources to meet the new energy demand for transportation and electricity is bound to change. The additional demand for electricity arising from this new vehicle adoption could be met from a variety of primary sources, such as wind, solar, nuclear and coal, taking into account their accompanying impact on economic and environmental conditions. Thus, there is an opportunity for developing appropriate policy actions to direct a state-wide energy dependence scenario.

## Research Objectives

To date, most PHEV-related analysis has focused on technology assessment, lifecycle analysis, battery R&D, and vehicle modeling. Also, a number of recent studies explored the environmental consequences of shifting transportation energy use from conventional fuels to electricity through wide deployment of PHEVs and showed promising GHG impacts and air quality benefits at the national and global levels. Yet, much uncertainty remains regarding the infrastructure and economic impacts of PHEVs at the local level.

This study has two main objectives:

- Enhance the understanding of consumers' perception of and demand for PHEVs, thereby informing policy development for wider PHEV deployment.
- Assess the market potential of PHEVs in Wisconsin and estimate the associated vehicle charging patterns, electricity consumption, and infrastructure needs.

In view of the time frame for the study, our analyses were limited to the Greater Madison area. As such, the project serves as a demonstration of research methodology as well as a preliminary study for future expansion to analyzing the PHEV impacts to the entire state of Wisconsin.

## Approach

The objectives outlined above were accomplished through three major research components: infrastructure readiness assessment, consumer preference analysis and grid impact recommendations. Each of these components is briefly described below.

### Infrastructure Readiness Assessment

PHEV Readiness is demonstrated by the availability of electricity and the capacity of the electric distribution network to furnish electricity at locations where reasonable demand for PHEV charging could be expected. In this study, a household is considered as being "PHEV ready" if it has the *ability* of at-home charging. PHEV readiness is therefore considered as the base criterion for a household to qualify as part of the market pool for early PHEV adoption.

The infrastructure readiness assessment began with determining where PHEV-ready households are. The demand load on the electric distribution network in these PHEV-ready areas was then analyzed for its capabilities; its readiness, to electrically charge and recharge a vehicle fleet at residential locations and represented by the potential market penetration of PHEV.

### Consumer Preference Analysis

While the infrastructure readiness assessment is concerned with residents' *capability* of being early PHEV owners, the consumer preference analysis focuses on analyzing residents' likelihood – as defined by preference – of being early PHEV owners. The preference analysis entailed designing and administering a survey to sampled residents in Madison. Participants were asked a series of questions aimed at uncovering their desire to purchase a vehicle within a given time frame, the price range of that potential vehicle, and whether they would be willing to consider an alternative fuel vehicle, such as a PHEV, for that next purchase. The survey also collected

standard demographic information to allow researchers to understand whether alternative fuel vehicles, such as PHEVs, could be accepted across all age, education and income levels.

## Report Outline

This report is organized as follows. Chapter 2 discusses the literature relevant to the three components of the study. Chapter 3 evaluates the household and electricity grids readiness for PHEV adoption. Chapter 4 describes the consumer preference analysis effort and the key findings. The final chapter provides a summary of conclusions.

# 2
# LITERATURE REVIEW

## Past Studies of PHEV Readiness

The use of home charging/refueling ability to define the upper bound of early PHEV market is not new and is drawn from past observations of ICE vehicle adoption. At the advent of the ICE vehicle introduction, gas stations as we know them were not prevalent. Motorists purchased vehicle fuel in bulk for storage at home. Doing so among these early ICE adopters sustained ICE vehicle growth, until stations became profitably operable. The same may be for PHEV. After a period when motorists who elect to own PHEVs do so with the exclusive home charging, a PHEV fleet may grow to demand secure, public recharging or battery swap stations that resemble, replace or replicate the current gas station infrastructure. Such stations, thereby may preclude the need or desire for additional home recharge stations, and may induce a market to those without home structural capacity for recharge stations.

The correlation between PHEV adoption and home charging is evaluated to some degree by Williams and Kurani (2007) noting that 120VAC outlet accessibility defines "prospective owners"; what we would call a Pool Market for potential PHEV adoption. Williams and Kurani (2006) indicates that, while garages can define the Pool Market, they too may need modification before motorists bring PHEVs home for recharging. In fact, in writing about home 120 volt and 240 volt charging, Morrow et al (2008) only briefly mentions the use of a standard wall outlet for charging a PHEV. It is conjectured in the study that existing circuits currently in garages could be used, but a switch may be required that deactivates the wall socket in favor of PHEV charging socket and vice versa. In such cases, homeowners, electrical codes and installers will need to assess continuous power to other garage appliances.

Two studies conducted surveys to quantify access to home charging locations. In Axsen and Kurani (2008a), 52.4% of 2,372 U.S. nationwide household respondents "identified an electrical outlet within 25 feet of their vehicle parking spot at their home location at some time during their 24-hour day". The precision of that question does account for vehicle owners who may not park in single home garages, yet still have access to an outlet. In Graham et al (2001), 400 consumers in Boston, Atlanta, Phoenix and Los Angeles were sampled for among other PHEV related items, "relatively easy access to a plug, with 120 volt systems being relatively hassle free". Unfortunately, the phrasing of the question is not evident and with 86% of households reporting such access, which seems intuitively excessive, by no means matches the rate reported by Axsen and Kurani (2008a). Nonetheless, the precision of not necessarily relying on single home garage information is noted.

For a larger sample size, Williams and Kurani (2006) uses the 1% Public Use Microdata Sample (PUMS) of the 2000 Census of the State of California. This data was used for the purpose of analyzing not just capabilities for only electric home refueling but for future hydrogen refueling as well. With it, housing stock built after 1974 was used as a proxy for "home connection hardware". Buildings built since 1974 have been wired according to the National Electric Code

revision of that year, and those authors intimate that code as sufficient for the purpose of their study. This limits the precision of the PHEV Pool market by underestimating older homes and specifically their garages that could easily have been wired for PHEV charging and overestimating the number of buildings, which could include apartments and condominiums. The result of that assessment was a Pool Market of 15% of households. Similarly the publicly available American Housing Survey is used by Vyas et al (2009) to identify the existence of a "garage or carport" amenity at a single unit house is a proxy for "likely PHEV buyers". The Pool Market assessment in this case yields 38.7% of households. Extending electricity to carports may be more code cost prohibitive than even doing so with detached garages, since electrical raceways exposed to the elements do require additional code adherence. So, assuming that builders included costs to serve carports with electricity may have overestimated the Pool market in this case.

The four abovementioned studies have delivered significantly different assessments of Pool Markets. As described above, Pool Markets among households are either 52.4%, 86%, 15% or 38.7%. Intuitively, the values, 86% and 15% seem respectively too large and too small. The values, 52.4% and 38.7% both seem reasonable, yet where 38.7% of single homes have garages or carports might overestimate the Market Pool on behalf of carports, that value is still less than the survey respondents' 52.4% Market Pool. Perhaps opening the Market Pool of that survey to include any outlets within 25 feet subsequently overestimated it.

A report on compressed natural gas (CNG) infrastructure of the 1980's shares lessons about alternative fuel transportation (Flynn, 2002). That report does call exception to the electricity utility infrastructure, "which is already available in homes, (…and…) can avoid this issue (inadequate infrastructure) through affordable repowering". The report also stated that "the main barrier was a lack of infrastructure to support the converted vehicles", and, "utilities or energy suppliers can be allies, but need to ensure that their actions are strategic in building the market".

## Past Studies of Consumer Preference for PHEV

The field of consumer adoption modeling as it concerns alternative fuel vehicles has been of increasing interest in recent years. The drive for citizens and politicians across the globe to decrease their country's dependence on foreign oil as a primary energy source has led more engineers to study alternative fuels. That research has triggered the field of consumer adoption research as a means to uncover which potential energy source would be the most acceptable to consumers.

One of the focal points of the research has been the study of hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV). Some critics have said that the United States is unprepared to shift from gasoline to electric and alternative fuel vehicles. However, one out of every three new vehicle purchasers has both the desire to purchase a PHEV and the infrastructure to support plug-in recharging already (Axsen and Kurani, 2007). Even that switch to non-gasoline operation could cut the U.S consumption of gasoline in half as it concerns transportation (Axsen and Kurani, 2007).

For the purposes of this study, it has been necessary to narrow this literature review to deal with studies that dealt with consumer modeling. Moreover, we focus on studies which utilized surveys for at least one section of their data analysis and attempted to discern the degree to

which alternative fueled vehicles, such as electric, could become viable transportation alternatives.

Stated preference surveys are one of the most popular methods for determining a consumer's opinion on alternative fuel for vehicle transport. "In such an approach respondents are asked to express preferences for hypothetical products described in terms of their attributes. Statistical models are then applied to estimate the relative values of the attributes to consumers" (Bunch, et al., 1993: p.238). The benefit of using a stated preference survey is that it allows the construction of scenarios based on current or future vehicle technology. Such scenarios allow the researcher to find out what consumers would choose when given potential "real-life" decisions regarding vehicle attributes. They are better than standard binomial surveys because a respondent can give an opinion on one attribute in relation to the others available instead of a rating each attribute on its merits alone and the surveys could be tailored for individual respondents.

For example, Ewing and Sarigöllü (2000) created stated preference surveys for respondents with different fuel costs and a different range of vehicle attributes. Tompkins, et al., (1998) described current market conditions for alternative fuel vehicles in the participant's community as well as other technological information, such as purchasing incentives. "The disadvantage of this approach is that it is based solely on the stated intentions of survey respondents, and has not been adjusted to incorporate available information on actual market-based behavior" (Bunch, et al., 1992: 34).

## *Analysis Focus*

Stated preference surveys are used to determine whether consumers would accept and purchase vehicles that use a cleaner fuel than current gasoline engines (Tompkins, et al., 1998; Brownstone, et al., 1999; Bunch, et al., 1992; Ewing and Sarigöllü, 2000; Bunch, et al., 1995; Segal, 1995; Golob, et al., 1991). The studies reviewed a wide-range of alternative fuels, such as electrical, ethanol, methanol, and natural gas, and compared them to the performance attributes of a conventional gasoline-powered internal combustion engine (ICE). Where it concerned electric vehicles, the studies examined true electric vehicles (EV) that ran on battery power, hybrid electric vehicles (HEV) that used a combination of electric and gasoline power, and plug-in hybrid electric vehicles (PHEV) that usually used the same engine as an HEV, but allowed the owner to recharge the battery through a cord that could be plugged into an electrical outlet.

Bunch, et al., (1995) took it one step farther and wanted to analyze the preferences of individuals and businesses with more than one vehicle. Most studies focused on the type of vehicle that consumers would buy as it relates to alternative fuel attributes (Tompkins, et al., 1998; Brownstone, et al., 1999; Bunch, et al., 1992; Ewing and Sarigöllü, 2000; Bunch, et al., 1995; Segal, 1995; Golob, et al., 1991). The reason vehicle type was the primary focus had to do with the fact that alternative fuel studies want to determine whether consumers would buy certain vehicles with alternative technology, not simply that they would be in favor of alternative technologies.

The studies focused on the most feasible methods of alternative fuel, such as electricity and ethanol. Tompkins, et al. (1998) looked at whether vehicles could be run on propane. A few

studies tested whether it would be possible for vehicles to run on natural gas (Brownstone, et al., 1999; Bunch, et al., 1995; Segal, 1995).

## *Model Structure*

Most studies use a multinomial model for data analysis. However, some studies preferred to use conjoint analysis (Segal, 1995) or the transactions model (Bunch, et al., 1995) when creating the survey or analyzing the data. In a conjoint analysis, researchers take data and break it down in order to understand which data attributes are the most important, such as the Segal study (1995) where he used conjoint analysis on various vehicle performance attributes, such as driving range when fully fueled, to determine how consumers might rank those attributes if they had to choose between them. Through the transactions model, researchers can "predict whether a vehicle transaction will occur during the current period and what type of transaction it will be" (Bunch, et al., 1995: 2).

## *Survey Methodology*

In order to get a quality sample of participants, most studies start with a large population of at least 1,000. Tompkins, et al. (1998) and Brownstone, et al. (1999) had more than 4,000 participants for one section of their studies. Golob, et al. (1991) had less than 400, but still found that to be a highly effective sample for their study.

Stated preference surveys consist of a series of scenarios where the participant gets to chose various vehicles from a variety of performance attributes. The most popular form of participant collection is through random selection and surveys can be sent to the participant or conducted through the Internet. Telephone contact of participants is possible to obtain general information, but it is quite difficult for a stated preference survey because participants must see and analyze different options (Golob, et al., 1991). The researchers use the computer-assisted telephone interview (CATI) process, where researchers read a script off the computer, to gather preliminary information from the participant. Then they use that information to design the scenarios available in the actual stated preference survey. Some studies want more than vehicle preferences and ask participants to record their daily driving information to determine whether driving behavior would make alternative fuel vehicle adoption more likely (Brownstone, et al., 1999). Bunch, et al. (1995) and Segal (1995) used the data from their stated preference phase as a means of forecasting the future of alternative fuel vehicle acceptance.

## *Question Design*

When it comes to stated preference survey design, most studies focus on giving participant selections based on fuel type and vehicle performance attributes. Some studies use the alternative fuel selection as the main criteria for the survey scenarios (Brownstone, et al., 1999). Other studies combine fuel type with vehicle type, such as small car or truck (Tompkins, et al., 1998). Bunch, et al., (1992) wanted to see which vehicle drivers, such as sports cars or pick-up trucks, would be most willing to adopt alternative fuel vehicles. Most studies use the alternative fuels as a means to creating a selection of vehicle performance attributes, such as driving range when fueled to the maximum or vehicle price, and then let participants chose from a variety of attributes (Golob, et al., 1991; Bunch, et al., 1992; Segal, 1995). Once the participants chose their particular vehicle attributes, the data is analyzed to determine if consumers would adopt a

new technology in their transportation vehicles or, if they wouldn't, what improvements would need to be made to alternative fuel vehicles to give them a better chance of consumer acceptance.

The studies varied in terms of how many options the stated preference surveys gave to participants. Tompkins, et al. (1998) used 192 different options on selected choice cards. Bunch, et al. (1992) combined their attributes to produce 64 "design treatments" and 16 different versions of the survey. In their later survey, Bunch, et al. (1995) produced 14 different vehicle body types and sizes with five different fuel choices. Although, each participant received one set of choices and none of them received every possible choice combination.

Most studies analyzed performance attributes in regards to whether they made alternative fuel vehicles more or less attractive. The most common attributes were purchase price, range from maximum to minimum fuel, fuel cost and fuel availability. Studies found that when purchase price increased, interest in owning an alternative fuel vehicle decreased. The same result was found regarding fuel cost. Range and fuel availability had the opposite effect on alternative fuel interest. When the range between refueling increased or the alternative fuel could be purchased at a greater number of locations, alternative fuel interest increased. The more consumers lost performance attributes relative to conventional vehicles, the less attractive they found alternative fuel vehicles (Golob, et al., 1991; Ewing and Sarigöllü, 2000).

### *Response Rates*

The response rates for the studies varied depending on the survey design. Most of the studies recorded a response rate of 60 percent or more (Tompkins, et al., 1998; Brownstone, et al., 1999; Bunch, et al., 1995). Not all studies were that successful. Bunch, et al. (1992) conducted a study with multiple "waves" where the response rate started at 40 percent and dropped to 20 for the third and final wave. Segal (1995) had a study were the response rate never rose above 30 percent.

### *Results*

The studies had some interesting findings. Bunch, et al. (1992) found that consumers liked a vehicle that could run on more than one fuel. Tompkins, et al. (1998) found that the "prestige" of owning an alternative fuel vehicle made a higher purchase price more acceptable. Ewing and Sarigöllü (2000) looked at attributes in relation to age demographics and found that younger respondents were more interested in alternative fuel vehicles because they were the most concerned about environmental issues. Segal (1995) found that people that commuted daily, younger consumers, consumers with more than one vehicle, and consumers with more income had the most interest in purchasing an alternative fuel vehicle. Also, the study found a significant interest in alternative fuel vehicles in households earning less than $25,000 per year even though alternative fuel vehicles are projected to cost that much at the least. These results weren't uniquely American. In their study of consumer adoption in Canada, Ewing and Sarigöllü (2000) found that the gasoline vehicle was the least preferred one when compared to alternative fuels such as electric. But the study was limited in that it focused on environmental impacts, an area where gasoline-fueled vehicles fail miserably compared to alternative fuels.

Tompkins, et al. (1998), and in a limited way Bunch, et al., (1992), looked at consumer adoption in regards to final purchase price. They wanted to determine how much more consumers would

be willing to pay for an alternative fuel vehicle with the same performance attributes as their current gasoline-fueled vehicle. For example, Bunch, et al., (1992) found that a one-cent per mile reduction in fuel cost equated to $1,400 reduction in purchase price. Tompkins' research team (1998) segregated the attributes to determine how much more consumers would be willing to spend on specific attributes, such as whether they would pay more for an alternative fueled vehicle in order to have more refueling or recharging stations. But the researchers derived these results from analyzing data and not direct questions.

Bunch, et al. (1992) found that electric vehicles weren't more attractive if the consumer could recharge at work. This result has been refuted in later studies that found people wanted the ability to recharge as often as possible (Brownstone, et al., 1999). Brownstone, et al. (1999) found that a participant's lack of knowledge regarding alternative fuel vehicles and their true levels of performance made results questionable.

Most studies concluded that there is a substantial interest in alternative fuel vehicles, if consumers don't lose the performance characteristics that they get in their conventional vehicles (Golob, et al., 1991; Ewing and Sarigöllü, 2000; Bunch, et al., 1992; Tompkins, et al., 1998). Then the studies come to different conclusions based on their design. Tompkins, et al., (1998) found that consumers would pay $1,660 for more electric recharging facilities. Brownstone, et al. (1999) found that electrical vehicles could eventually make up 20 percent of the U.S. automobile market. Bunch, et al., (1992) found that consumers were willing to pay more for an alternative fuel if they could get the same performance from their alternative vehicle as they did their conventional vehicle.

However, many studies suffered from fuel conclusions that have been discredited. Two studies stated that natural gas could be a good alternative fuel (Bunch, et al., 1995; Segal, 1995). Segal (1995) also found that young drivers were less attracted to electric vehicles than older drivers. In his study, Golob (1991) said that hybrid electric vehicles aren't a viable option when compared to dedicated electric vehicles. The HEV model Toyota Prius has been a popular vehicle for the last decade, while there is no dedicated electric vehicle available from a major automaker. Also, he found that recharging at work is not an added advantage while other studies have proven that the more places an owner can recharge a vehicle, the more popular electric vehicles could be (Tompkins, et al., 1998; Bunch, et al., 1992).

# 3
# PHEV READINESS ASSESSMENT

In order to accurately assess current and future infrastructure needs, it is imperative that the electrical utility organizations and agencies know both how much PHEV load will be added to their infrastructures and the locations where that PHEV load will be added. For that, local utilities will need quantitative and geospatial insight into assessments of the PHEV Pool Market. The work described below is intended as a tool for this purpose. Specifically, we present a method of geospatially determining PHEV electricity demand for distribution planners. This may be one of only a few, if any, methods that will assist the assessment of PHEV Readiness at the community level.

## Operational Definition of PHEV Readiness

The ability for motorists to refuel their personal vehicles at home with connection to an electric outlet is one of the touted advantages of PHEVs. Focusing on the present for a first assessment of PHEV infrastructure support directs consideration of detached housing units that are known to have the secure and convenient personal vehicle parking location of a garage. A survey conducted by the research team confirms that of the 267 sampled households residing in single detached houses with attached garages in the City of Madison, WI, 98.5% have access to 120 volts in their garages. Of the 43 sampled households residing in single detached houses with detached garages, 100% have access to 120 volts in their garages. Acknowledged are potential early or present PHEV adopters who have no access to home charging sources, yet know they can rely on electrical outlets at their employers' parking locations or their other activities' parking locations. Similarly acknowledged are potential PHEV adopters, who live in condominiums or apartment complexes, yet can still arrange vehicle charging connections. While such dwelling facilities may or may not, and moreover infrequently, have secure charging amenities, we are certain that most garages associated with detached homes do.

Based on earlier reasoning above, our analysis of PHEV readiness in the City of Madison, WI, is based on the assumption that all single detached houses with garages in the City of Madison, Wisconsin, have electric service in their garages for recharging. Differing from previous studies that used the Census data to identify the aggregate distribution of such housing units across census reporting units, we opt for the City's Property Tax Assessment data which provides housing information at the land parcel level. This allows us to pinpoint the exact locations of housing units that are PHEV ready or not.

## Tax Assessment Data

In the United States, municipalities such as cities or counties maintain databases that contain information regarding myriad attributes of each and every land parcel. Each parcel of land is assessed for a monetary value according to the parcel's use and the quantities and qualities of

attributes associated with improvements to the parcel. The predominant improvements to the land parcel are subsequently related to the structure(s) on it. The municipality levies a tax to each parcel according to the assessed total monetary value of it, and bills the owner of the property accordingly. Some parcels, that are themselves municipally owned or otherwise tax exempt, are assessed accordingly, but incur no tax levy. All such assessments and levies in the United States are public information, and subsequently, entire digital databases containing such information for all parcels are available for no to a nominal fee ($150, -2009 for the City of Madison, WI). The agency responsible for a municipality's tax assessment and levying is thus usually referred to as the assessor.

Each parcel in the tax assessment data is key-coded with a number and in more and more municipalities, each number is associated with standard Geographical Information System (GIS) coding with which the parcel's polygon can be displayed with appropriate computer software. An assessor or its database may not necessarily contain the GIS data. However, that data, if not available from the assessor will likely be available from a municipality's associated metropolitan planning organization (MPO), again for no to little fee. For geospatial display of assessment data, the assessor database and the GIS database may need to be merged.

## Data for City of Madison

For our PHEV readiness analysis for Madison, WI, we acquired the tax assessment database from the City of Madison Assessor's Office. The database was provided in the format of multiple MS Excel tables. As such, one of our first steps in preparing the data for analysis is to link it to the Madison Area Transportation Planning Board's land parcel boundary data in ArcGIS format. Since the tax assessment data and the GIS data come from different custodians, it was not surprising that some discrepancies existed between the datasets and the joining of the two datasets by parcel ID was more than a straight forward task. According to the City of Madison Assessor's Office, work is underway in providing future assessment data in a geospatial database format.

The assessor's database contained data describing land parcels of four property classes: Residential, Commercial, Industrial and Agricultural. The Residential Class include land parcels with the Property Use codes of "Vacant", "Single Family", "Condominium", "2-Unit", "3-to-7 Unit" and "Other". Note that larger (eight or more units) apartment building parcels were not included in the residential class. Instead, those were included in the Commercial Class, which include Property Use codes such as "Apartments", "Apartments and Rooms" and "Rooming House".

The assessor's database did not explicitly attribute any electrical receptacle data to parking spots. The only variables related to any aspect of parking are garage type, number of garage stalls and shared-driveway. Further, only the parcels in the Residential Class had garage data available. Some residential units, such as condominiums and some apartments, were not attributed with any of those values. Garage Type was coded as "none", "detached", "attached" and "underground"[1]

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[1] In Wisconsin, "carport", which is an attributed "other structure", occurs infrequently enough and the National Electric Code installation of electrical receptacles for such locations is restrictive enough to consider any carports as "none" for garage type.

and was a key variable for our subsequent analysis. The other two garage-related variables were not used.

## PHEV Readiness Analysis for City of Madison

Based on the operational definition of PHEV readiness developed in Section 3.1, we propose to designate a land parcel with the following properties as PHEV ready:

Property Class = "Residential"
Property Use Code = "Single Family"
Garage Type = "Detached" or "Attached"

Of the 59,879 land parcels in the City of Madison Tax Assessment Data, 50,039 are classed as "Residential" (seven or fewer dwelling units on a physical land area). Of these residential parcels, 46,774 are occupied by single family houses. Figure 1 shows the spatial distribution of garage types among these single detached housing units. The proportions of single home with attached garage, single home with detached garage, single home with no garage, and non-single home parcels are 49.2%, 19.4%, 5.7%, and 25.7%, respectively. The first two groups of the four (coded in two shades of gray in Figure 1) correspond to what we refer to as PHEV ready residential units, which represent nearly 70% of all residential parcels. One can see that these PHEV ready parcels show up in distinct clusters which not only represent the market pool for PHEV early adoption, but also areas where utility agencies need to pay special attention. Notably interesting is also those parcels with single detached homes without garages. The spatial distribution of this varies from very few within single-home clusters to distinct micro-clusters of themselves (for example, to the southwest of Lake Mendota).

It must be emphasized that, since the garage type information is not available for condominiums and parcels with eight or more apartment units, these housing units were excluded from our PHEV readiness analysis. There are at least two good reasons for which one should analyze the current electrical receptacle availability or potential for future accommodation in these housing structures separately from the analysis of single detached homes. First, the decision making regarding parking and utility infrastructure is different between these two scenarios. For single detached homes, the decision is up to either the occupants or the landlord. For multi-unit housing structures, parking in these housing structures is usually limited and is provided through underground parking garages, parking ramps or street parking. The facilities are usually centrally administered by private or public property management entities who have different considerations from the occupants. Second, residents in high density housing structures are generally considered to use transit and non-vehicular modes of transportation more than occupants of single detached houses. As policy makers are looking to the private car users as the market pool to promote PHEV, it is of less public interest at the moment to enable (or encourage) the likely transit riders, cyclists, and pedestrians to make the shift to PHEV use. For the above two reasons, PHEV readiness among single detached homes is of higher priority.

## Assessment of Grid Readiness

Charging PHEVs in household garages substantiates a notable change in household electricity use, which in turn impacts the temporal and spatial load distribution seen by utilities. For

instance, charging a fully depleted PHEV-40 from a standard 120 volt outlet would be on the order of operating a small hair dryer or one-third of a central air conditioning unit (different voltages aside), non-stop for two hours every other day (assuming full depletion of the PHEV-40 is a result of 40 miles all-electric driving; 20 miles/day x 2 days) all year. This could potentially be the second largest energy load in the cooling months and, in the course of a year, perhaps the single largest energy load, at the household level.
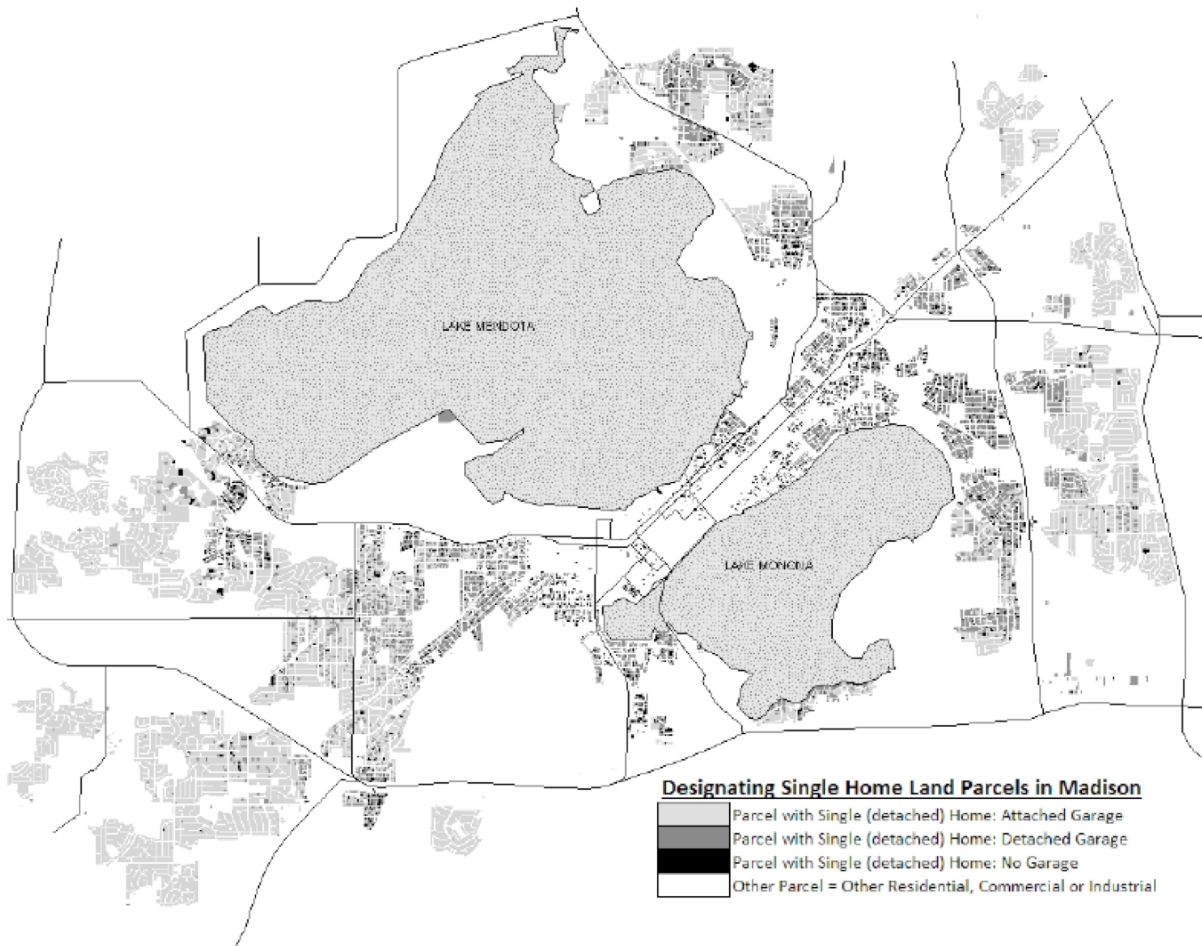


**Figure 3-1. Distribution of single family residential units by garage type**

Fundamentally all electrified homes, and subsequently their garages, are connected to electric power utilities, and the generators that serve them, through a network of transmission equipment and distribution lines. With the aforementioned substantial load of one household's PHEV in mind, the aggregate load of many households with PHEVs will merit study.

Following from out PHEV readiness analysis, we present a preliminary analysis performed to gauge the impact of adding significant PHEV load at the transformer level. According to a study performed by Duke Energy, the most significant impacts of PHEV market penetration will likely be due to geographic clustering of vehicles (1). Such demand clustering suggests the need for analyzing areas with high concentration of PHEV ready households.

Our grid impact analysis is based on data provided by Madison Gas & Electric (MG&E), the local utility serving the City of Madison, Wisconsin. MG&E provided a typical peak-day load curve for the daily consumption of eight customers fed from a single 50kVA transformer. The data obtained is an approximation based on the load curve for a primarily residential feeder within MG&E's service territory. This approximation was used because MG&E does not record hourly load data at the transformer level.

As a case study, a small neighborhood clustered with eight PHEV ready households in Madison who share a selected transformer is the focus for our grid impact analysis. The scenarios of one, two, three, …, and up to all eight of these households becoming owners of PHEV are examined. These households are assumed to charge their vehicle from a standard 120VAC 15A outlet available in their garage. Although these outlets are rated to provide power up to 1.44kW, preliminary studies on actual charging patterns from converted Hymotion Prius PHEVs show that the average power drawn by the vehicle when charging is approximately 0.77kW (Mohseni and Stevie, 2009).

Combining the transformer data and the vehicle data we were able to determine the energy impact of adding discrete PHEV load to the selected transformer. Given that the transformer is rated at 50kVA, and assuming an average residential power factor of 0.8, it is possible to determine how adding PHEV load will impact the percent loading of the transformer. Utilities may likely attempt to minimize PHEV contribution to peak load by implementing certain rate structures. These issues are discussed in more detail in Chapters 5 and 6. However, as a worst-case scenario, we can assume that customers will elect convenience over cost and charge their vehicles in the late afternoon. In this case, the additional loading coincides with the typical residential peak load. Figure 2 illustrates the impact of adding PHEVs to the selected 50kVA transformer assuming each adopter owns a single PHEV.

It should be noted that, prior to adding any PHEV load to the system, this selected transformer is already approaching its rated value. Recall that this is not the typical load seen by the transformer, but rather the load seen on a particularly warm day within the last five years. Thus in the worst case scenario, adding four PHEVs to this transformer does increase the percent loading to over 107% and adding eight PHEVs to this transformer increases the percent loading to nearly 115%. It may be concluded that it will be important for utility planners to understand when, where, and how much the PHEV load will add to the system in order to adequately plan maintenance, upgrades, and additions to the distribution system, or seek other measures to shift the peak load as discussed further in Chapters 5 and 6.

## Discussion

This chapter described an analysis of PHEV readiness at the community level using parcel level, Tax Assessment data for the City of Madison, WI. Nearly 70% of all residential parcels in Madison are found to be PHEV ready. That is, these parcels are occupied by single detached homes with either attached or detached garages. Based on results on the readiness analysis, a scenario analysis of electrical grid impact due to varying levels of PHEV adoption is also described. Both analyses serve to demonstrate the benefits and the need for parcel-level analysis to support utility planning and PHEV market promotion at a refined geographic scale. Compared to past studies of PHEV readiness that typically utilize aggregate data provided for census

geographies, our parcel-level analysis provides much higher spatial accuracy regarding where the PHEV-ready households are. Our analysis also allow electrical utility organizations and agencies to analyze their distribution network under scenarios of maximum near-term PHEV load.
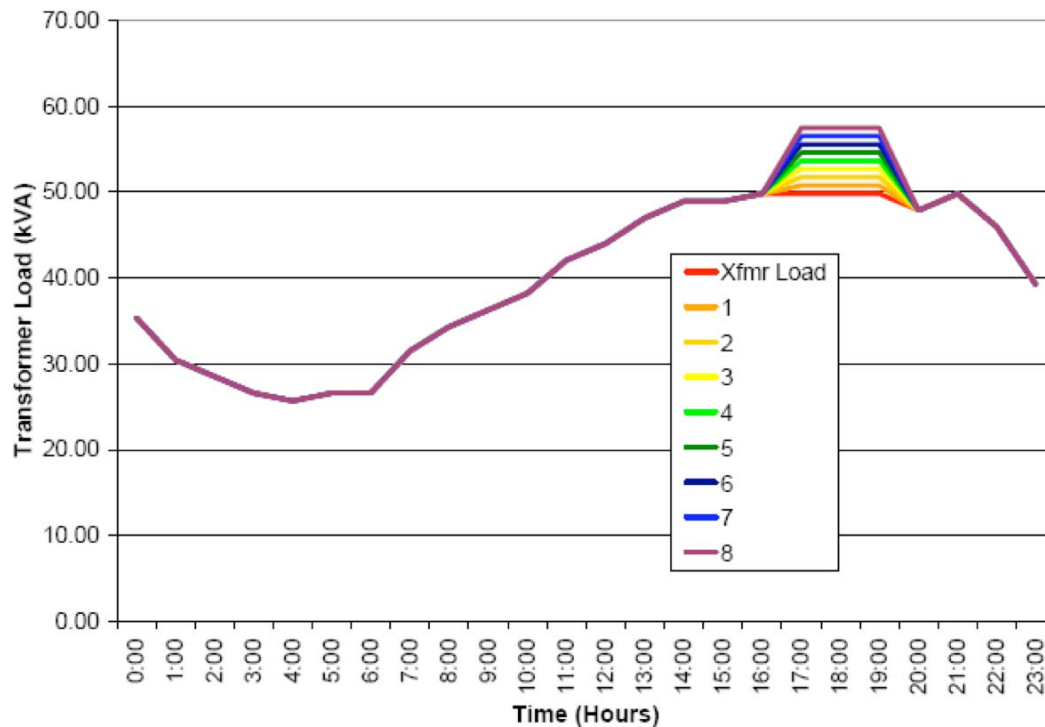


**Figure 3-2. Worst-case transformer load profiles for the base and the eight levels of PHEV adoption scenarios**

Obviously, the tax assessment database is still not ideal for a comprehensive PHEV readiness analysis of all housing stock and commercial recharging opportunities. The analysis presented in this paper was limited to that of the single detached homes and its accuracy depends on the assumptions made along the way (for example, having either an attached or detached garage is equated to having recharging capability). Our analysis should also not be mistaken as a PHEV market analysis. Recharging capability (at home or elsewhere) is a necessary but not a sufficient condition for early PHEV adoption. In fact, the likelihood of a household becoming an early adopter depends on a suite of factors ranging from infrastructure availability, charging methods, vehicle and fueling costs, vehicle performance characteristics, to household's income, life style, and attitudes towards environmental issues. Future studies are needed to better understand the relationship between PHEV preference and PHEV readiness, between the true market and the potential market pool.

In the long run, the possibility for recharging PHEV at commercial sites or public stations will not only change market behavior but also load distribution across the utility network. This aspect of PHEV is not covered herein, but to do so in the future would require an analysis of

commercial/industrial geographic areas where such opportunities are more likely to be installed. It is hoped that our work presented here would assist with those expanded efforts.

Additionally, agencies that wish to adopt policies encouraging denser built environments with goals of fewer road miles may reveal a contradiction with PHEV home charging. If single unit personal garages remain the universal primary charging locations, the inclusion of those garages will use more land. Further, residents who choose to live in denser urban environments may be served well by PHEV if they must own personal vehicles, yet may not have adequate access to PHEV charging opportunities. It is anticipated that our geospatial approach would be extended to assist in these future assessments.

# *4*
# CONSUMER PREFERENCE ANALYSIS

## Survey Design

The data used in the consumer preference analysis was collected through a survey carried out in Madison, Wisconsin in 2009. The initial household sample of 1500 was randomly selected from 12 zip code zones covering urbanized area of Greater Madison. The households' telephone numbers and addresses were purchased from a proprietary provider.

The survey was designed as a computer-aided telephone interview (CATI). Each telephone number was contacted a maximum of three times. During each call, there were three possible outcomes. First, a member of the household answered the phone and accepted the request to participate in the survey. Second, a member of the household answered the phone and rejected the request. Third, the call went unanswered. If the household member participated in and completed the survey, they were included in the survey sample. If they rejected the request, they were eliminated from the sample. If the call went unanswered, the phone number was called a second and possibly third time. After the third unanswered call, the phone number was removed from the sample.

As shown in Appendix B, the survey instrument started with an introduction that introduced the caller, identified the reason for the call, and then asked respondents if they would be willing to participate in Phase 1 of the study. If they accepted the request, the participants were asked 20 questions, starting with three questions concerning the number and type of vehicles owned by the participants and concluded with a question that asked the participants if they planned to purchase a new vehicle in the next five years. If they did intend to make that purchase, they were asked seven additional questions regarding the type of vehicle they wished to purchase, the price of that vehicle, and whether they had the desire and infrastructure to support an alternative fuel vehicle as that next purchase.

Regardless of whether the participants planned to purchase a new vehicle in the next five years, all participants were asked nine basic demographic questions to ensure that the survey provided an adequate representation of Madison residents. The questions in this section asked participants about their age, education, household income, number of people in the household, number of licensed drivers in the household, and the type of housing where they reside.

Then the telephone calls concluded with thanking for participants for their time.

## Survey Deployment

A group of students from the University of Wisconsin were hired and trained for the survey. The interviewers were trained on basic telephone etiquette, use of CATI, and interview techniques.

The telephone calls were made between the hours of 5 p.m. and 9 p.m. from Monday through Friday. On Saturday and Sunday, the telephone calls were made between the hours of 11 a.m.

and 9 p.m.  The study designers took special care to guarantee that no calls were made after 9 p.m.  In special instances, callers asked permission to continue a telephone survey if the survey started before 9 p.m. but continued past that time of day.

From the 1,500 telephone numbers in the sample population, 497 households answered and completed our study. The residential locations of these valid responses are shown in Figure 3 below.
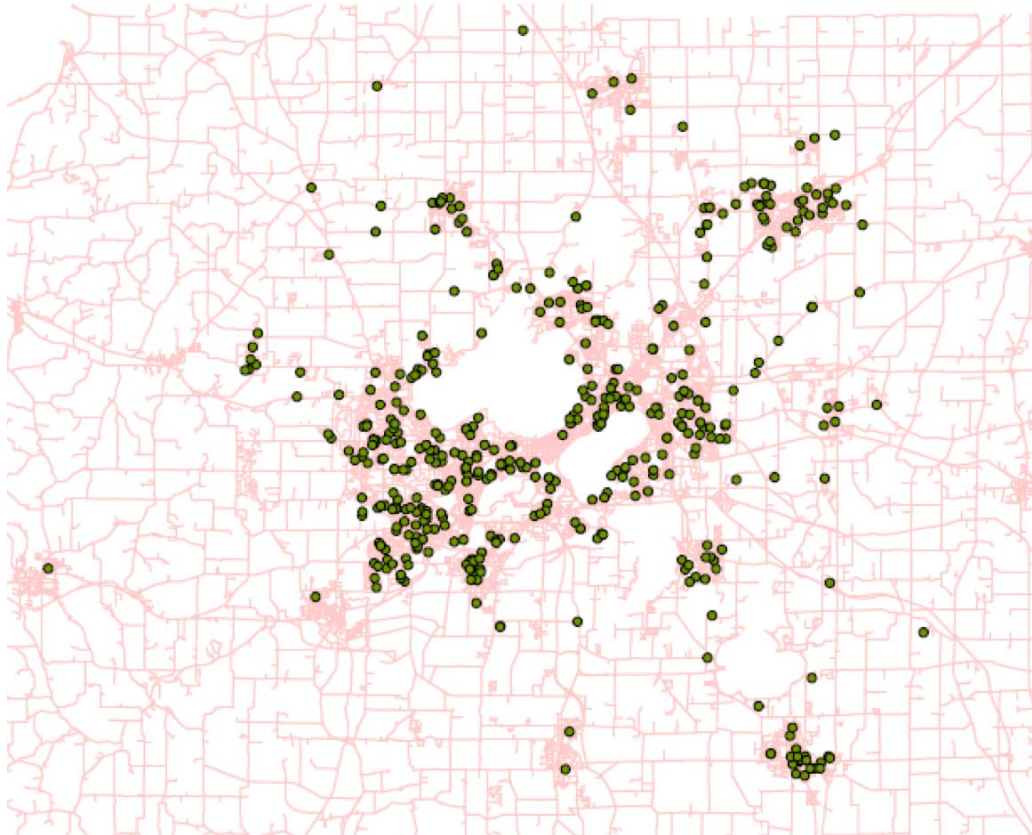


**Figure 4-1. Geographic locations of households participated in the survey**

## Analysis and Results

SPSS was used to analyze the 497 valid responses. The findings are summarized below.

***Parking facility and electricity access by housing type***

Single Detached Houses (77.6%)
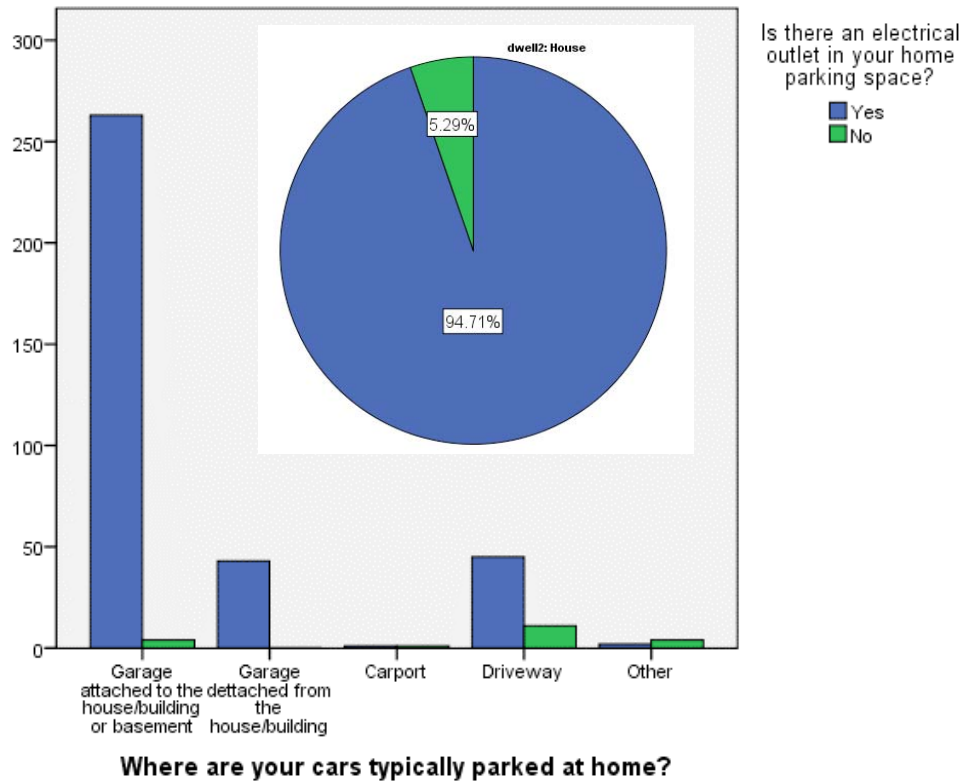


**Figure 4-2. Question and response summary on parking facility among single detached houses**

Apartments, Condos, Townhouses, Other Housing (22.4%)
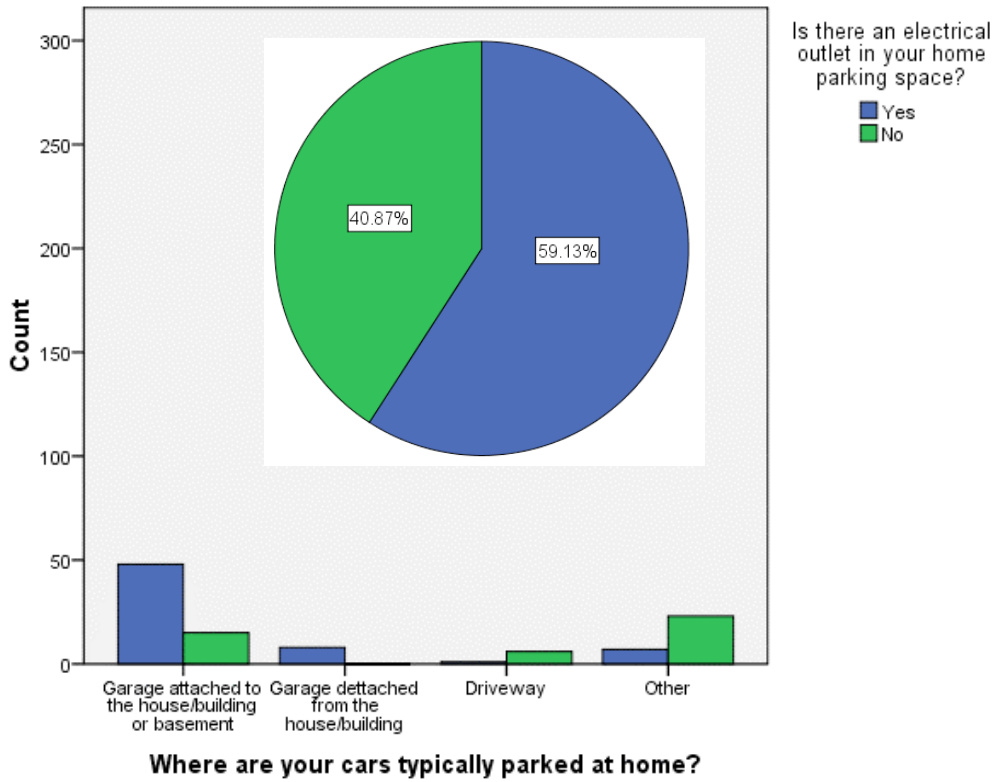


Figure 4-3. Question and response summary on parking facility among apartments, condos, townhouses and other housing

## *Current Vehicle Holding*

## Vehicle Vintage
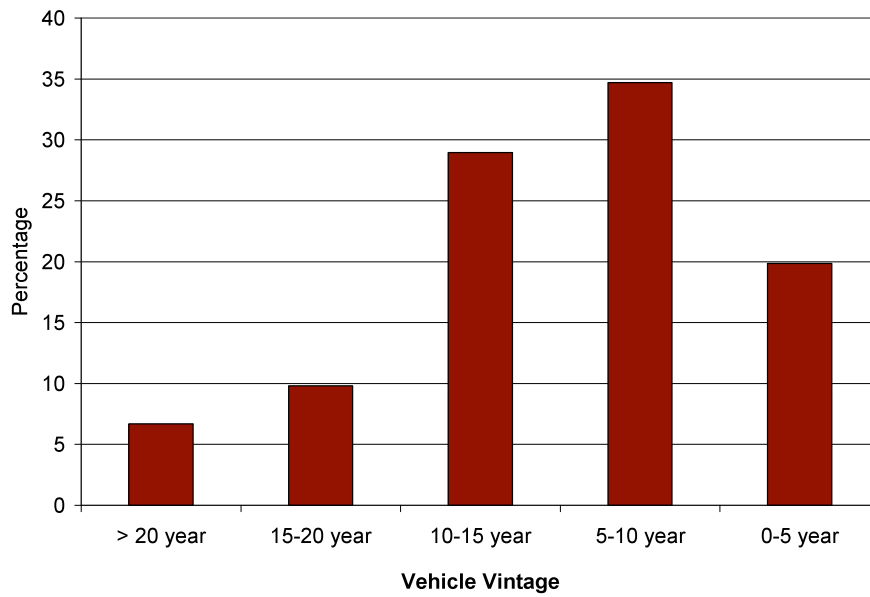


**Figure 4-4. Response summary on vehicle ownership vintage**

Vehicle Type

**What type is the car?**

Legend:
- Missing
- Compact Car
- Mid/Full Size Car
- Station Wagon
- SUV
- Pickup Truck
- Other (ex. Minivan, van, etc.)

15.36%
17.76%
12.33%
34.59%
16.61%
3.24%

**Is it a hybrid?**

Legend:
- No (not hybrid)
- Yes (hybrid)

2.51%
97.49%
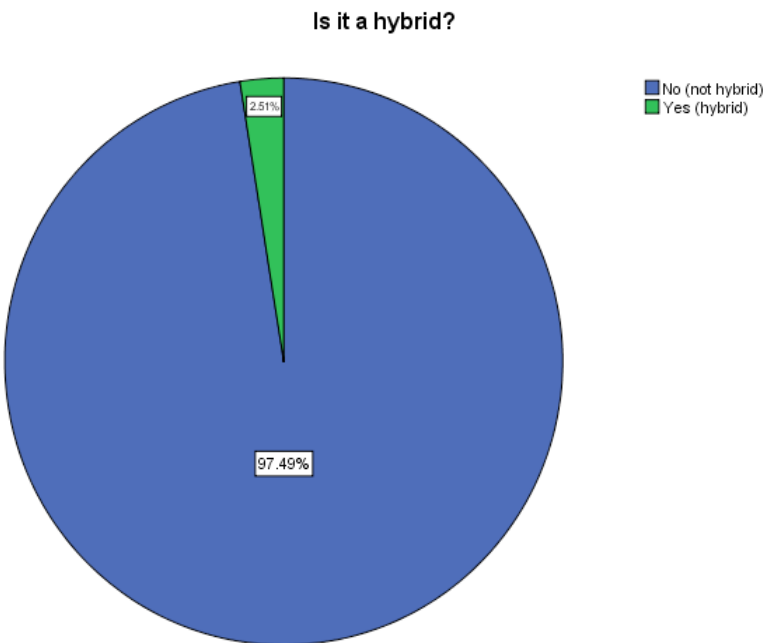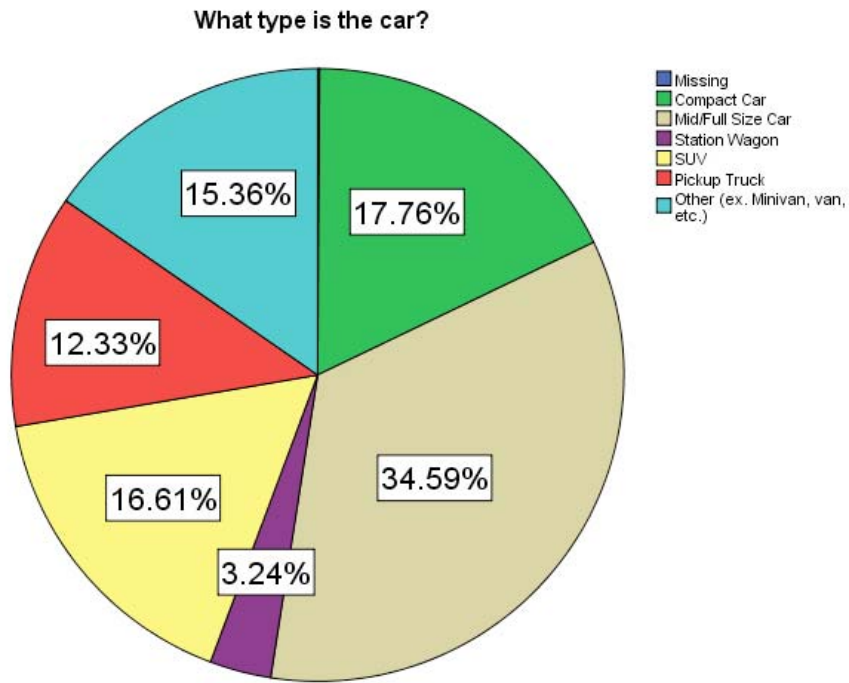
**Figure 4-5. Question and response summary on type of vehicle**

Vehicle Vintage by Type
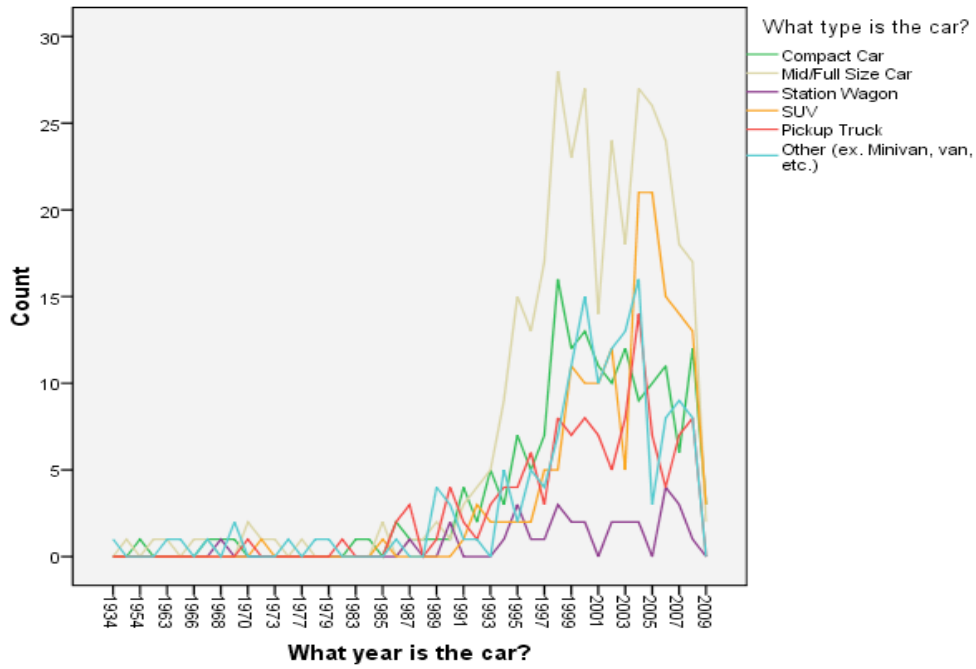


**Figure 4-6. Question and response summary on type of car**

## *Future Vehicle Purchase*

Purchase Interest
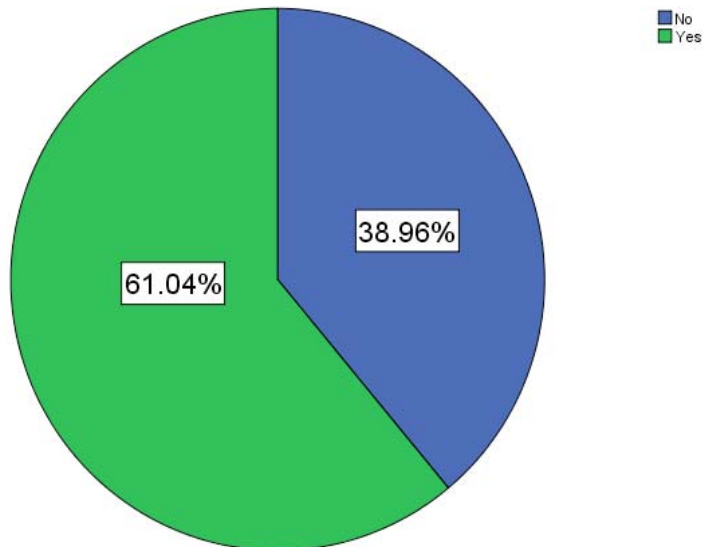


**Figure 4-7. Question and response summary on vehicle purchase plans**

This translates to approximately 87,000 households considering purchasing a vehicle within the next five years.

## Purchase Timeframe

**Within what time frame would you be looking to purchase that vehicle?**
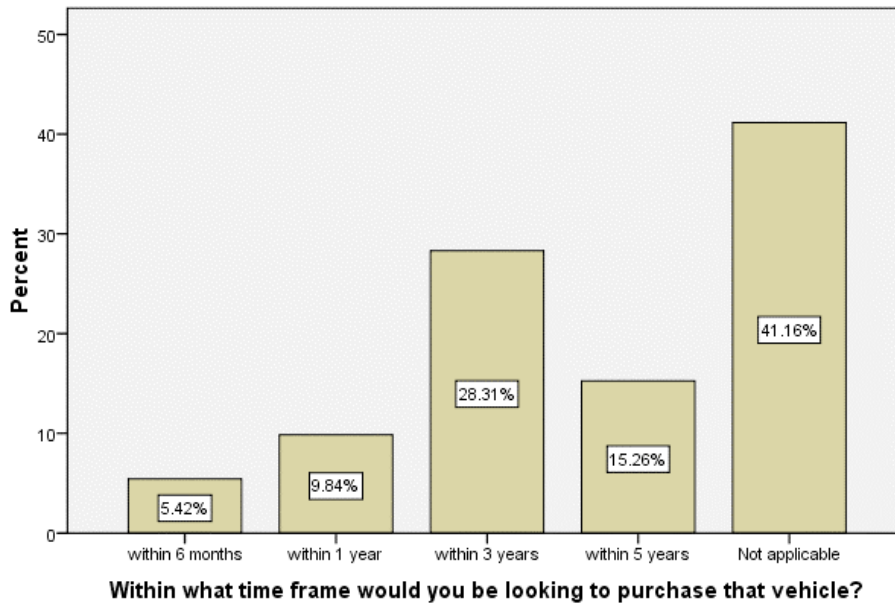


Figure 4-8. Question and response summary on vehicle purchase timeframe

## Purchase Reason

Would that vehicle replace your current vehicle or be an additional vehicle?



replace existing vehicle
additional vehicle

9.90%

90.10%
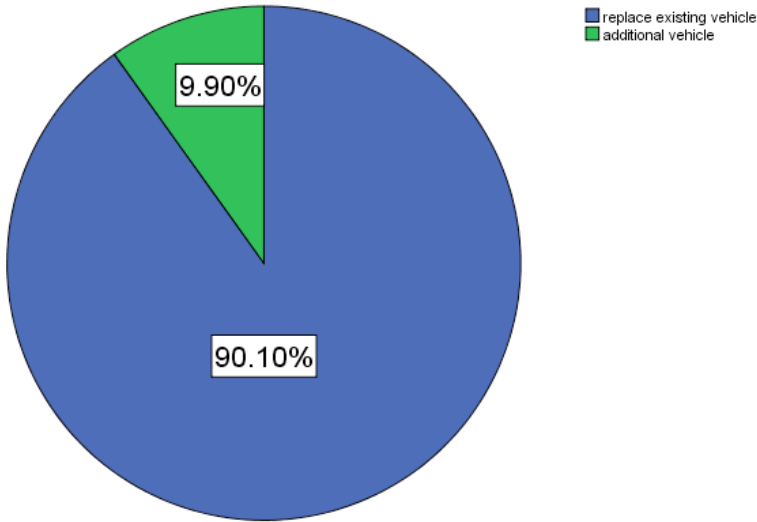
**Figure 4-9. Question and response summary on vehicle replacement/addition case**

## Type of Purchase

Would that vehicle be a new vehicle, a used vehicle or would you consider either option



= 'New '
Used
Either (New or Used)

25.33%

52.63%

21.71%
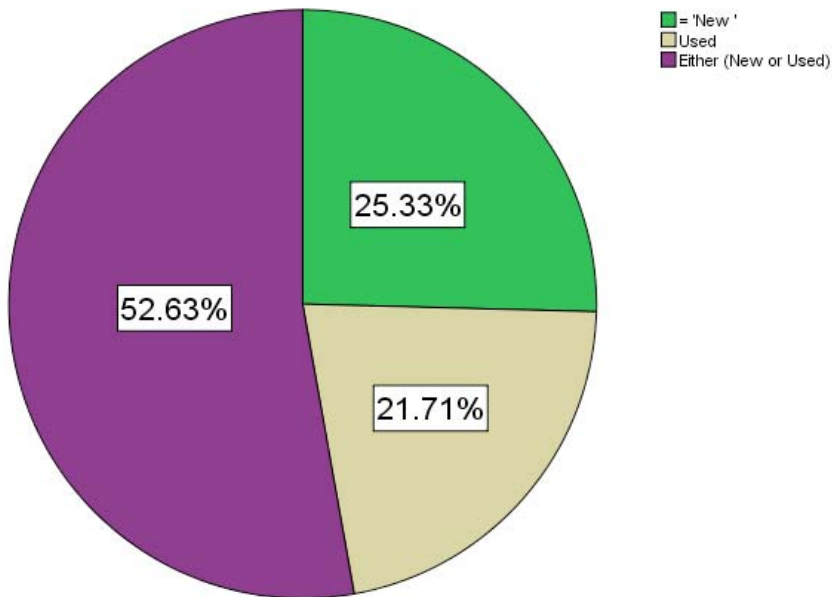
**Figure 4-10. Question and response summary on vehicle purchase option (new/used)**

**Type of Vehicles Households Interested in Purchasing**
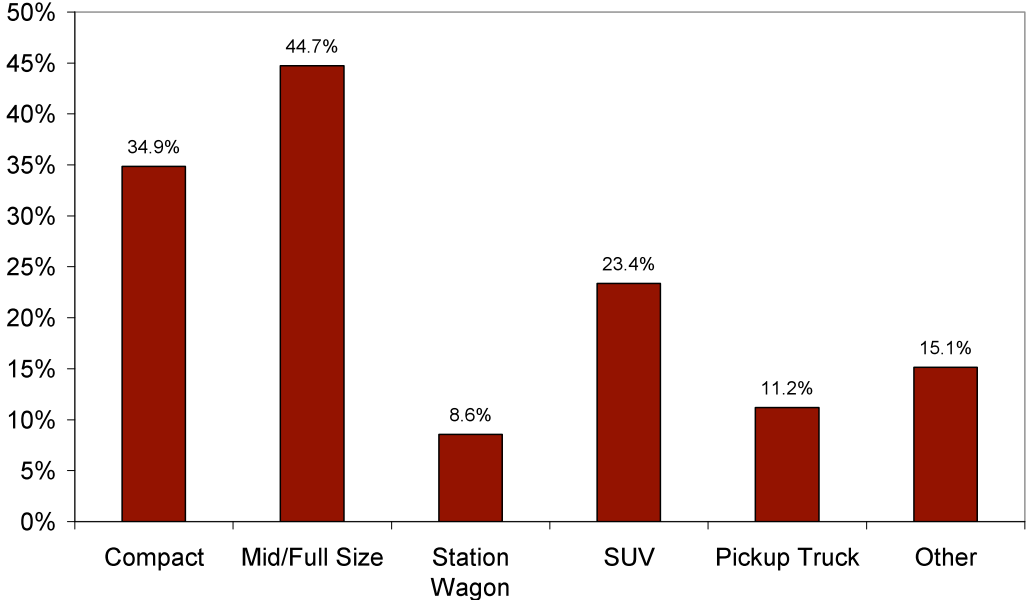


Figure 4-11. Response summary on vehicle purchase type

Price Range

### expected price range - high end
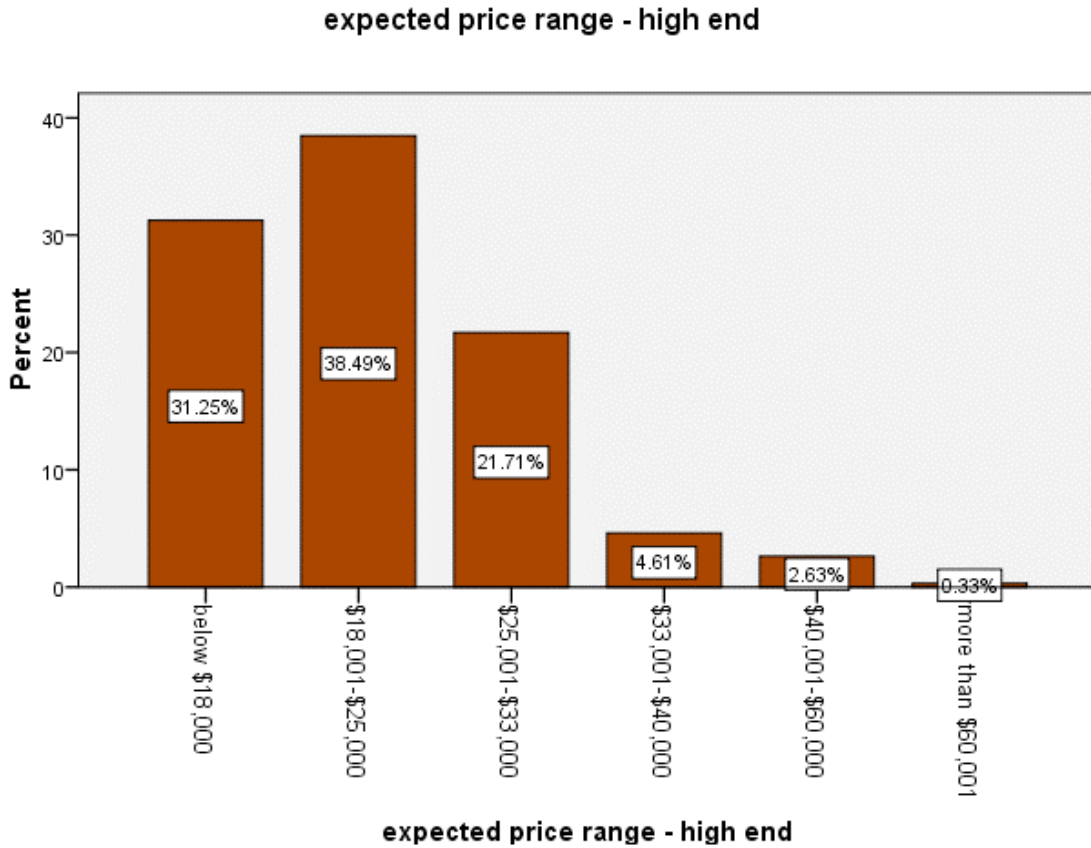


**Figure 4-12. Question and response summary on vehicle purchase price**

70% of the respondents are not willing to spend over $25K. Given the current expected price of PHEV, this leaves us with only 30% of the buying market; not all 30% would be willing to consider non-ICE vehicles.

PHEV Possibility



Would you be willing to consider a hybrid vehicle or a vehicle that uses an alternative fuel or plug-in rechargeable battery for your next vehicle purchase?

- No
- Yes

19.41%

80.59%
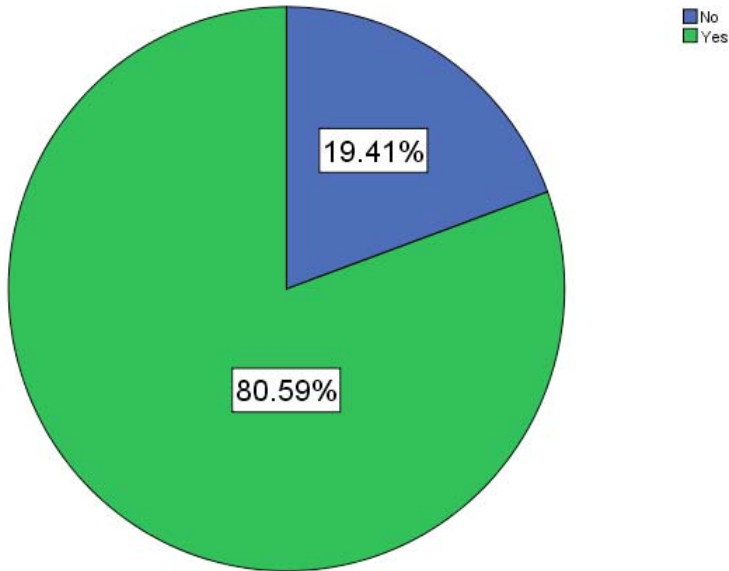
**Figure 4-13. Question and response summary on PHEV purchase**

For those households who are not willing to consider PHEV purchase, their reasons included:

"Believe there is plenty of oil and gas"; "It is impossible to drive it long enough to make up for the extra cost in price and global warming is a total hoax"; "Prefers conventional vehicles, not concerned about mileage"

"I like to travel, don't think on the road there will be enough places to stop to fill up or recharge the vehicle"

"Not at my age, its too much to learn"; "Lack of knowledge about technology"

"I don't believe in hybrid vehicles."; "Don't think tech is there yet"; "don't believe they are trustworthy"; "Not enough mechanics to fix hybrids"

"I don't think they are going to be in my price range ($18,000)"; "Too expensive"; "maintenance cost"; "battery cost"

"Not enough speed at this point with those vehicles"; "Not capable of being used for work, to pull things"; "hybrid doesn't have enough power"; "won't be available for the type he wants"

"I'm very happy with what we have now, and it takes a lot for me to change."

"College kid could not use"

"Don't want to deal with replacing batteries"

### *Factors correlating with PHEV Market*

Current Vehicle Holding
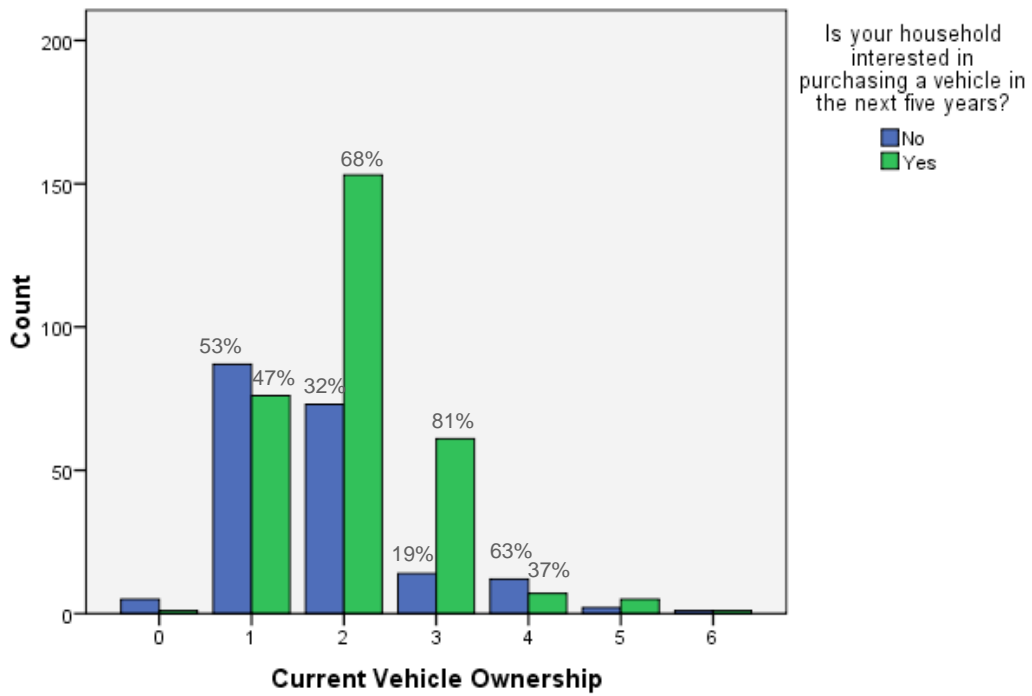


**Figure 4-14. Correlation of PHEV market with current vehicle ownership number**

Purchase Timeframe
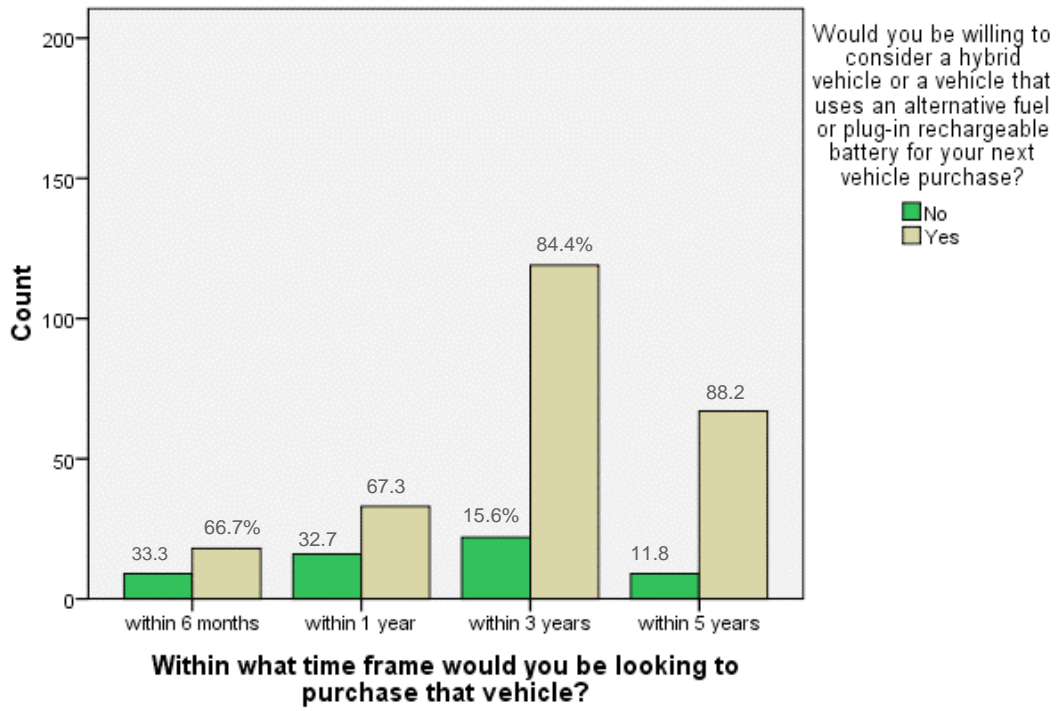


**Figure 4-15. Question and response summary on PHEV purchase timeframe**

Budget Range
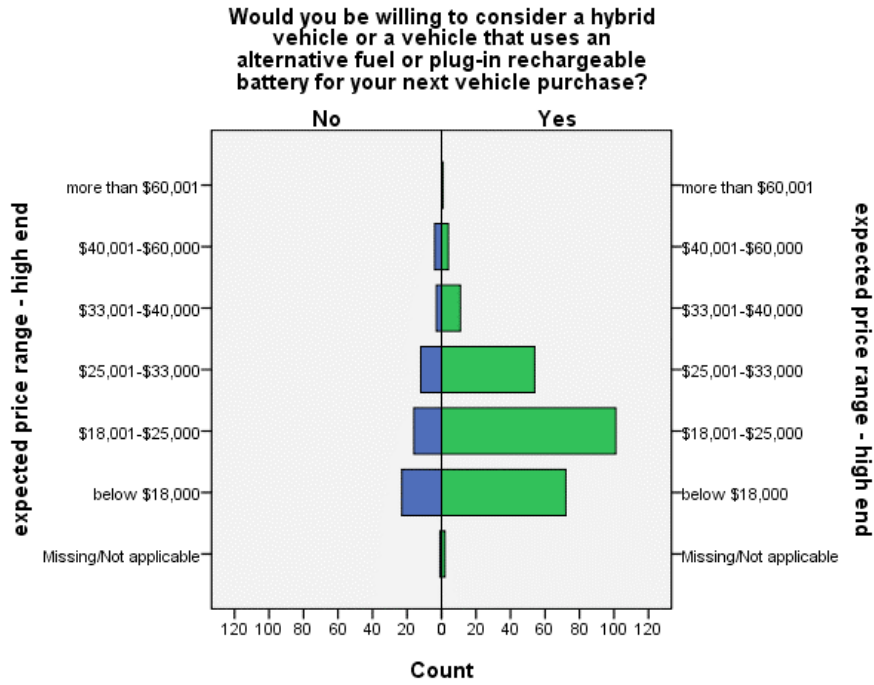


Figure 4-16. Question and response summary on PHEV purchase budget

## Income

Households' income does **not** appear to influence willingness to purchase alternative fuel vehicles.
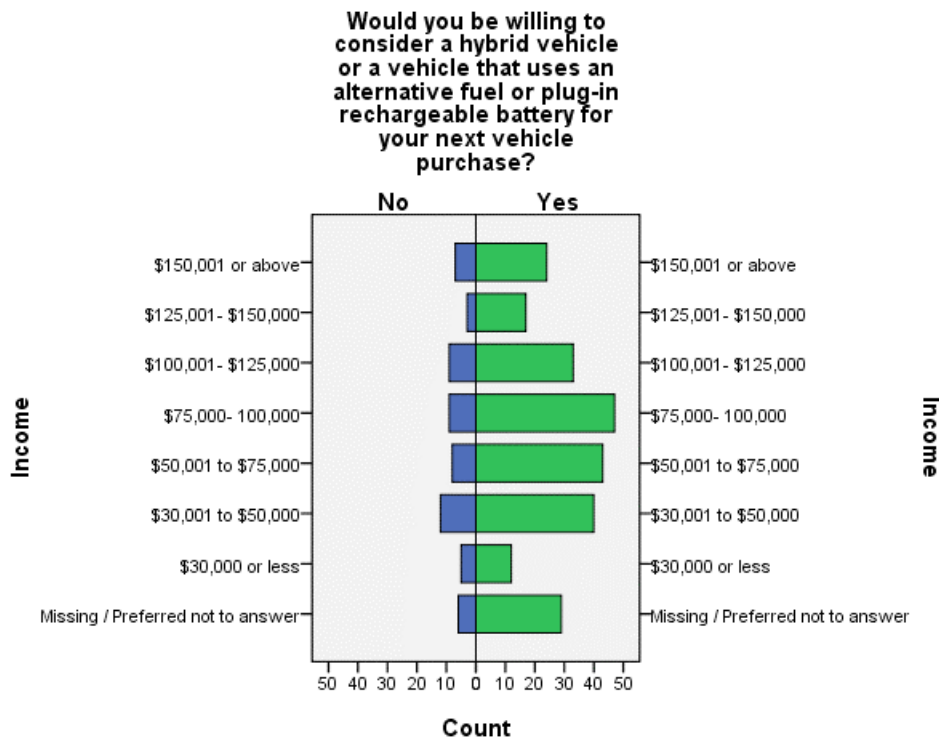


**Figure 4-17. Question and response summary on PHEV purchase correlated with income**

## Conclusion

Out of the 61% respondents that are interested in purchasing a vehicle in the next five years, 80.59% are willing to consider purchasing an alternative vehicle. This equates to 49% of the sample being willing to consider purchasing an alternative vehicle in the next five years. Applying this proportion to the population gives an estimated 70,000 households as the PHEV willing households in the Madison area in the five-year timeframe. However, when one considers the expected price of PHEVs in the range of $30,000 and upwards including subsidies, this translates to about 21,000 households that are able and willing to purchase PHEVs in the next five years. This would represent an annual increase of about 4.3% of the residential electrical utility customer base of the Madison Gas and Electric. The present level of survey data does not definitively develop the geospatial location of the households where this growth would occur, particularly in light of sharing confidential consumer information of the survey respondents for correlation with Madison Gas Electric's customer information database. Thus more detailed studies on the resulting impact of the near term PHEV adoption potential by 4.3% of households connected to the distribution grid becomes highly speculative. On the other hand, PHEV readiness analysis and worst case transformer loading studies results presented in Chapter

3 indicates that the impact of PHEVs that call for concern tend to occur in rare occasions at rare locations. Therefore, in light of such uncertainties, it would rather be effective to focus on creative solutions that avert such rare events as opposed to developing guidelines or roadmaps for additional infrastructure investments in the distribution network. Preliminary investigations indicate that existing demand side management approaches may be effectively tailored for this purpose, as discussed further in the following chapters.

# 5
# CONCLUSIONS

## Project summary

This study focuses on assessing the demand for plug-in hybrid electric vehicles (PHEV) in Wisconsin and provides near term recommendations to manage its impacts on the State's electric grid.

PHEVs are expected to provide a range of about 40 miles per drive cycle using plug-in recharging from the electric grid, in addition to the virtually unlimited range offered by conventional and hybrid vehicles. Given the concern over global warming and the need for reducing America's dependence on foreign oil, PHEV are among the emerging 'green' alternatives to conventional fossil-fuel vehicles. Although they are recognized to have the potential to play a key role in climate change and energy security strategies, projected levels of market adoption, charging patterns, and impacts on electricity market and infrastructure supply are uncertain.

To date, most PHEV-related analysis has focused on technology assessment, lifecycle analysis, battery R&D, and vehicle modeling. Also, a number of recent studies explored the environmental consequences of shifting transportation energy use from conventional fuels to electricity through wide deployment of PHEVs and showed promising GHG impacts and air quality benefits at the national and global levels. Yet, much uncertainty remains regarding the infrastructure and economic impacts of PHEVs at the local level.

This study has two main objectives:

- Enhance the understanding of consumers' perception of and demand for PHEVs, thereby informing policy development for wider PHEV deployment.
- Assess the market potential of PHEVs in Wisconsin and estimate the associated vehicle charging patterns, electricity consumption, and infrastructure needs.

In view of the time frame for the study, our analyses were limited to the Greater Madison area. As such, the project serves as a demonstration of research methodology as well as a preliminary study for future expansion to analyzing the PHEV impacts to the entire state of Wisconsin.

The objectives outlined above have been accomplished through three major research components: infrastructure readiness assessment, consumer preference analysis and grid impact recommendations.

**Project Findings**

*Infrastructure readiness*

A PHEV readiness analysis at the community level using parcel level has been completed using Tax Assessment data for the City of Madison, WI. Nearly 70% of all residential parcels in Madison are found to be PHEV ready. That is, these parcels are occupied by single detached homes with either attached or detached garages. Based on results on the readiness analysis, a scenario analysis of electrical grid impact due to varying levels of PHEV adoption is also described. Compared to past studies of PHEV readiness that typically utilize aggregate data provided for census geographies, our parcel-level analysis provides much higher spatial accuracy regarding where the PHEV-ready households are. Both analyses serve to demonstrate the benefits and the need for parcel-level analysis to support utility planning and PHEV market promotion at a refined geographic scale. The methods allow electrical utilities to analyze their distribution network under scenarios of maximum near-term PHEV load.

However, recharging capability (at home or elsewhere) being a necessary but not a sufficient condition for early PHEV adoption, the likelihood of a household becoming an early adopter depends on a suite of factors ranging from infrastructure availability, charging methods, vehicle and fueling costs, vehicle performance characteristics, to household's income, life style, and attitudes towards environmental issues. Future studies are needed to better understand the relationship between PHEV preference and PHEV readiness, between the true market and the potential market pool.

In the long run, the possibility for recharging PHEV at commercial sites or public stations will not only change market behavior but also load distribution across the utility network. This aspect of PHEV is not covered herein, but to do so in the future would require an analysis of commercial/industrial geographic areas where such opportunities are more likely to be installed. It is hoped that our work presented here would assist with those expanded efforts.

Additionally, agencies that wish to adopt policies encouraging denser built environments with goals of fewer road miles may reveal a contradiction with PHEV home charging. If single unit personal garages remain the universal primary charging locations, the inclusion of those garages will use more land. Further, residents who choose to live in denser urban environments may be served well by PHEV if they must own personal vehicles, yet may not have adequate access to PHEV charging opportunities. It is anticipated that our geospatial approach would be extended to assist in these future assessments.

*Consumer Preference*

An in-depth consumer survey was conducted among consumers in the Madison area using a specifically designed survey instrument to study the impact of consumer preference on PHEV adoption.

Out of the 61% respondents that are interested in purchasing a vehicle in the next five years, 80.59% are willing to consider purchasing an alternative vehicle. This equates to 49% of the sample being willing to consider purchasing an alternative vehicle in the next five years. Applying this proportion to the population gives an estimated 70,000 households as the PHEV willing households in the Madison area in the five-year timeframe.

However, when one considers the expected price of PHEVs in the range of $30,000 and upwards including subsidies, this translates into an *upper bound* of about 21,000 households that are able *and* willing to purchase PHEVs in the next five years. This would represent an annual increase of about 4.3% of the residential electrical utility customer base of the Madison Gas and Electric. The present level of survey data does not definitively develop the geospatial locations of the households where this growth would occur, particularly in light of the inability in sharing confidential consumer information of the survey respondents for correlation with Madison Gas Electric's customer information database. Thus any extrapolation on the resulting specific grid impact of the near term PHEV adoption by households connected to the distribution grid becomes highly speculative. On the other hand, infrastructure readiness analysis and worst-case transformer loading study results indicates that critical aspects of PHEV adoption that lead to circuit overloading tends to occur in rare occasions at rare locations. Therefore, in light of such uncertainties, it would rather be effective to focus on creative solutions that avert such rare events as opposed to developing guidelines or roadmaps for additional infrastructure investments in the distribution network. Preliminary investigations indicate that existing demand side management approaches may be effectively tailored for this purpose.

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# *B*
# SURVEY INSTRUMENT

1. Interviewer Last Name

2. List participant name and address. Copy address to QUESTION 27

   ID:

   Title:

   Name:

   Address:

   Hello, I would like to speak with _____ (Title) _____ (Name)

   (A) (If Female prefers different title (Ex. Mrs. vs Ms.) go back to question 2 and update)

   (B) (If Title=Mr. and Female answers phone) Oh, I'm sorry. Is this Mrs. _____?

   (C) (If Title= Mrs. and Male answers phone) Oh, I'm sorry. Is this Mr. _____?

   (D) (If Child answers) Is _____ (title) _____ (name) available?

   (If Respondent answers "NO"): Thank you for your time. Have a great night/day. (END CALL)

   (If Respondent says "YES" to any of the above, proceed)

   (Title and Respondent name) _____, my name is _____. I'm a student at the University of Wisconsin and I am conducting research for my university on the potential market for the next generation of automobiles.

   If you have a few minutes, we would like to ask you some basic questions about your household and vehicle preferences. As part of the university's strict privacy policy, I can assure you that your information would not be disclosed to any other party.
   Is this a convenient time for you to help with our study?

   (If Respondant answers "NO"): Thank you for your time. Have a great night. (END CALL)

   (If YES, proceed)

   **Great, I will continue with the survey now.**

3. How many motor vehicles in working condition does your household have available for use? This would include cars, minivans, trucks and SUVs.

**4.** (If only one car) What type and what year is the car? And it is a hybrid? (If multiple cars) What type and what year are the cars? Any of them a hybrid car?
If participants want an explanation of Compact, state that a Compact car has an interior volume of less than 110 cubic feet. An example of a Compact would be a Honda Civic and Ford Focus.

| | Compact Car | Mid/Full Size Car | Station Wagon | SUV | Pickup Truck | Other (ex. Minivan, van, etc.) |
|---|---|---|---|---|---|---|
| Vehicle #1 | ○ | ○ | ○ | ○ | ○ | ○ |
| Vehicle #2 | ○ | ○ | ○ | ○ | ○ | ○ |
| Vehicle #3 | ○ | ○ | ○ | ○ | ○ | ○ |
| Vehicle #4 | ○ | ○ | ○ | ○ | ○ | ○ |
| Vehicle #5 | ○ | ○ | ○ | ○ | ○ | ○ |
| Vehicle #6 | ○ | ○ | ○ | ○ | ○ | ○ |
| Vehicle #7 | ○ | ○ | ○ | ○ | ○ | ○ |
| Vehicle #8 | ○ | ○ | ○ | ○ | ○ | ○ |

**5.** (This is part of Q4. Enter vehicle year and any supplementary information here)

| | Year | Hybrid? (enter 'x' if yes) | Supplementary Note |
|---|---|---|---|
| Vehicle #1 | | | |
| Vehicle #2 | | | |
| Vehicle #3 | | | |
| Vehicle #4 | | | |
| Vehicle #5 | | | |
| Vehicle #6 | | | |
| Vehicle #7 | | | |
| Vehicle #8 | | | |

**6.** Is your household interested in purchasing a vehicle in the next five years?

○ Yes

○ No (If NO, proceed to question 13)

**7.** Within what time frame would you be looking to purchase that vehicle?

○ 6 months

○ 1 year

○ 2-3 years

○ 4-5 years

○ Other (list range)

8. Would that vehicle replace your current vehicle or be an additional vehicle?
   - ○ Replace
   - ○ Additional

9. Would that vehicle be a new vehicle, a used vehicle or would you consider either option?
   - ○ New
   - ○ Used
   - ○ Either Option (New or Used)

10. From the following selection, what type of vehicle would you consider buying? Feel free to include more than one vehicle type in your answer

    Again, If participants want an explanation of Compact, state that a Compact car has an interior volume of less than 110 cubit feet. An example of a Compact would be a Honda Civic and Ford Focus.

    - ☐ Compact Car
    - ☐ Mid/Full Size Car
    - ☐ Station Wagon
    - ☐ SUV
    - ☐ Pickup Truck
    - ☐ Other (ex. Minivan, van, etc.)

    [                    ]

11. What is the expected price range for your next vehicle purchase? Again, please feel free to include more than one price range in your answer.

    These figures outline common price ranges for various types of vehicles

    - ☐ Below $18,000
    - ☐ $18,001-$25,000
    - ☐ $25,001-$33,000
    - ☐ $33,001-$40,000
    - ☐ $40,001-$60,000
    - ☐ more than $60,001

12. Would you be willing to consider a hybrid vehicle or a vehicle that uses an alternative fuel or plug-in rechargeable battery for your next vehicle purchase? (If NO, ask why not)
    - ○ Yes
    - ○ No - reason:

    [                    ]

13. Where are your cars typically parked at home?
    - ○ Garage attached to the house/building
    - ○ Garage dettached from the house/building
    - ○ Carport
    - ○ Driveway
    - ○ On-street
    - ○ Other, please specify

    [                    ]

**14.** Is there an electrical outlet in your home parking space?

<span style="color:orange">Parking space refers to the response to the previous question</span>

- ○ Yes
- ○ No

**In order for us to make sure this survey represents all residents in the Madison area, I need to ask you some questions about you and your household.**

**15.** This might sound obvious, but what is your gender?

- ○ Male
- ○ Female

**16.** What is your age? Are you between...?

- ○ 18-25
- ○ 26-35
- ○ 36-45
- ○ 46-55
- ○ Over 55

**17.** What is the highest grade or year of school that you have completed?

- ○ High School or less
- ○ High School Diploma and GED
- ○ Some College, Trade, or Vocational School
- ○ College Graduate
- ○ Graduate Work beyond College Degree
- ○ Master's Degree
- ○ Doctorate

**18.** Which of the following ranges would include your total taxable income for your household, when you consider the income of all employed individuals? Was it above or below $75,000?

<span style="color:orange">Taxable income would be all wages, salaries and income from investments earned last year.</span>

- ○ Below $75,000 <span style="color:blue">(Go to Question 19)</span>
- ○ Above $75,000 <span style="color:green">(Go to Question 20)</span>
- ○ Preferred not to answer

**19.** Please stop me when I state the range that best describes your household's total annual income...**

<span style="color:orange">If respondent seems hesitant to answer, offer the last choice</span>

- ○ $30,000 or less
- ○ $30,001 to $50,000
- ○ $50,001 to $75,000
- ○ Preferred not to answer

**20.** Please stop me when I state the range that best describes your household's total annual income...
*If respondent seems hesitant to answer, offer the last choice*

- ○ $75,000- 100,000
- ○ $100,001- $125,000
- ○ $125,001- $150,000
- ○ $150,001 or above
- ○ Preferred not to answer

**21.** How many people live in your household currently?

- ○ 1
- ○ 2
- ○ 3
- ○ 4
- ○ more than 4, please specify

  [                                      ]

**22.** Are you a licensed driver?

- ○ Yes
- ○ No

**23.** How many of the other people in your household are licensed to drive?

(Enter number below:)

[                ]

**24.** From the following choices, which would best fit your current dwelling?

- ○ Apartment/ Duplex
- ○ Condominium
- ○ House
- ○ Other, please specify

  [                                      ]

**25.** Do you own your home or are you renting?

- ○ Own
- ○ Rent

That completes the first phase of our research.

(Title and Participant Name)_____, we want to thank you for helping us with our study.

**State of Wisconsin**
**Department of Administration**
**Division of Energy**


# Environmental Research Program


**Final Report**
May 2010


## *Consumer Adoption and Grid Impact Models for Plug-in Hybrid Electric Vehicles in Wisconsin*
*Part B: Grid Impact Studies*


**Prepared by:**
University of Wisconsin-Madison

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# EXECUTIVE SUMMARY

This study focuses on assessing the demand for plug-in hybrid electric vehicles (PHEV) in Wisconsin and provides near term recommendations to manage its impacts on the State's electric grid.

This study has two main objectives:

- Enhance the understanding of consumers' perception of and demand for PHEVs, thereby informing policy development for wider PHEV deployment.
- Assess the market potential of PHEVs in Wisconsin and estimate the associated vehicle charging patterns, electricity consumption, and infrastructure needs.

In view of the time frame for the study, our analyses were limited to the Greater Madison area. As such, the project serves as a demonstration of research methodology as well as a preliminary study for future expansion to analyzing the PHEV impacts to the entire state of Wisconsin.

The objectives have been accomplished through three major research components: infrastructure readiness assessment, consumer preference analysis and grid impact studies.

## *Infrastructure Readiness Assessment*

A PHEV readiness analysis at the community level using parcel level has been completed using Tax Assessment data for the City of Madison, WI. Nearly 70% of all residential parcels in Madison are found to be PHEV ready. That is, these parcels are occupied by single detached homes with either attached or detached garages. Based on results on the readiness analysis, a scenario analysis of electrical grid impact due to varying levels of PHEV adoption is also described. Compared to past studies of PHEV readiness that typically utilize aggregate data provided for census geographies, our parcel-level analysis provides much higher spatial accuracy regarding where the PHEV-ready households are. Both analyses serve to demonstrate the benefits and the need for parcel-level analysis to support utility planning and PHEV market promotion at a refined geographic scale. The methods allow electrical utilities to analyze their distribution network under scenarios of maximum near-term PHEV load.

However, recharging capability (at home or elsewhere) being a necessary but not a sufficient condition for early PHEV adoption, the likelihood of a household becoming an early adopter depends on a suite of factors ranging from infrastructure availability, charging methods, vehicle and fueling costs, vehicle performance characteristics, to household's income, life style, and attitudes towards environmental issues. Future studies are needed to better understand the relationship between PHEV preference and PHEV readiness, between the true market and the potential market pool.

In the long run, the possibility for recharging PHEV at commercial sites or public stations will not only change market behavior but also load distribution across the utility network. This aspect of PHEV is not covered herein, but to do so in the future would require an analysis of commercial/industrial geographic areas where such opportunities are more likely

to be installed. It is hoped that our work presented here would assist with those expanded efforts.

Additionally, agencies that wish to adopt policies encouraging denser built environments with goals of fewer road miles may reveal a contradiction with PHEV home charging. If single unit personal garages remain the universal primary charging locations, the inclusion of those garages will use more land. Further, residents who choose to live in denser urban environments may be served well by PHEV if they must own personal vehicles, yet may not have adequate access to PHEV charging opportunities. It is anticipated that our geospatial approach would be extended to assist in these future assessments.

### Consumer Preference Analysis

An in-depth consumer survey was conducted among consumers in the Madison area using a specifically designed survey instrument to study the impact of consumer preference on PHEV adoption.

Out of the 61% respondents that are interested in purchasing a vehicle in the next five years, 80.59% are willing to consider purchasing an alternative vehicle. This equates to 49% of the sample being willing to consider purchasing an alternative vehicle in the next five years. Applying this proportion to the population gives an estimated 70,000 households as the PHEV willing households in the Madison area in the five-year timeframe.

However, when one considers the expected price of PHEVs in the range of $30,000 and upwards including subsidies, this translates into an *upper bound* of about 21,000 households that are able *and* willing to purchase PHEVs in the next five years. This would represent an annual increase of about 4.3% of the residential electrical utility customer base of the Madison Gas and Electric. The present level of survey data does not definitively develop the geospatial locations of the households where this growth would occur, particularly in light of the inability in sharing confidential consumer information of the survey respondents for correlation with Madison Gas Electric's customer information database. Thus any extrapolation on the resulting specific grid impact of the near term PHEV adoption by households connected to the distribution grid becomes highly speculative. On the other hand, infrastructure readiness analysis and worst-case transformer loading study results indicates that critical aspects of PHEV adoption that lead to circuit overloading tends to occur in rare occasions at rare locations. Therefore, in light of such uncertainties, it would rather be effective to focus on creative solutions that avert such rare events as opposed to developing guidelines or roadmaps for additional infrastructure investments in the distribution network. Preliminary investigations indicate that existing demand side management approaches may be effectively tailored for this purpose.

### Grid Impact Studies

Demand response is quickly evolving and playing a greater role in the electric industry, particularly with recent promotion of smart grid activities across the nation. PHEV have the potential to provide a significant amount of demand response through a variety of methods. A brief overview of different demand response scenarios from a US-Midwest regional

perspective has been studied along with an outline of the different future possibilities of the ways in which PHEV may participate as demand response resources. Furthermore, the case for developing a vision that encourages PHEVs to participate in demand response for their energy storage potential, thus enabling a higher penetration of intermittent and variable generation such as wind and solar energy resources is been put forth.

Specifically, in developing demand response incentives, there should be a clear benefit for PHEV owners who choose to participate in time-of-use programs and charge their vehicles during off-peak hours. However, if PHEV owners are unable to charge during off-peak hours, participation in time-of-use metering programs is detrimental. Additional quantitative studies are needed to determine if the potential savings accrued through time-of-use metering and reduction is gasoline consumption is sufficient to recoup the purchase premium of a PHEV over a hybrid electric vehicle or a conventional vehicle. In addition, if the usable storage capacity of a battery is allowed to time shift household residential electricity usage to off-peak hours, it is likely that the required levels of subsidy may change or even become unnecessary. In such a case, a temporary subsidy would be sufficient to encourage residential customers to participate in time-of-use metering programs.

Continuing comprehensive modeling and analytical studies are necessary to determine the necessary magnitude of these subsidies in order to enable PHEV owners to achieve cost recovery on the purchase premium of a PHEV over the life of the vehicle.

Part A of the report concerns with Consumer Adoption Models, and Part B of the report concerns with Grid Impact Studies.

# ACKNOWLEDGMENTS

# *Contents*

# List of Tables

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| | |
|---|---|
| AC: | Alternating Current |
| AEIC: | Association of Edison Illumination Companies |
| AMI: | Advanced Metering Infrastructure |
| ANSI: | American National Standards Institute |
| ASHRAE: | American Society of Heating, Refrigerating, and Air-Conditioning Engineers |
| ATC: | American Transmission Company |
| BACnet: | Building Automation and Control Networks |
| CEA: | Consumer Electronics Association |
| CIM: | Common Information Model |
| DC: | Direct Current |
| DDR: | Dispatchable Demand Response |
| DER: | Distributed Energy Resource |
| DG: | Distributed Generation |
| DMS: | Distribution Management System |
| DOE: | Department of Energy |
| DRR-I: | Type I Demand Response Resource |
| DRR-II: | Type II Demand Response Resource |
| DSM: | Demand-side Management |
| EDR: | Emergency Demand Response |
| EISA: | Energy Independence and Security Act |
| EPACT: | Energy Policy Act of 1992 |
| EPRI: | Electric Power Research Institute |
| FERC: | Federal Energy Regulatory Commission |
| HEV: | Hybrid Electric Vehicle |
| IEC: | International Electrotechnical Commission |
| IEEE: | Institute of Electrical and Electronics Engineers |
| ISO: | Independent System Operator |
| ITU: | International Telecommunication Union |

| | |
|---|---|
| LMR: | Load Modifying Resource |
| MGE: | Madison Gas & Electric |
| NDDR: | Non-dispatchable Demand Response |
| NEC: | National Electric Code |
| NEMA: | National Electrical Manufacturers Association |
| NERC: | North American Electric Reliability Corporation |
| NIST: | National Institute of Standards and Technology |
| NPTS: | National Personal Transportation Survey |
| OpenADR: | Open Automated Demand Response |
| OpenSG: | Open Smart Grid |
| PAP: | Priority Action Plan |
| PHEV: | Plug-In Hybrid Electric Vehicle |
| PUHCA: | Public Utility Holding Company Act |
| PURPA: | Public Utilities Regulatory Policy Act |
| RTO: | Regional Transmission Organization |
| SAE: | Society of Automotive Engineers |
| SEP: | Smart Energy Profile |
| SG: | Smart Grid |
| SOC: | State Of Charge |
| TC: | Technical Committee |
| TOU: | Time-of-Use |
| V2G: | Vehicle-To-Grid |
| VMT: | Vehicle Miles Traveled |
| WPPI: | Wisconsin Public Power Incorporated |

**Motivation**    The relative success and failure of new technologies is greatly impacted by the governing political environment.   For example, zero-emissions vehicle mandates in the 1990's spurred the early development of electric vehicles.   However, reduced regulations were partly to blame for the nonsuccess of those initial electric vehicles.   The Obama administration has set a goal to put 1 million PHEVs on the road by 2015.   Automobile manufacturers are just preparing to ramp up production and marketing of these vehicles. This alignment of politics and industry has created an environment in which we can expect to see significant penetration of PHEVs.

Why should we be concerned about the future penetration of PHEVs?  How are they any different from the plasma televisions and influx of other appliances that have contributed to rising electricity consumption in the past?   First and foremost, PHEVs exist at the intersection of the electric and automotive industries.  Historically, these two industries have primarily operated in parallel, but PHEVs offer a unique opportunity to reduce reliance on crude oil as the only transportation fuel.   There is also a spatial aspect to PHEV load that is unique among devices that consume electricity.   In addition to the uncertainty inherent in forecasting load levels, there is an added uncertainty about the location in which load will occur.   Finally, PHEVs have the potential to serve as an energy storage resource.   This has important implications for integration of renewable resources and grid reliability as a whole.

**Objectives of the research**   Assuming that future penetration of PHEVs is inevitable, this research attempts to explore the potential impacts that these vehicles will have on the electric

industry. As the market share of PHEVs increases, there are three distinct penetration phases to consider. During the first phase of vehicle penetration, the primary impacts will likely occur on distribution equipment as vehicle clustering leads to local overloads. Increasing participation in demand response programs will likely mitigate the impact of vehicle charging during the second phase of PHEV penetration, if appropriate incentives are embraced. Finally, implementation of vehicle-to-grid technology will enable PHEVs to play a larger role in demand response programs, to the extent that vehicles might provide reserve and regulation services or emergency energy. The potential impacts are dependent on the regional electric infrastructure and vehicle customer base. Thus, this research presents a detailed case study of the future impacts in Dane County, WI. The methods described in this paper can be expanded over larger geographic/electric regions or used to more narrowly predict the impacts in more local regions.

**Document organization**

Chapter 1 briefly describes changes that have occurred in the electric industry since its inception in the days of Thomas Edison. Significant changes have led to striking revolutions in operating strategies. Relatively recent attempt to deregulate the industry and foster competition through energy markets have had unexpected impacts on reliability. In particular, the creation of open access transmission tariffs has caused existing infrastructure to be used in unprecedented ways. The multitudes of recent changes have contributed to the need to understand how PHEVs will further compound or alleviate existing concerns.

Chapter 2 provides background material on existing demand response programs and current efforts to remove any remaining barriers to demand response. Again, the interests of

government and industry are aligned to more fully utilize demand response to alleviate constraints on existing infrastructure. Demand response has been shown to increase competition in energy markets, reduce the carbon intensity of electricity production, and increase the robustness and flexibility of the bulk electricity system. Appropriate use of demand response resources has been shown to postpone or lessen the need to invest large amounts of capital in electric infrastructure.

Chapter 3 presents information relevant to PHEV-related standards development. In order for PHEVs to successfully participate as demand response resources, standards must be developed in areas such as metering, charging, and communications. These standards will be essential in effectively integrating PHEVs in with existing electric infrastructure. They will also ensure smooth transitions as we progress through the three stages of PHEV penetration.

Chapter 4 includes a list of relevant assumptions that were made in order to complete the Dane County case study. These assumptions are regionally specific to Dane County. The primary assumption made during the analysis are related to vehicle charging characteristics, vehicle adoption models, the regional policy environment, and regional characteristics of electric infrastructure. Numerous scenarios were considered in order to account for the inherent uncertainty associated with forecasting.

Chapter 5 depicts the initial infrastructure impacts of PHEVs during the first phase of vehicle penetration. During this first phase of vehicle penetration, the majority of impacts will occur on distribution infrastructure due to the natural clustering of vehicle owners. However, if PHEV charging remains unchecked, it has the potential to exacerbate existing constraints on transmission infrastructure, making day-to-day operation more difficult.

Chapter 6 portrays the benefits that can be derived from increased participation in demand response programs by PHEV owners. Existing demand response programs such as direct load control programs and time-of-use pricing programs can enable PHEV owners to save money on monthly electricity bills, while simultaneously reducing the negative impacts associated with uncontrolled charging of PHEVs. Additional demand response programs particularly designed for PHEVs can take advantage of variable charging rates to further minimize charging impacts. In order to effectively deploy demand response programs certain incentives will be required to encourage participation by PHEV owners.

Chapter 7 considers how bi-directional power flow will further facilitate PHEVs' participation as demand response resources. With vehicle-to-grid technology, PHEVs will be able to provide valuable ancillary services such as reserve and regulation to enhance grid flexibility and robustness. Traditionally, generators have been the sole providers of these resources. Enabling demand resources to provide these services will greatly further competition within energy markets. Also, taking advantage of the existing unused battery capacity of the PHEV fleet will provide some of the energy storage that is needed to continue integration of variable, renewable resources. Finally, utilizing the energy storage capacity of PHEVs will enable a certain degree of peak power usage to be shifted to off-peak hours. This will further reduce the need to invest large amounts of capital into additional infrastructure reinforcements and will result in cleaner operation of existing assets.

Chapter 8 summarizes the key findings that are developed throughout the paper. It attempts to paint a broad picture of potential impacts stemming from PHEV adoption to PHEV

owners, electric utilities, and policymakers.  Finally, it highlights areas in which future work

is needed in order to more fully understand the full impacts of PHEV penetration.

1.1 **A Brief History of Electric Utility Regulation**

In 1882, Thomas Edison began generating electric power at Pearl Street Station in lower Manhattan. This first central generation station was initially capable of serving four hundred lamps owned by eighty-five customers using direct current (DC) transmission technology. Edison chose to locate Pearl Street Station in lower Manhattan based on its proximity to the central financial district and the customers that he intended to serve [1]. Due to significant electrical losses associated with the high currents, transmitting large amounts of power over large distances was impossible.

A few years later, George Westinghouse used technology developed by Nikola Tesla to build the first high-voltage transmission line using alternating current (AC) technology [1]. Higher transmission voltages resulted in lower currents, directly corresponding to lower line losses. Lower line losses enabled electricity to be transmitted over much larger distances. With this increased ability to transmit power it was now possible to construct larger and more efficient generating plants away from population centers. Smaller electric companies began to consolidate in order to more effectively cover the costs of larger plants and longer lines. Due to the capital intensity of building power plants and transmission lines it was much more practical for a single electric company to provide service to a given area [2]. The requirement for a direct connection between generation and individual end-use consumers made competition between electric companies absurd. Imagine the cost and annoyance of three sets of distribution lines tied to a single home in order to give the residents a choice of

electric service providers. Without competition, electric companies were able to set prices and primarily provide service to densely populated, profitable areas.

These early electric monopolies operated unchecked into the beginning of the 20<sup>th</sup> century. In 1907, New York and Wisconsin were the first states to extend the jurisdiction of their state regulatory commissions to include electric companies. By 1943, an additional forty-three states had followed suit [2]. However, in the mean time the continuing consolidation of companies had resulted in electric companies with service territories that crossed multiple state borders. These companies were exempt from state jurisdiction, leading to the necessity of establishing regulation at the federal level.

President Roosevelt signed the Public Utility Holding Company Act (PUHCA) into effect in 1935. PUHCA placed limits on the geographic scope and corporate structure of electric utilities. It also established the Federal Power Commission, known today as the Federal Energy Regulatory Commission (FERC) [3]. The Federal Power Act of 1935 explicitly divided regulation responsibilities between federal and state governments. The Federal Power Commission was given jurisdiction over wholesale power sales and over transmission. State governments continued to control siting issues and distribution rates [3]. Electric policy has since, until very recently, been dictated by the assumption that the electric industry is a natural monopoly due to high fixed costs and economies of scale.

1.2 **Current Attempts to Encourage Competition in Energy Markets**

The electric industry is currently experiencing its greatest transformation since the inception of federal regulation with PUHCA in 1935. The first hints of change arose due to increasing

energy costs and slowing expansion of generating capacity during the 1970s. Skyrocketing oil prices led to a fear of relying too heavily on fossil fuel imports from foreign countries with potentially unstable governments and a fear that there was a limited remaining amount of fossil fuels available for consumption [4]. Also, people were just beginning to consider the negative environmental consequences that would result from continued fossil fuel plant operations [4].

These changes gave rise to the Public Utilities Regulatory Policy Act (PURPA) of 1978. PURPA created a market for non-utility electric power producers. The ultimate goal was to increase the amount of renewable generation and simultaneously reduce dependence on foreign oil. Existing utilities were required to purchase the power generated by these non-utility electric power producers at a price equivalent to the avoided cost of building a new generating plant [4]. The existing utilities argued that it was unfair to allow independent power producers to generate power without the added capital costs of transmitting and distributing this power; however, they were unsuccessful in preventing implementation of the act. Existing utilities eventually came to appreciate the reduced need to make uncertain capital expenditures [4]. PURPA ultimately resulted in a large number of new hydro generation plants and natural gas cogeneration plants. Following implementation of PURPA, some people began to question the validity of the natural monopoly model. The establishment of non-utility electric power producers had unwittingly introduced a certain amount of competition into the generation side of the electric industry [4].

The Energy Policy Act of 1992 (EPACT) further separated the electric industry from a monopolistic model by removing some of the remaining obstacles to wholesale power

competition. EPACT also directed FERC to require wholesale wheeling in an effort to encourage development of generation resources [5] FERC fulfilled its responsibilities by issuing Orders 888 and 889 in 1996, thus promoting non-discriminatory open access transmission service [5]. Essentially, this required all transmission owners to transmit inexpensive power from any electric company to areas with high demand. Smaller electric service providers were now able to purchase power from the cheapest source if unable to generate enough electricity internally to meet demand. Previously, smaller electric service providers were limited to the generation prices set by its nearest neighbors with direct transmission connections. In order to ensure that transmission owners were abiding with the new regulations they were required to openly share information about their transfer capabilities and schedules.

Orders 888 and 889 had a positive impact on generation resources; however, they placed additional burdens on the transmission system. Soon after implementation of Orders 888 and 889, the North American Electric Reliability Corporation (NERC) published a reliability assessment claiming that "the adequacy of the bulk transmission system has been challenged to support the movement of power in unprecedented amounts and in unexpected directions [6]." In response to these concerns, FERC issued Order 2000 in 1999. Order 2000 encouraged the establishment of Regional Transmission Operators (RTOs) to provide transmission services and independently operate energy markets within their service territory. According to the final order passed by FERC, RTOs would improve efficiencies in the management of the transmission grid, improve grid reliability, remove opportunities for

discriminatory transmission practice, improve market performance, and facilitate lighter-handed governmental regulation [7].

1.3 **Unintended Consequences of Incorporating Competition in Energy Markets**

Despite significant progress towards deregulation and a competitive energy market, mounting evidence suggests that modernization of the current transmission system is still required. The transmission system must be flexible enough to match generation to load every second of every day. Historically, load patterns have been very predictable. This has enabled generation resources to be scheduled in order to meet the typical demand. Small fluctuations in demand have been accounted for by automatic governor response of certain generators. This is increasingly difficult in the face of growing demand and integration of variable resources. Essentially, the number of unknown operational quantities has been increasing significantly. This requires additional transmission infrastructure in order to ensure that the bulk electric system is capable of withstanding numerous different system biases and configurations. For example, transmission infrastructure in Wisconsin has to be capable of importing large amounts of power from the Wisconsin – Minnesota interface when large amount of wind generation in operational in the Iowa and the Dakotas. However, during periods when there is little wind generation, the system must be able to withstand large energy imports from the Wisconsin – Illinois interface in order to meet demand within the state. Also, federal regulations require that the system will remain intact for loss of any single contingency.

Additionally, end-use customers want to have access to the lowest cost generation, which is often not located in proximity to densely populated areas. In order to allow low cost

generation to adequately compete in the new electric markets, additional transmission lines must be built to connect these low cost generators to areas of high load. With the onset of state renewable portfolio standards and the potential for a federal renewable portfolio standard, there is an increasing realization that the existing transmission infrastructure will need to be supplemented in order to adequately transmit solar and wind energy. Along with biomass, these two technologies are anticipated to play a large role in reducing greenhouse gas emissions and slowing the impacts of climate change. However, the most efficient solar power installations will be located in the southwestern United States and the most efficient wind turbines will be located in the Midwest. Neither of these locations is highly populated. Thus, a great deal of infrastructure expansion will be needed to fully take advantage of the available resources. A large, nation-wide network of 765 kV lines has been proposed to connect locations with high renewable generation potential to areas with high demand [8].

The restructuring of the electric industry has created the need for a discussion between government officials and industry representatives to discuss who will build and pay for new transmission lines. Vertically integrated utilities have historically built sufficient transmission infrastructure to transmit the energy that they generated to their customers. With required open access transmission tariffs, there is less incentive for these vertically integrated utilities to build new infrastructure. Also, new financial uncertainties in electric power markets have made raising sufficient capital to build new transmission difficult. However, transmission constraints are contributing to increasing electricity costs and additional reliability concerns. According to an independent study conducted by the Department of Energy (DOE), interregional transmission congestion costs consumers

hundreds of millions of dollars annually [9]. Over the past decade, these changes have led to the formation of two transmission-only companies. The first of these two companies, American Transmission Company, owns and operates approximately two-thirds of the transmission infrastructure in Wisconsin. The second independently owned transmission company, International Transmission Company, owns and operates transmission infrastructure in parts of Iowa, Minnesota, and Michigan. Both of these companies are operated independently of generation which enables them to be unbiased when considering future transmission upgrades. Because they receive revenue based on the amount of power that flows across their lines, reducing system losses and congestion are important considerations. All potential transmission upgrades are reviewed and approved by the state Public Service Commissions in order to prevent abuse in the form of overbuilding.

However, these two companies have limited service territories. As a whole, the bulk electric system is still suffering from insufficient transmission capacity due to vertically integrated utilities that have not placed sufficient interest in expanding the transmission system over the past decade. In a National Transmission Grid Study performed in 2002, the National Energy Policy Development group proposed to relieve transmission bottlenecks by completing the transition to competitive regional wholesale markets through better operations and effective investments [9]. The DOE has taken an increased leadership role in transmission by creating the new Office of Electricity Transmission and Distribution to lead national efforts to modernize the electric grid, enhance security and reliability of the energy infrastructure, and facility recovery from disruptions to energy supply. Although there appears to be potential efficiency and rate benefits due to increasing competition in energy markets, it is very

important to take certain precautions during the transition in order to prevent a repeat of a situation such as the California electricity crisis. Severe system reliability issues were experienced in California due to manipulation of the energy markets that occurred during deregulation. Deregulation can be accompanied by additional opportunities to make a profit at the expense of reliability of the system if care is not taken to ensure that the system is not abused.

Demand response has been proposed as a potential method to increase competition within the electric industry while simultaneously improving the reliability of the bulk electric system. Essentially, the power to determine energy prices no longer resides solely with the cost of generation. Energy customers that feel that the price is too high can reduce energy consumption. When sufficient energy customers reduce consumption, higher cost generation will no longer need to run. A great deal of research has gone into determining the benefits of demand response and defining the remaining barriers to wide-spread use of demand response. Combining appropriate use of demand response resources with the existing attempts at deregulation of the industry will ideally minimize unintended congestion and reliability impacts that have been associated with deregulation thus far. The next chapter more fully explores the potential benefits of demand response and the remaining barriers to wide-spread participation in demand response programs.

2.1 **Definition of Demand Response**

FERC has defined demand response as any "changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized [10]." Essentially this refers to the ability of variable load to address energy emergencies, respond to high energy prices, and potentially maintain system frequency. Demand response programs have been offered by local utilities for many years under the name 'interruptible loads.' Interruptible loads have always been a last resort available to electricity companies during periods of extremely high demand or system contingencies with significant reliability impacts. More recently, Independent System Operators (ISOs) and (RTOs) have begun to create market programs for use of demand response resources, enabling these resources to be used on a more regional basis. This coincides with the general trend within the industry to optimize operations across the entire grid, as opposed to optimizing operations within smaller company service territories.

Demand response programs can be separated into dispatchable demand response (DDR) and non-dispatchable demand response (NDDR). DDR programs include direct load control, interruptible tariffs, and certain demand bidding programs. In all cases listed above, the local balancing authority has a direct method to curtail load. NRRD programs, on the other hand, rely on customer response to a price signal reflecting the cost of energy production and

delivery. Examples of NDDR programs include time-of-use pricing, critical peak pricing, real-time pricing, and certain demand bidding programs [11].

The informal interruptible load contracts that existed prior to the onset of electricity markets were typically made with large industrial loads. These resources could be dispatchable or non-dispatchable depending on the preferences of the customer. Compensation was provided for the willingness to reduce demand during system reliability emergencies; however, electric companies tried to avoid prolific use of these resources. Over use could result in an unwillingness to participate in such programs in the future. Competitive electricity markets have the potential to open up the market for demand resources to any customer that is capable of sufficient metering and response times. New demand response programs will need to be designed such that there is a significant benefit to the consumer in order to promote adoption and a significant benefit to the reliability of the system in order to ensure that the electric companies feel justified in making the effort to offer these programs.

Demand response is expected to complement existing energy programs, such as distributed generation and demand-side management (DSM). The National Energy Policy Development group has suggested that increasing the role of all types of energy management is the only way to ensure a robust and reliable electric system in the future [9]. Distributed generation (DG) is primarily composed of small-scale power production, typically connected to distribution systems. Often located at sites such as hospitals and industrial facilities, these resources have traditionally been used as emergency back-up power sources for essential local operations in the event of a blackout. In many cases, these generation resources are located behind-the-meter and are therefore unable to be monitored separately from the local

demand. DG can also include small solar panel or wind turbine installations that individuals install at their homes. These installations typically are only used to offset energy purchases from the grid; however, there are certain times when these generators can actually feed energy back into the grid.

DSM includes both energy efficiency and demand response. Energy efficiency programs attempt to permanently reduce electricity demand during all hours of the year. Examples of energy efficiency measures include replacing incandescent light bulbs with compact fluorescent bulbs, insulating homes in order to minimize wasted heat and air conditioning, and replacing old appliances with new energy efficient appliances. In addition to the overall energy savings achieved through the use of energy efficiency programs, the corresponding reductions in the peak demand may defer the need for new investments in both generation and transmission. Demand response programs, on the other hand, are designed to decrease electricity demand only during peak periods based on high wholesale prices or low-reserve conditions. Demand response is expected to become a critical resource for maintaining system reliability in the future.

## 2.2 Benefits of Demand Response

Demand response has already proven itself as a valuable tool to ensure reliability of the bulk electric system. During the summer heat wave of 2006, the Midwest ISO avoided firm load shed using interruptible load, demand-side management, and public appeals. Over 2,500 MW of load curtailment occurred on August 1st alone.
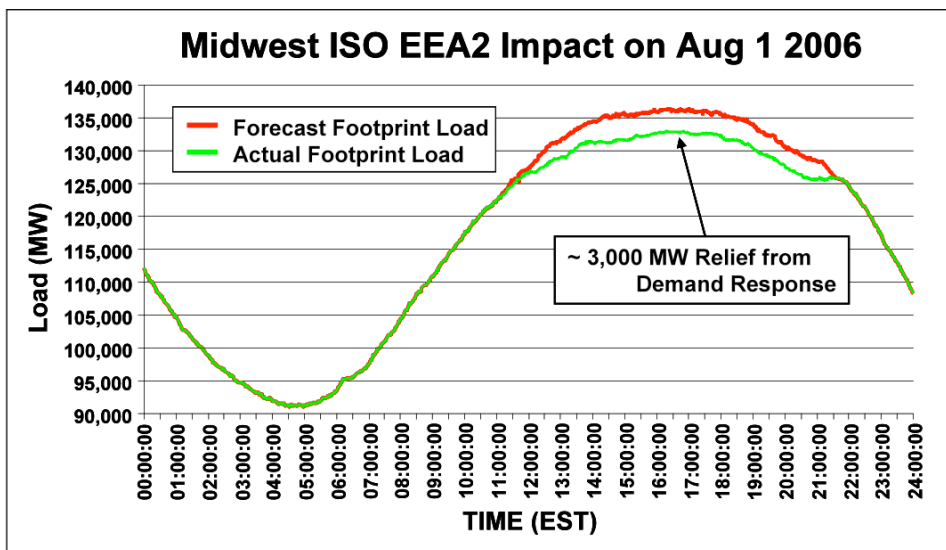


**Figure 1: Impact of Demand Response on Reliability in the Midwest ISO's Footprint**

Many other regions also utilized demand response to avoid firm load shed in July and August of 2006 as high temperatures swept across the nation. In this example, demand response (a.k.a. interruptible load and public appeals) helped to maintain reliability of the bulk electric system [13]. Even if it means spending a significant amount of money, paying energy customers to reduce their load during system emergencies is much less expensive than paying for the damages that result from cascading blackouts. Forced customer outages lead to significant expenses including lost production and sales, food spoilage, or overtime for employees that work an extra shift to make up for lost production.

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Some energy customers are more suited towards provided certain types of demand response than others. For example, an automobile manufacturing facility can relatively easily stop production and pick it right back up without damaging any equipment. However, processes such as the smelting of aluminum require a certain range of temperatures at all times. If the temperature deviates beyond a certain bandwidth and the molten aluminum hardens it can be weeks before the equipment is functioning again. As demand response participation increases and demand response resources are allowed to more fully participate in energy markets, there is a great potential for these resources to provide economic benefits in addition to reliability benefits. Some of the positive impacts that are expected to result from increasing participation of demand response are reliability benefits, market performance benefits, market-wide financial benefits, and participant financial benefits. Each of these impacts is discussed in further detail below.

### 2.2.1 Reliability Benefits

Appropriate use of demand response resources can enhance system reliability by sending more efficient generation and transmission capacity signals. Depending on the geographical distribution of these resources, it is possible that they can be used to mitigate congestion and optimize the flow of electricity on the grid [14]. In addition to the actual amount of infrastructure required to meet system demand, electric companies are required to have a certain amount of capacity in case equipment fails or demand changes. Some types of demand response can also be used to fulfill resource adequacy requirements. This means that these resources can be used during system emergencies in order to ensure that no firm load is shed. Finally, demand

response will be able to provide the robustness and flexibility that the grid needs to support increasing amounts of variable generation.

### 2.2.2 Market Performance Benefits

A great deal of the interest in demand response can be linked back to changes in governmental regulation and policy. For instance, tighter environmental regulations have required the electric industry to look for new methods to decrease the amount of greenhouse gas emissions. Reducing demand during select peak hours throughout the year instead of running peaking units may result in an overall cleaner electrical system footprint, depending on the local generation mix [14].  For example, areas with a great deal of old coal technology or constrained generators will benefit more than areas with cleaner and more efficient cogeneration plants.  It is possible that the government will place some sort of tax on carbon emissions in the future.  In this scenario, the increase in the price of electricity generated using fossil fuel technology will likely be accompanied by a corresponding increase in demand response participation, helping to maintain reasonable energy prices.  Also, the government is currently pushing the electric industry to remove any remaining barriers to true competition in electric markets.  Allowing demand resources to participate in energy and ancillary services markets will lead to reduced potential for generators to exert market power [14].

### 2.2.3 Market-Wide Financial Benefits

Demand response can play a crucial role in reducing the volatility of power prices

[14]. This is especially important in the face of widely fluctuating gas prices, increasing concerns about dependence on foreign fuels, and large proposed amounts of renewable generation. As the price of natural gas increases, reducing load for a few hours each day instead of turning on a peaking plant to meet demand can result in significantly lower locational marginal prices. Generator prices are typically inelastic over the vast majority of demand levels. This is illustrated by the primarily horizontal nature of the supply curve shown in Figure 2. At a certain level of demand, more expensive generators must be brought online. Suddenly, small increases in demand can cause significant increases in the price of electricity. Thus, a small amount of demand reduction corresponds to a much larger electricity price reduction.
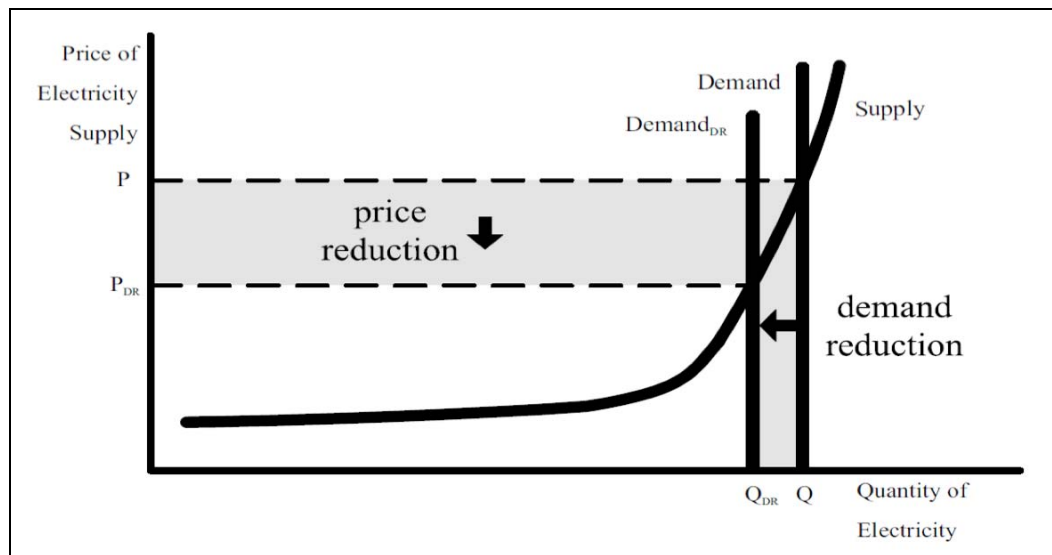


**Figure 2: Illustration of the Economic Benefits of Demand Response**

Certain types of demand response are capable of providing regulation services. An example of a demand response resource that can provide regulation services is an aluminum smelting plant. The output of the plant is dependent on the amount of

energy that is used to heat the smelter. However, small increases or decreases in energy will not have a significant impact on output, provided that the average amount of energy supplied remains the same. In this situation, the variations in wind energy output can be matched by variations in load instead of generation. Also, since some types of demand resources can be used to fulfill resource adequacy requirements, less over-building of infrastructure will be needed. The increased use of demand response can lead to delayed or avoided generation and transmission infrastructure [14].

### 2.2.4    Participant Financial Benefits

Increased prevalence of demand response will heighten customer awareness of the time-dependent nature of actual electricity costs [14]. At this time, few demand response programs are offered to residential customers. Existing programs include controlled air conditioner and water heater programs. This is partially because residential customers only have a significant impact on reliability or price when they are aggregated together. Recent developments in some states have created a market for aggregators to offer bids on behalf of a number of residential customers into energy markets [14]. In the future, customers will be able to define the value of the electricity that they consume, and feel more empowered to control their consumption. Some customers will be more capable of reducing load during periods of high locational marginal prices. Customers that reduce demand will be compensated for their services. The ultimate result will be lower costs for safe and adequate electric service for all customers [14].

## 2.3 **Demand Response Participation in the United States Today**

Significant benefits from demand response will accrue only with sufficient levels of customer participation. In 2008, nearly 8% of customers in the United States were participating in at least one type of demand response program [16]. FERC estimated that the potential annual resource contribution of demand response resources available in the United States was approximately 41,000 MW, or 5.8% of the forecasted U.S. peak demand for 2008 [16]. This number is a nine percent increase from the availability of approximately 38,000 MW of total potential peak load reduction in 2006 [16]. Actual load reductions are less than half of the total potential load reduction. Sixty-nine percent of the actual load reduction that occurs in the United States is located in the regions that include the Reliability First Corporation, the Midwest Reliability Organization, and the Southeast Electric Reliability Council. This is likely due in part to the relatively large geographical area, high populations, and significant amounts of heavy industry that exist in each of these regions [16].

The difference between actual load reduction and potential peak load reduction can be partly explained by the fact that many demand response resources are reserved for use during system emergencies. The actual peak load reduction for economic-based demand response resources in a given year is very much dependent on the volatility of electricity prices. Economic demand response programs are only utilized when locational marginal prices reach a certain set point. If the price to generate and transmit electricity remains low, these resources will not be used [16]. For example, total demand in the United States has been lower than anticipated this year, coinciding with the economic downturn. Without high electricity demand, low cost coal and nuclear generators are capable of meeting the demand

throughout the entire day. More expensive gas units are not needed, thus reducing overall price volatility. Most demand response resources have fairly high costs to reduce load. Without high levels of price volatility it does not make economic sense to utilize these resources. Ancillary services that can be offered by demand response participants include operating reserves, frequency support, and voltage support. Resources capable of providing ancillary services are not necessarily called on during system peaks, but rather are called on throughout the year [16]. These numbers will not be reflected in the ratio of actual to potential peak load reduction, further contributing to the difference between actual load reduction and potential peak load reduction.

## 2.4 Remaining Barriers to Demand Response

Despite the observed and anticipated benefits of demand response, there are several barriers that must be addressed before it becomes standard within the electric industry. FERC published a report in 2008 that identifies some of the significant barriers. One major barrier is the limited number of residential customers that participate in time-based rate programs [16]. Residential customers are largely protected from the variable nature of energy prices. Without direct exposure to energy prices customers have no incentive to reduce energy usage, nor do they know when conservation is most needed. Ideally, exposing all customers to the real-time locational marginal price would require people to actually consider the value of the electricity that they use. In lieu of real-time pricing, time-based rates encourage customers to use electricity during periods that typically see less demand.

The lack of customers participating in time-based rate programs is due in part to the limited variety of demand response programs that are offered by utilities [16]. Encouraging

residential participation in demand response programs is a pivotal step in demand response policy because the residential sector ultimately has the potential to surpass other sectors in total demand response reductions. Figure 3 shows the achievable peak reduction by different sectors under a range of demand response scenarios [10]. The business-as-usual scenario assumes the same level of advanced metering infrastructure deployment and dynamic pricing programs as exist today. The expanded business-as-usual scenario assumes that additional dynamic pricing programs will be available to customers, and 5% of customers will voluntarily participate in these programs. The achievable participation scenario assumes full advanced meter deployment and assigns dynamic pricing as the default rate structure for customers. Based on the ability of customers to choose not to participate, it is assumed that 60 – 75% of customer will actually participate in one of the dynamic pricing programs. The full participation scenario assumes full deployment of advanced meters and mandatory participation in dynamic pricing programs.
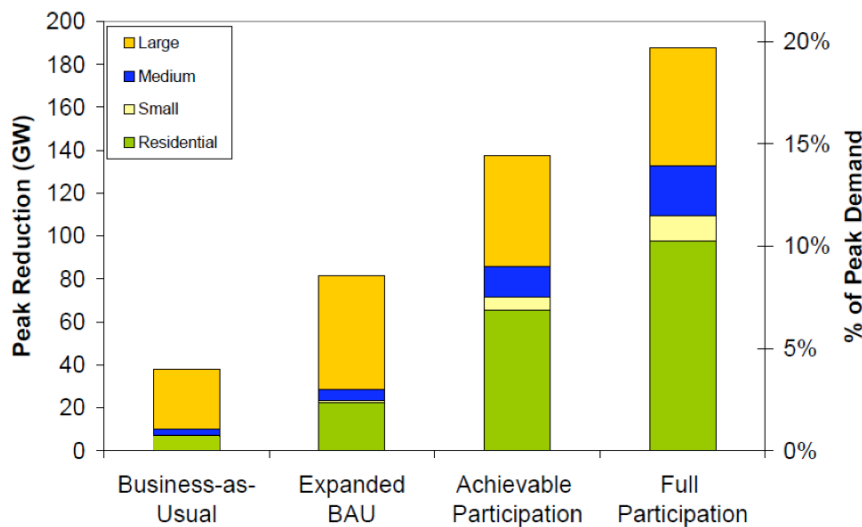


**Figure 3: United States Demand Response Potential by Sector**

Another remaining barrier to demand response is the relatively low penetration of advanced

metering devices [16]. Advanced metering devices are needed for demand response participants in order to measure the duration and amount of actual load reduction. Without an accurate measurement, compensating the participant is impossible. Also, utilities need accurate measurements of actual load reduction in order to verify the ability of participants to provide the expected amount of curtailment in the pre-defined time period. Many utilities are planning to replace their existing meters with advanced metering devices in the near future. Existing installations of advanced metering devices have demonstrated their ability to reduce costs; however, there is still a significant up front installation cost which makes it difficult for some utilities to make the change [16].

The FERC report also found that policies regarding access to meter data can be a barrier to demand response, even in areas with high penetration of advanced metering devices [16]. The time and money required to access meter data can prevent customers from participating in demand response programs. Enhanced meter transparency could optimize utility operations and planning through better tracking of consumer demand and patterns.

2.5 **Creation of a National Action Plan for Demand Response**

In order to facilitate the removal of remaining barriers FERC is in the process of creating a National Action Plan for demand response. The three objectives to be fulfilled through the National Action Plan include "identification of requirements for technical assistance to States to allow them to maximize the amount of demand response resources that can be developed and deployed, design and identification of requirements for implementation of a national communications programs that includes broad-based customer education and support, and development or identification of analytical tools, information, model regulatory provisions,

model contracts, and other support materials for use by customers, states, utilities and demand response providers [17]." The proposed method to achieve these objectives is the creation of a coalition of stakeholders. This coalition will make decisions about methods to ensure a graceful transition to an electric industry with extensive demand response participation [17]. Ideally, this means that the individuals that are making the decisions will be those that have the most expertise in the area. It will also ensure that input from all interested parties is considered. The coalition must include federal/state regulators and policymakers, ISOs/RTOs, generation/transmission/distribution owners and operators, goods and services providers, and concerned consumer advocates and non-profit agencies. Such a large and diverse membership will likely extend the duration of the process; however, the outcome will more comprehensively address barriers to implementation.

A number of possible activities to promote demand response in accordance with the three specified objectives have been proposed. One of the first tasks will be to begin organization of a national forum on demand response in order to facilitate conversations on a nation-wide basis [17]. In addition to the national forum, information sessions and communications training will be provided to policymakers, regulators, and local governing officials [17]. These activities will ensure that those in the upper echelon are better prepared to implement demand response in their respective regions. Opening these training sessions to load serving entities would be beneficial since they will be playing a major role in encouraging end-use consumers to participate in demand response programs. Also, this will provide an additional outlet for representatives from the policy world to interact with industry representatives. Other activities intended to provide technical assistance include building a panel of demand

response experts, sponsoring technical papers, establishing a demand response assistance program, and establishing a demand response grant program [17]. Combining the goals of building a panel of demand response experts and sponsoring technical papers will result in the greatest efficiency of resources. Technical experts will be the most qualified authors of demand response related papers. Conversely, authors of demand response related papers will be highly qualified as technical experts.

A number of activities are planned to support the establishment of a national communications program. The ultimate goal of all these communications-related activities is to present a consistent messaging framework on a national level [17]. This will require a great deal of foundational market research in order to determine the most effective vocabulary and means for communicating. There are already a number of smart energy usage marketing campaigns such as energy efficiency and energy conservations. It will be important to determine if consumers will be more open to demand response if it is marketed as an additional subset of existing energy usage campaigns or as a new and unique concept. Also, different marketing strategies will need to be developed based on the customer class. For example, large industrial customers may respond better to a national campaign because they are likely able to participate directly in energy markets. However, residential customers are much more dependent on the local programs offered in their immediate areas. A national campaign may not be suitable for marketing to smaller customers. In order to maintain a consistent messaging framework, the coalition may elect to provide communications toolkit materials and assistance for more local campaigns [17]. There are also plans to create corporate and organizational partnerships to increase effectiveness and visibility in a low-cost manner [17].

Manufacturers and retailers that are allowed to market their products as demand response capable will contribute to customer awareness and interest without any effort on the part of the coalition. An example of this is the marketing of Energy Star appliances. The consumer is encouraged to purchase these products due to the energy savings that they will achieve on their monthly electricity bill; however these customers are simultaneously contributing to nation-wide energy efficiency efforts.

Tools and materials that the coalition will be working to create include demand response estimation tools and processes, standards and protocols for demand response, information to design pilot demand response programs, and guidelines on rate designs for dynamic pricing [17]. These tools are intended to facilitate the transition to increased demand response penetration for policymakers, utilities, and demand response participants. Some of these tools will be used to demonstrate the potential benefits incurred through demand response participation. After-the-fact verification that demand response actually has the anticipated results will be equally important in order to encourage additional demand response participants, and to determine just how much demand response resources can be relied on to meet their commitments.

Another suggested activity for the coalition is to compile information and case studies on a web-based clearing house that will be made available to those in the electric industry attempting to incorporate demand response [17]. This will provide the coalition with an accessible means to disseminate information. Summaries from the national forum and regional meetings might be additional items of interest to include. Creating a separate website with the purpose of providing information to and answering the questions of end-use

consumers about demand response might also be beneficial.

## 2.6 **Plug-In Hybrid Electric Vehicles in the National Action Plan**

Many discussions have taken place about the ability of Plug-In Hybrid Electric Vehicles (PHEVs) to provide significant amounts of demand response. Although the proposed National Action Plan will likely have positive implications for demand response on a national basis, there has been very little specific research on implementation and impacts of large amounts of PHEVs providing various types of demand response services. Specific mention of PHEVs occurs in the National Action Plan discussion draft in two sections. The first section suggests that PHEVs should be included in the technical paper sponsorship categories of interest. More specifically, the interest lies in "a study of how PHEVs interact with demand response programs, examining whether demand response rate design provides a price signal that encourages PHEVs to charge during off-peak hours as well as how different demand response pricing mechanisms interact with PHEVs and their net impacts on how electricity might change [17]."

An additional concern is addressed in the section of the National Action Plan discussion draft that addresses standards and protocols for demand response. One of the suggested areas to explore is "adoption of nationwide standards for PHEVs and all electric vehicle charging station, with appropriate communications, metering and electric flow control, and standardized plug interface would facilitate use of PHEVs and electric vehicles variable storage potential to provide ancillary services to the electric grid and would reduce barriers to interoperability posed by having various state-by-state standards [17]."

PHEVs have the potential to more fully allow residential customers to participate as demand response resources. Customers with flexible charging patterns may be able to use smart charging systems to charge their vehicles when demand and energy prices are low. Similar to the way utilities are able to control some air conditioners and water heaters, PHEVs could potentially be a large load source that can be cut in times of emergency or high prices. The utility could then pool all participating PHEVs and bid this into energy markets, lowering prices and increasing reliability. However, before investing in the metering and charging infrastructure that will be required to fully optimize PHEV demand response participation, it is important to consider all the potential impacts.

The following chapter describes some of the specific standards that are under development in order to facilitate PHEV adoption and participation in demand response programs. Even in the absence of PHEVs, numerous standards are in development that will facilitate and simplify participation in demand response programs. Many of these standards are related to smart grid initiatives that are intended to increase the overall reliability and robustness of the bulk electric system. Other standards are needed to more explicitly address characteristics that are unique to electric vehicles.

# 3  Overview of Relevant Standards Development

## 3.1 Importance of Standards to Plug-In Hybrid Electric Vehicle Penetration

Development of appropriate standards will be essential in order to smoothly integrate PHEVs into the existing electric and transportation sectors. Standards are important for a number of reasons. First of all, standards ensure that new products will not pose a threat to the safety and health of end-use consumers. Standards also serve to align product development goals between different research entities, and thus allow product research to be divided among different specialty areas. For example, an automobile manufacturer is able to design and produce a new gasoline-fueled vehicle with the knowledge that any individual purchasing the vehicle will have access to refueling stations. The automobile manufacturer does not need to concern itself with developing and installing new refueling infrastructure. An additional benefit stemming from the alignment of product development goals is increased competition within specialty areas. For example, a common refueling mechanism enables numerous automobile manufacturers to compete in the automotive market. Finally, standards are able to guide consumer usage patterns. This enables consumers to receive optimal benefits from their products, but prevents them from abusing the rights of others.

Recent changes in policy priorities have set an aggressive schedule for the deployment of new technologies in both the electric and transportation sectors. The electric and transportation industries have historically operated independently of each other. However, the deployment of PHEVs has suddenly forced the two industries to operate in much closer proximity. The difficulties presented by this new interdependency between the electric and

transportation sectors are exacerbated by additional changes faced by the electric industry including installation of advanced metering devices, development of demand response programs, and integration of variable resources. These changes have created a need to review existing standards and develop new standards to guide the electric and automotive industries through this significant transition.

Numerous organizations exist to develop and publish standards applicable to the electric and transportation industries. Determining which organizations have the appropriate expertise to develop standards can be an extremely tedious and difficult task. The Energy Independence and Security Act (EISA) of 2007 assigned "primary responsibility to coordinate development of a framework that includes protocols and model standards for information management to achieve interoperability of smart grid devices and systems [18]" to the National Institute of Standards and Technology (NIST). In partial fulfillment of its responsibilities, NIST partnered with the Electric Power Research Institute (EPRI) to identify a preliminary set of existing standards pertinent to smart grid applications and potential areas that merit new standard development [19]. This preliminary information was then used to develop a number of Priority Action Plans (PAPs) to specifically address certain areas related to smart grid implementation. The stated goal of each PAP is to "define the problem, establish the objectives, and identify the likely standards bodies and users associations pertinent to the standards modifications, enhancements, and harmonization required [21]."

3.2 **Development of Standards Nonspecific to Plug-In Hybrid Electric Vehicles**

There are a number of standards gaps that must be addressed in order achieve a smooth transition as PHEVs enter the consumer market. However, there are a number of broader

smart grid issues that need to be addressed prior to considering standards specific to PHEVs. NIST has classified these broader issues into the following categories: advanced metering, customer interactions with the smart grid, and smart grid communications [21]. A number of PAPs have been developed within each of these categories.

### 3.2.1 Priority Action Plans Related to Advanced Metering

Advanced metering infrastructure is of crucial important when attempting to facilitate any form of demand response, including PHEVs. Many utilities are currently in the process of installing advanced metering devices within their footprints. However, the possibility of installing infrastructure that will be incapable of complying with future smart grid standards has caused many utilities to hesitate. PAP 00 was intended to ensure that near-term installations of advanced metering devices will be capable of complying with future standards. This will allow utilities to continue the installation of smart grid infrastructure prior to full development of smart grid standards. The National Electrical Manufacturers Association (NEMA) took the lead on developing standards for meter upgradeability. Due to its high priority, NEMA Smart Grid Standards Publication SG-AMI 1-2009 – Requirements for Smart Meter Upgradeability was approved by NEMA's Codes & Standards Committee approximately 90 days after issuance of PAP 00 [21].

PAP 05 was developed to create standard meter data profiles, thus facilitating timely access to meter data. Ideally, this will enable increasing numbers of end-use consumers to obtain data to help them manage energy consumption. It will simultaneously allow electric utilities to more efficiently access the data required to

implement demand response programs [21]. American National Standards Institute (ANSI) Standard C12.19 contains information about which data elements may be stored in meters, relays, communications modules, and data management systems. The PAP 05 task force plans to determine any changes that may need to be made to this standard in order to more fully facilitate demand response resources. Also, this task force will play a role in creating the Association of Edison Illumination Companies (AEIC) Guidelines v2.0 to ensure that ANSI C12.19 is utilized in the most effective manner [22].

### 3.2.2    Priority Action Plans Related to Smart Grid Customer Interactions

PAP 10 was developed in order to further facilitate access to meter data through the creation of standards for energy usage information. The inability to conveniently access data from advanced metering devices is one of the remaining barriers to demand response. Simplifying accessing to energy usage data will enable end-use energy customers to more easily identify potential methods to control energy consumption and measure their progress. Ultimately, increased awareness and control over energy consumption will increase reliability of the bulk electric system while simultaneously reducing end-use customers' monthly electricity bills [21]. The PAP group tasked with developing standards for energy usage information has identified a number of existing models on which to base future metering information requirements. These models include OpenADR, IEC CIM, IEC 61850, ZigBee SEP, and ASHRAE BACnet, among others. The PAP 10 task force is currently extracting

requirements from these existing models and attempting to create a standard composite information model [21].

Ideally, increasing numbers of installed advanced metering devices, coupled with simplified data acquisition methods, will enable additional end-use consumers to participate in demand response programs. However, there is still a great deal that needs to be accomplished in order to standardize demand response signals. Demand response resources can be signaled on the basis of threats to reliability, high locational marginal prices, or violation of predefined environmental metrics. PAP 09 was created to define signals that can be used to call on demand response resources and to explore various methods of implementation. The PAP 09 task force plans to create a comprehensive set of demand response signal specifications, drawing on existing standards bodies such as OpenADR, OpenSG, and IEC TC57 [21].

PAP 03 was developed to create a common specification for price. Energy regulators are currently pushing the electric industry to embrace competitive energy pricing. In a perfectly competitive market, price is a reflection of numerous product characteristics including availability, quality, and demand. Heavy regulation, and the assumption that the electric industry must operate as a natural monopoly, has historically prevented electricity prices from reflecting actual market conditions. Recent regulatory changes are forcing the electric industry to completely restructure operations, with particular emphasis on encouraging competition in energy markets. In order to ensure successful implementation of energy markets, PAP 03 has been

assigned the task of creating a common price model to define which characteristics should be associated with electricity prices [21].

Of equal importance to developing a common pricing model is development of a common scheduling model. PAP 04 was developed to streamline scheduling communications in energy transactions. Scheduling is of particular importance to the electric industry due to limited storage mechanisms and a constant need to instantaneously match supply and demand. Historically, scheduling has consisted of forecasting load and dispatching sufficient generation resources. Increasing penetration of variable resources has added an extra dimension of uncertainty in available generation resources. Also, demand response programs are beginning to play a larger role in balancing supply and demand. This sudden influx of unknown variables has resulted in the need to identify key players in energy scheduling and standardized methods to convey the necessary information to these players [21].

### 3.2.3 Priority Action Plans Supporting Smart Grid Communications

One of the anticipated benefits from smart grid implementation is an increased capability for communication between elements in the bulk electric system. Three PAPs have been developed to address smart grid communication mechanisms. PAP 01 was intended to create guidelines for the use of IP protocol suite in the smart grid and PAP 02 was intended to create guidelines for the use of wireless communications in the smart grid. The increased capability for communication is accompanied by increasing concern about protection of critical infrastructure. When determining how the electric industry should proceed in the realms of internet and wireless

communications, cyber security is of utmost importance. PAP 15 is devoted to harmonizing power line carrier standards for appliance communications in the home. Power line-based communications will be an essential part of integrating appliances, meters, and other consumer communications into the smart grid. There are a number of existing power line-based communications standards including ITU G Hn (HomeGrid), IEEE P1901 (HomePlug™), and ANSI/CEA 709.2 (Lonworks™). Unfortunately, these existing standards are not interoperable and may negatively interfere with each other. The PAP 15 task force is focused on facilitating consistency among these standards [21].

## 3.3 Standards to Address Mobile Aspect of Plug-In Hybrid Electric Vehicles

Wide spread adoption of PHEVs has the potential to place a significant strain on existing electric infrastructure if charging characteristics are not carefully controlled. However, appropriate control mechanisms will enable PHEVs to increase utilization of existing infrastructure while simultaneously increasing reliability and robustness of the bulk electric system. Based on the increasing role that energy markets are playing in electric operations, demand response is a likely method that will be used to control PHEV charging characteristics. The previous sections have outlined a number of PAPs that will be crucial in setting the stage in order to enable PHEVs to participate in demand response programs. However, there are a number of additional standards that will need to be developed in order to address the mobile nature of PHEVs.

PAP 11 was designed to facilitate development of the interoperability standards required to support PHEVs. The mobile nature of PHEVs is a key concern to be addressed vie PAP 11.

Assuming that PHEVs will ultimately be capable of charging outside their home locations, determining appropriate settlement mechanisms will be essential [21]. For example, PHEV owners are likely to participate in certain rate structures offered by their local electric service provider. The utility can then track vehicle consumption and charge based on the applicable rate structure. However, when extended traveling takes PHEV owners outside the footprint of their local electric service provider the settlement mechanism becomes much more complex. Another concern being considered by the PAP 11 task force is the ability for Distribution Management Systems (DMSs) to communicate with PHEVs that are enrolled in demand response programs. The ability to access the PHEV fleet and influence charging profiles is essential if PHEVs are to contribute to increasing the reliability and robustness of the bulk electric system. Four pressing items that have been identified by the PAP 11 task force are discussed below.

### 3.3.1    IEC 61850-7-420 for Distributed Energy Resource Equipment

Increasing numbers of distributed energy resource (DER) installations prompted the International Electrotechnical Commission (IEC) to begin drafting IEC 61850-7-420 in order to provide standards related to the communications aspect of monitoring and controlling DER systems [23]. The standard currently includes information relevant to photovoltaic systems, fuel cells, diesel generators, batteries, and combined heat and power systems [21]. Additional forms of DERs and energy storage devices require that this standard be expanded. Other existing standards that also need to be reviewed in order to ensure smooth communications as the number of PHEVs interfacing with the grid increases include ANSI C12.19/22 and ZigBee SEP 2.

### 3.3.2 IEC 61968 Distribution Common Information Model

Closely related to communication with DERs and energy storage devices is standard IEC 61968. This standard outlines information exchanged concerning the configuration and status of distribution electrical networks and will need to be updated in order to incorporate models for new forms of DERs and energy storage devices. IEC 61968 and IEC 61850-7-420 need to be updated in conjunction with each other in order to facilitate unimpeded communications [21].

### 3.3.3 Electricity Resale Rules and Metering Requirements

At this time there is a great deal of uncertainty about how PHEVs will interact with electricity markets. Unlike existing DERs and energy storage devices, the spatial distribution of PHEVs is an unknown quantity. This is a cause of concern both within a single utility's footprint and between different utilities' footprints. PHEVs have the flexibility to participate in energy markets as demand response resources, energy storage devices, or ancillary service providers. Continuation of existing electricity market regulations will place a significant burden on utilities to manage complex accounting and settlement processes. However, utilizing retail methods might simplify accounting and settlement for both utilities and PHEV owners. Members of the PAP 11 task force are exploring numerous new methods to facilitate simplified market transactions [21].

### 3.3.4 IEEE 1547 Standard for Interconnecting Distributed Resources

If PHEVs are to serve as DERs, the Institute of Electrical and Electronics Engineers (IEEE) 1547 standard needs to be reviewed to ensure that it adequately addresses relevant interconnection requirements. It is possible that additions will need to be made in order to protect local distribution equipment and the vehicle itself during charging and discharging events [21]. Article 705 of the National Electric Code (NEC) relating to interconnected electric power production sources may need to be revised in order to accommodate the needs of PHEVs [24].

There will also need to be a review of standards relevant to the actual charging connection that is used by PHEV owners to charge their vehicles. This will be important to understand the impacts that vehicle charging may have on local distribution systems and to ensure the safety of individuals as they connect and charge PHEVs. Society of Automotive Engineer (SAE) standard J1772 covers physical, electrical, communications protocol, and performance requirements for an electric vehicle conductive charging system and coupler [25]. SAE standard J1773 provides the same information for an electric vehicle inductive charging system and coupler [26]. Article 625 of the NEC includes requirements for design and installation of equipment necessary for electric vehicle charging [27]. These three standards need to be reviewed in order to verify that they are sufficient to safely utilize PHEVs as demand response resources, energy storage devices, and ancillary service providers.

# 4 Relevant Assumptions and Background Information

## 4.1 Plug-In Hybrid Electric Vehicle Charging Characteristics

To adequately evaluate the potential impacts of PHEVs it is essential to understand how they will interact with the electric grid. Although there may eventually be energy flow to the grid through vehicle-to-grid (V2G) technology, the initial interaction will most likely be one-way charging. This has the potential to place additional stress on distribution system. The amount of stress added is highly dependent on the level of charging. The Electric Power Research Institute has defined three potential levels of charging. Level 1 charging will most likely be the primary method of charging PHEVs as they first enter the market. At this level, vehicles are charged from a standard 120VAC 15A outlet that is available in many attached garages. These outlets are rated to provide power up to 1.4kW [28].

Some early PHEV adopters may also have access to a 240VAC 30A outlet in their garage. This has been defined as Level 2 charging and is usually considered the preferred means to charge PHEVs because of the reduced amount of time required to fully charge the vehicle [28]. Level 2 charging could potentially result in an instantaneous power consumption of 6 kW [29]. As the market penetration of PHEVs increases, Level 2 charging stations may be constructed in public places for the convenience of patrons or employees.

When higher penetrations of PHEVs are achieved, PHEV owners may begin to see fast charging stations that are similar to today's gas stations. At these charging stations vehicles can achieve 50% charge in just 10 to 15 minutes through a 480VAC, three phase circuit. This is referred to as Level 3 charging [28]. An alternative to Level 3 charging stations are

battery exchange stations. Instead of stopping to recharge the PHEV battery, the battery is actually swapped out for a fully charged battery. The battery exchange station would maintain fully charged batteries as needed to meet demand in the area. This option would require less additional infrastructure than the fast charging station; however, there would also be a significant investment in batteries. In addition, ownership of the batteries at end-of-life becomes a concern.

While increasing the charging level reduces the amount of time required to charge PHEVs, the total charging time also depends on the size of the battery pack. Most PHEVs are classified based on the number of pure electric miles that they can travel. For example, a PHEV20 is capable of driving twenty miles before starting the internal combustion engine. Similarly, a PHEV40 is capable of driving forty all-electric miles and a PHEV60 is capable of driving sixty all-electric miles. Figure 4 presents daily driving distance data collected by the 1995 National Personal Transportation Survey (NPTS) [30]. It also shows the utility factor calculated based on the cumulative percentage of trips that are less than or equal to a given distance.
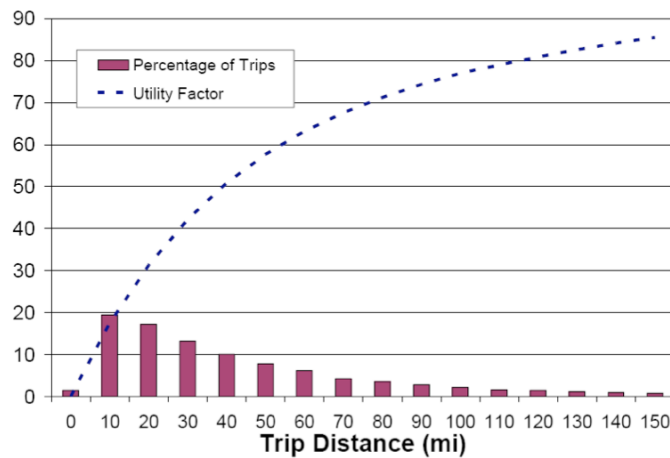


**Figure 4: 1995 Data on Daily Driving Distance Distribution and Resulting Utility Factor**

From Figure 4, it is apparent that 30% of daily vehicle miles traveled (VMT) are less than or equal to twenty miles and 50% of daily VMT are less than or equal to forty miles. These lower-ranged vehicles will likely be the most accessible to consumers due to smaller and less costly battery packs. These vehicles provide sufficient all-electric miles for many consumers to complete the majority of typical trips without using the internal combustion engine. The amount of time required to charge these vehicles will be less than that required to charge vehicles with larger battery packs. In the future, vehicles with larger battery packs will likely be capable of more fully participating in certain types of demand response programs. As the ability of PHEVs to participate in demand response programs increases, there will be a corresponding increasing incentive for consumers to purchase vehicles with larger battery packs.

PHEVs with equal all-electric ranges will not necessarily have the same sized battery packs. The actual battery pack size will be dependent on the size and weight of the car. Table 1 summarizes the typical size of battery packs required for different passenger vehicle types with an all-electric range of twenty miles [29]. The charging times below are calculated assuming that the battery has been fully discharged to 20% state of charge (SOC) and incorporates one to two hours of battery conditioning prior to start of charging [29].

**Table 1:  Charging Requirements for PHEV20**

| PHEV20 Vehicle | Battery Pack Size | Charger Circuit | Charging Time (from 20% SOC) |
|---|---|---|---|
| Compact Sedan | 5.1 kWh | 120VAC/15A | 3.9 – 5.4 hrs |
| Mid-size Sedan | 5.9 kWh | 120VAC/15A | 4.4 – 5.9 hrs |
| Mid-size SUV | 7.7 kWh | 120VAC/15A | 5.4 – 7.1 hrs |
| Full-size SUV | 9.3 kWh | 120VAC/15A | 6.3 – 8.2 hrs |

The charging characteristics for different PHEV20 passenger vehicle types are displayed graphically in Figure 5 below [29]. The figure assumes Level 1 charging, or a maximum charging rate of 1.4kWh. As the battery pack approaches its full state of charge a reduction in charging rate is required in order to prevent overcharging the batteries. This reduction in charging rate is reflected in Figure 5 in the final hour of charging.
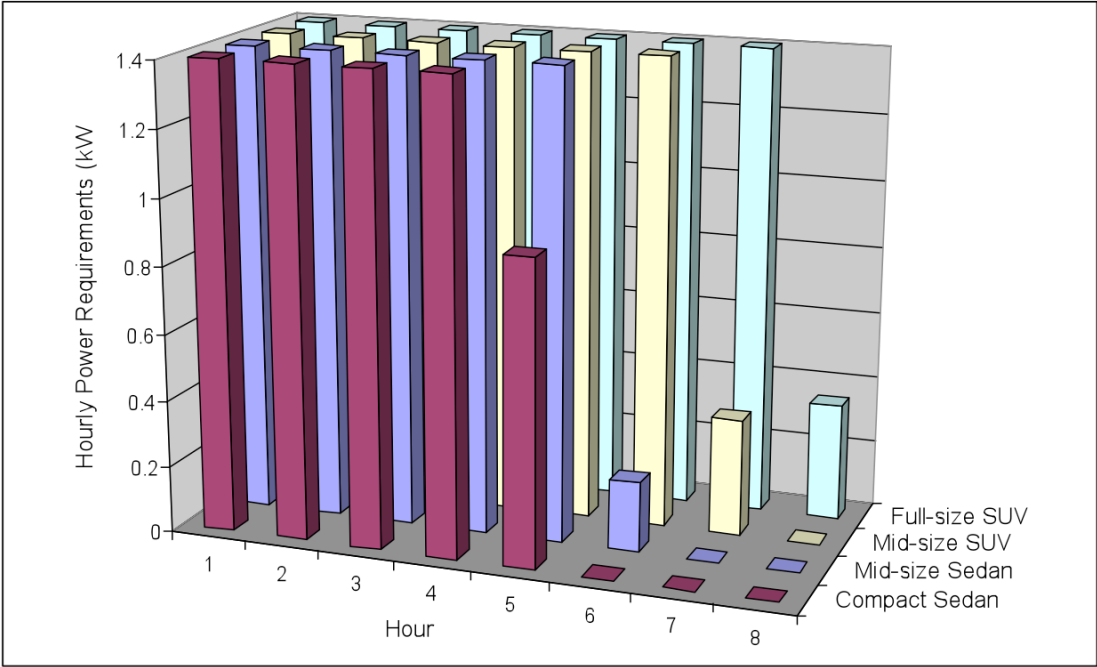


**Figure 5: Power Requirements by Hour for PHEV20 at 120VAC/15A**

With Level 1 charging, the differing battery pack sizes have a relatively significant impact on total charging time. Each additional increase in vehicle size adds an hour to the total amount of time required to fully charge the vehicle. If access to higher levels of charging is unavailable, consumers in the market for larger vehicles are likely to be dissuaded from purchasing PHEVs due to the prohibitively large amount of time required for charging.

Increasing to Level 2 charging rates has a significant impact on the amount of time required to charge a single PHEV. Figure 6 illustrates the charging characteristic for different PHEV20 vehicle types at Level 2 charging rates [29]. At Level 1 charging rates, a mid-size SUV required seven hours to fully charge. As indicated in Figure 6, the amount of time required to charge the same mid-size sedan at Level 2 charging rates drops to two hours.
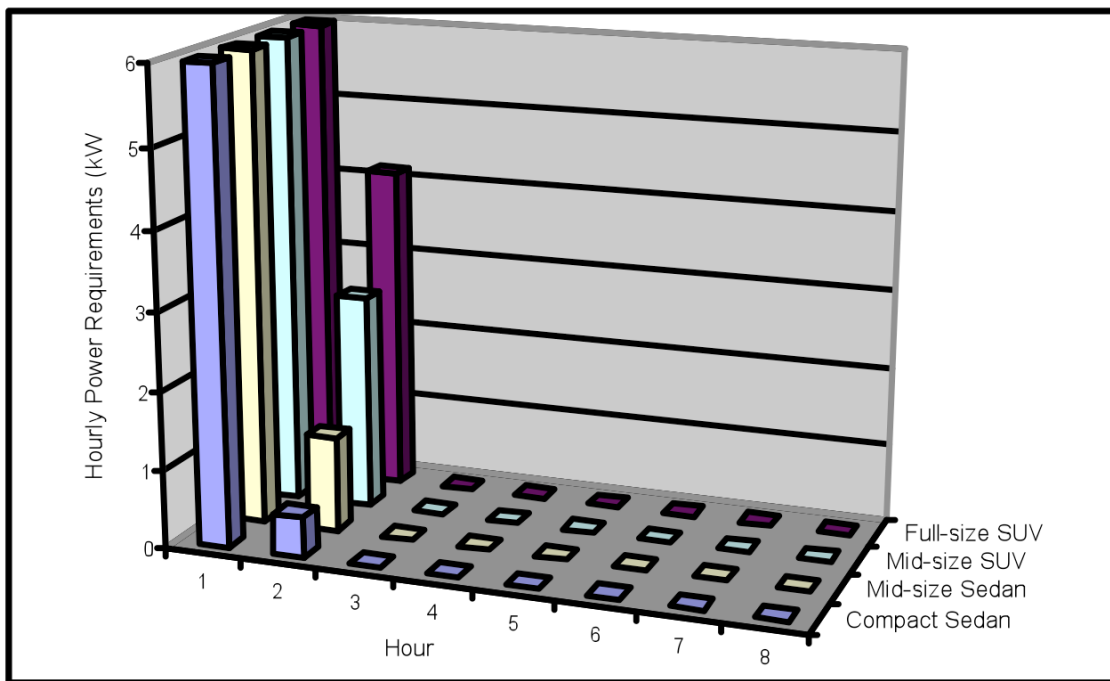


**Figure 6: Power Requirements by Hour for PHEV20 at 240VAC/30A**

In fact, Level 2 charging rates essentially negate any differences in charging time between vehicles of different sizes. Thus, increasing to Level 2 charging has a much more significant impact on convenience for owners of larger vehicles.

## 4.2 **Plug-In Hybrid Electric Vehicle Adoption Models**

It is necessary to make certain assumptions about the market penetration rate of PHEVs prior to considering any potential future impacts. There are a number of unknown variables that

will affect the actual market penetration of PHEVs; however, according to the Duvall report, a reasonable approximation is to assume a national market potential of 25% of passenger vehicle sales by 2018 [31]. Passenger vehicles include cars, pickups, vans, sport utility vehicles, and other light trucks. The assumed PHEV market penetration characteristics that result in the desired national 2018 market potential are shown in Figure 7. The market penetration characteristics are typical of new technology deployment. Initial technology adoption is relatively slow. As the technology matures there is a period of rapid adoption which gradually slows as the new technology saturates the market. Technology improvements that occur during market penetration can increase the adoption period prior to market saturation. However, the development of alternative technologies can reduce the adoption period prior to market saturation. Governmental incentives and subsidies intended to encourage new technology adoption often play a role in encouraging an earlier transition to the period of rapid adoption.
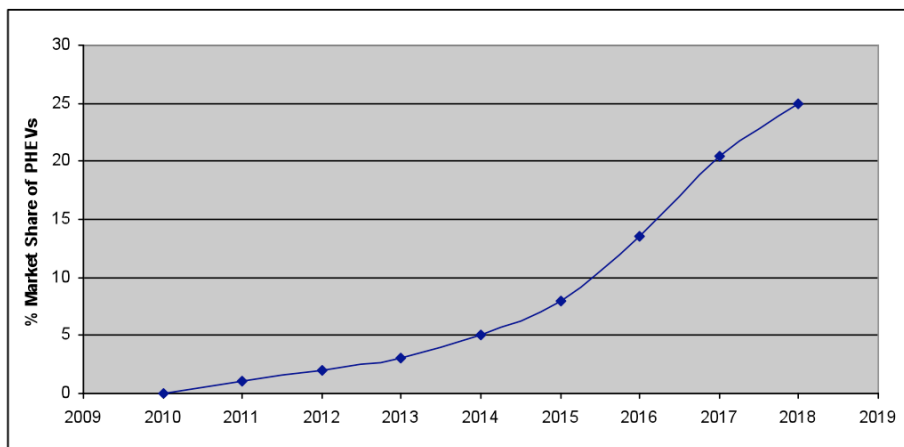


**Figure 7: Aggressive Assumptions for Percent Market Share of PHEVs between 2010 and 2018**

The actual annual number of vehicles sold can be calculated by multiplying the percent market share of PHEV and the total number of vehicles sold per year in the United States

[29].  Because this analysis is primarily concerned with PHEV impacts specific to Dane County, the total number of PHEVs sold nationwide must be scaled to accurately represent the number of vehicles sold in Dane County.  This is accomplished using the number of vehicles sold per year in the United States [32], vehicle registration data available per state [33], and population data available per county [34].  The number of PHEVs sold in Dane County through the year 2018 is shown in Figure 8.  The cumulative number of vehicles comprising the Dane County PHEV fleet through the year 2018 is also shown.
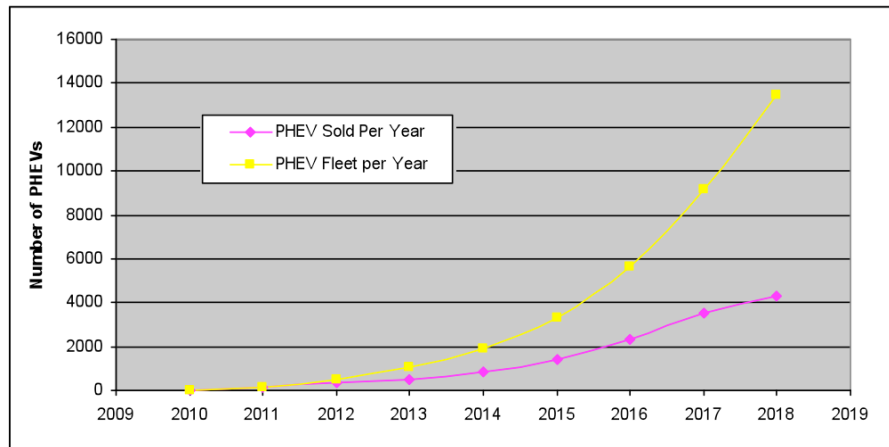


**Figure 8:  Total Number of PHEVs Sold per Year and Total Fleet Size Assuming Aggressive Penetration**

The worst-case charging scenario would be for the entire PHEV fleet to begin charging at the same time.  This maximum instantaneous demand can be calculated by multiplying the total number of fleet vehicles by the charging rate that corresponds to each charging level.

Figure 9 shows the maximum instantaneous vehicle load for Level 1 and Level 2 charging, based on the previous market penetration assumptions.
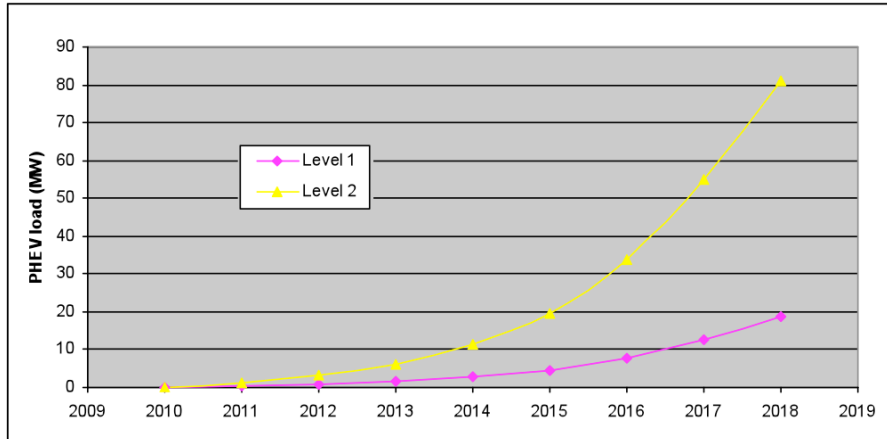


**Figure 9: Maximum Instantaneous Demand for PHEV Fleet per Year with Uncontrolled Level 1 and Level 2 Charging, Assuming Aggressive Penetration**

According to the forecasting method used, the PHEV fleet in Dane County, WI will exceed 6,500 vehicles by the year 2015. This corresponds to a national PHEV fleet of 3.8 million in 2015. In 2008, the Obama administration set a goal to put 1 million PHEVs on the road by 2015 [35]. Assuming the same technology adoption pattern as the Duvall report, Figure 10 illustrates this less aggressive penetration scenario for PHEVs through 2018.
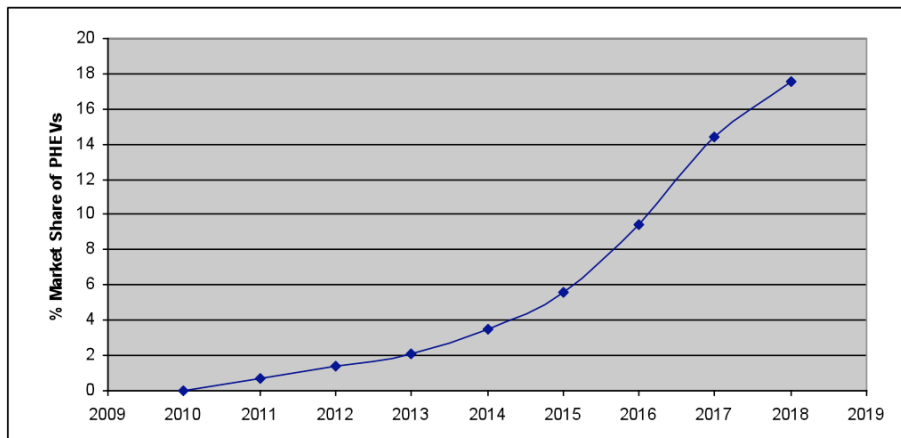


**Figure 10: Non-Aggressive Market Penetration Assumption for PHEVs between 2010 and 2018**

The two scenarios presented will be used in order to provide upper and lower bounds for the magnitude and time frame of effects stemming from PHEV penetration. The corresponding number of vehicles that can be expected in Dane County, WI is shown in Figure 11.
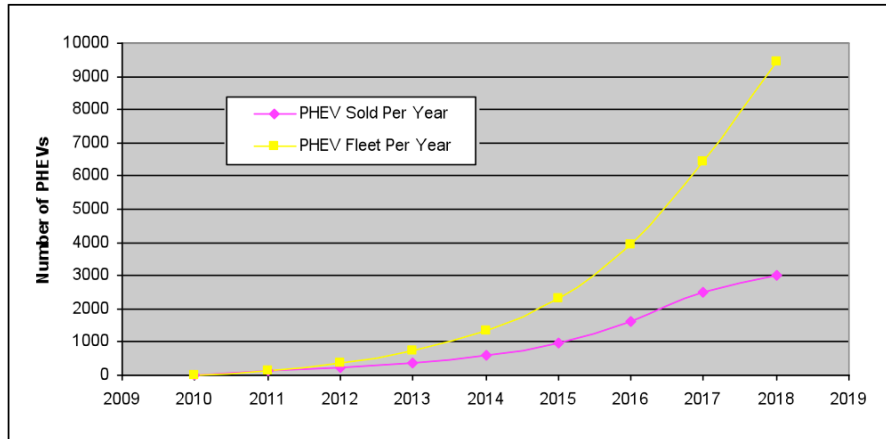


**Figure 11:  Total Number of PHEV Sold per Year and Total Fleet Size**
**Assuming Non-Aggressive Penetration**

Figure 12 illustrates the worst-case instantaneous demand that would result from concurrent charging of all vehicles under the non-aggressive market penetration scenario.
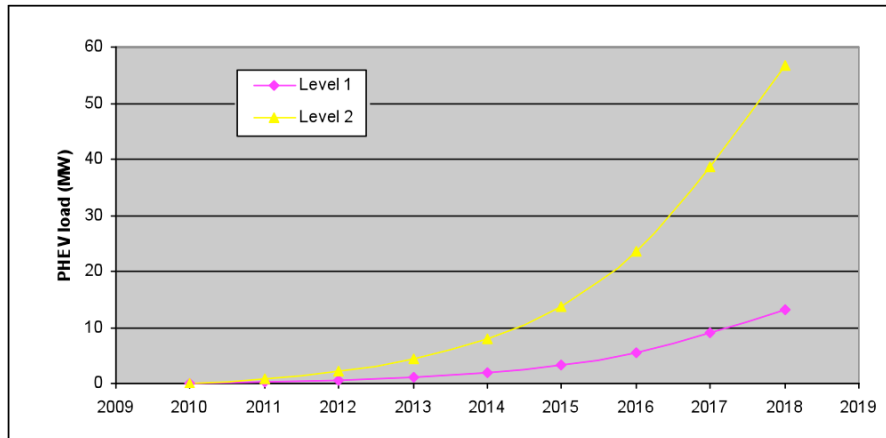


**Figure 12:  Maximum Instantaneous Demand for PHEV Fleet per Year with Uncontrolled**
**Level 1 and Level 2 Charging, Assuming Non-Aggressive Penetration**

Preliminary research indicates that there are three likely stages of PHEV penetration and participation as demand response resources. Initially, distribution infrastructure will likely need to be reinforced in order to meet the additional charging demand of the PHEVs. The extent of infrastructure reinforcement required will be highly dependent on the rate of vehicle adoption and the spatial distribution of the charging locations of the adopted vehicles. Higher penetration rates will certainly increase the amount of reinforcement necessary. However, even low penetration rates might require a significant amount of infrastructure reinforcement depending on the proximity of charging locations. It is likely that most initial PHEV adopters will not participate in demand response programs because these programs will still be in the very initial stages of implementation. Also, due to limitations in the number of charging locations available, most PHEV owners will only charge their vehicles at night.

As demand response becomes more widely accepted and utilized, the majority of PHEV owners will begin to participate in these programs due to the large potential for fuel savings. Ideally, enabling technology will allow PHEV owners to take advantage of the benefits possible through demand response participation with little personal inconvenience. This is the second stage of PHEV penetration. These first PHEV demand response programs will likely allow vehicles to regulate their charging rates to maintain low locational marginal prices and enhance system flexibility and robustness.

Finally, the third stage of PHEV penetration and demand response participation will evolve from 'smart grid' initiatives and vehicle-to-grid technology. Also, increased penetration of charging locations outside the home will contribute to an increased number of vehicles

connected to the grid throughout the day. At this point, PHEV will be able to charge during off-peak hours and then supply stored energy back into the grid during periods of high locational marginal prices or system reliability events. Potentially even more beneficial, the aggregate fleet of PHEV will be capable of providing regulation services throughout the day.

4.3 **Existing Policy and Regional Characteristics in Dane County, Wisconsin**

When considering the potential future impacts of PHEV penetration, clearly defining the geographical scope of interest is of utmost importance for a number of reasons. First of all, the existing robustness of the bulk electric system varies in different areas. For example, certain areas are more likely to be constrained by voltage limitations while other areas are constrained by the thermal limits of equipment. Also, generation profiles for an area can be significantly different from generation profiles for another area. Actual dispatched generation resources are often dependent on the economics of bringing certain generation resources online, in addition to ensuring compliance with any local environmental restrictions. In 2006, over half of the state of Wisconsin's electricity was generated by coal-fired plants [36]. However, there is currently a push to increase the amount of wind resources available in the area. Additionally, many of the proposed upgrades to the existing transmission infrastructure are designed to import renewable or alternative generation resources into Wisconsin from surrounding states. The potential for increasing renewable generation is certainly regionally specific. For example, the Midwest has more accessible wind power than any other region of the United States. However, the Midwest is not likely to see a large amount of commercial solar generation. Solar generation is much more likely to be seen in the Southwestern United States.

Secondly, customer behavior varies greatly due to climate and geographical differences. For example, customers residing in warmer climates typically consume more electricity for air conditioning needs than customers in cooler climates. The amount of humidity in the air can also impact air conditioning use in certain areas. Customers in cooler climates often use more electricity during the winter months due to increased lighting and heating needs. The magnitude of impact due to increased heating depends on whether the heating infrastructure in an area is predominantly gas or electric. The temperature, snow, and road conditions in colder climates often result in reduced average vehicle efficiencies.

Finally, electric industry regulations and environmental policies vary between regions. For example, many areas in the United States are currently in the process of establishing regional electricity markets for generation dispatch. Other areas still allow utilities to operate in a more traditional, vertically-integrated fashion with strict regulations in place to prevent monopolistic behavior. Independent of the broader regulatory setting, rate structures and programs offered by local electric service providers are not consistent across different utilities. Residents in some areas may not be capable of participating in any demand response programs while residents in other areas may have an array of demand response options from which to choose. Many of the existing environmental policies are implemented at the state level. Certain states have set forth renewable portfolio standards while others have not. For example, the Wisconsin Public Service Commission has set a goal of meeting 10% of electric demand with renewable resources by 2015, but states including Tennessee, Florida, and Wyoming have no similar goals [37].

The geographical scope of this study includes Dane County, Wisconsin. The city of Madison and the surrounding communities electrically dominate the Dane County area. Alliant Energy, Madison Gas & Electric (MGE), and Wisconsin Public Power Incorporated (WPPI) are the three distribution utilities that serve residents in the Dane County area. The city of Madison is the most likely area for significant PHEV load to impact distribution equipment due to its large population density, and its centralized commercial sector. For this reason, all initial distribution impact analyses are based on information collected on the policies, electric system, and customer base of MGE.

MGE currently offers a direct load control program and a time-of-use metering program to residential customers. Participants in the direct load control program agree to allow MG&E to remotely shut off their air conditioners when emergency power is needed. This service is only utilized during the select few times a year when peak demand is nearing excess of available generation resources. Participants are compensated $8 per hour of interruption and can expect to be interrupted six cumulative hours over a ten-year period [38]. The expected return for a single month's participation in the direct load control program is $0.40. Individuals who participate in the time-of-use metering program pay a premium for electricity service during peak hours, but receive a significant rate reduction on electricity service during off-peak hours. Peak hours are defined between 10am and 9pm on weekdays. Off-peak hours include weekends and weekdays between 9pm and 10am [38]. Time-of-use metering program is intended to reduce peak demand on a daily basis, as opposed to select hours throughout the year. Unlike energy efficiency programs, direct load control and time-of-use metering programs are not designed to reduce overall electricity consumption.

American Transmission Company (ATC) owns and operates the transmission network that serves the Dane County area. The region is primarily served by a double circuit 345-kV line from the Columbia Power Plant to the northern edge of Dane County and by a double circuit 138-kV line from the Christiana Power Plant to the southwest corner of Dane County. Several 69-kV lines tie into this area as well. Table 2 summarizes the existing Dane County area interface tie lines [39].

**Table 2:  Dane County Area Interface Tie Lines**

| From Bus | To Bus | Voltage | Line Name |
|----------|--------|---------|-----------|
| Stoughton | Sheepskin | 69-kV | Y-12 |
| Kegonsa | Christiana | 138-kV | G-CHR21 |
| Kegonsa | Christiana | 138-kV | X-59 |
| Verona | Belleville | 69-kV | Y-42 |
| Mount Horeb | Forward | 69-kV | Y-135 |
| Arena | Spring Green | 69-kV | Y-62 |
| Dane | Lodi | 69-kV | Y-8 |
| Deforest | Arlington | 69-kV | Y-28 |
| North Madison | Columbia | 345-kV | L-COL21 |
| North Madison | Columbia | 345-kV | W-7 |

The Dane County area includes the Blount Power Plant and the West Campus Cogeneration Facility; however, these generators may be offline if more economical generation is available outside the region. Smaller generations within the Dane County area include the Fitchburg Power Plant, the Sycamore Power Plant, and the Nine Springs Power Plant. Although the Christiana Power Plant is geographically located within Dane County, loss of the double

circuit 138-kV line isolates this generation from the Dane County area load. Table 3 summarizes Dane County generation [39].

**Table 3: Dane County Area Generation Resources**

| Station | Generator | Capacity | Fuel |
|---------|-----------|----------|------|
| Blount Power Plant | G3, G4, G5, G6, and G7 | 189.2 MW | Coal |
| West Campus Cogeneration Facility | CT1, CT2, ST | 160.0 MW | Gas |
| Fitchburg Power Plant | G1 and G2 | 43.0 MW | Gas |
| Sycamore Power Plant | G1 and G2 | 36.5 MW | Gas |
| Nine Springs Power Plant | G1 | 12.3 MW | Gas |

The Dane County area is susceptible to voltage instability when load is high compared to generation and a critical transmission system outage occurs. The critical transmission system outages include the loss of either double circuit line into the Dane County area [39]. These N-2 contingencies are typically not included in real-time contingency analyses programs used by ATC. These critical outages only become a concern during planned outages of one or more element in the area or during inclement weather such as tornado warnings or blizzard alerts. Following loss of either double circuit line, generation in the Dane County area can be used to alleviate transmission constrains. This will potentially allow additional load in the area to be supported following a critical transmission system outage. The generators most likely to be utilized in the event of a critical transmission system outage include the Blount Power Plant and the West Campus Cogeneration Facility [39]. Potential reactive power contributions vary between generators in the Dane County area.

In addition to the concerns faced by the Dane County area transmission network for the loss of a critical transmission system outage, there are a number of low voltage and transmission facility overloads that have been identified in the ATC 10-yr Transmission Assessment. These problems have been attributed to rapid growth in the area, increased import capability from Illinois, and changes to generation dispatch scenarios. The transmission system in the Dane County area is shown in Figure 13 along with the identified areas with low voltage concerns and areas with transmission facility overloads [40]. The areas with low voltage concerns are highlighted in yellow and the areas with transmission facility overloads are highlighted in green.
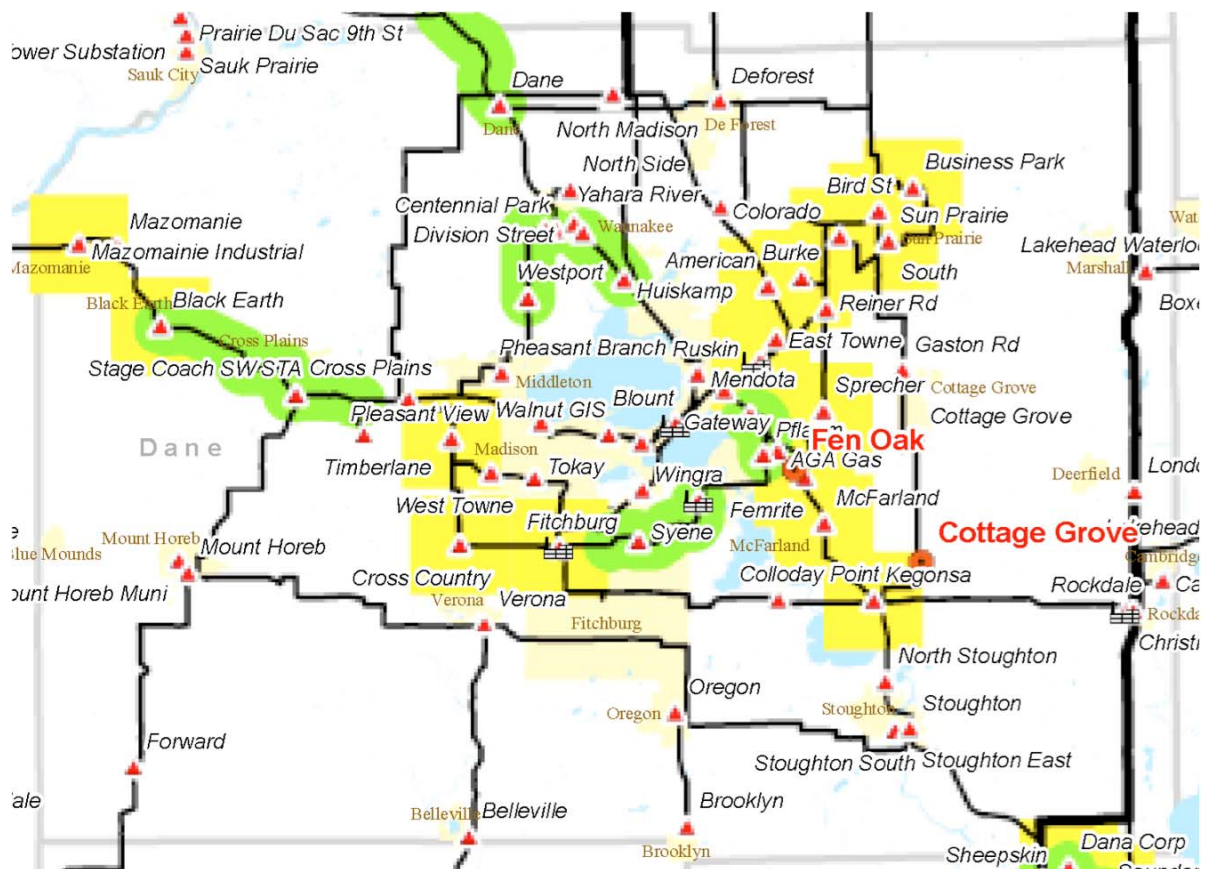


**Figure 13: Dane County Area Transmission System Map with Potential Low Voltages Denoted in Yellow and with Potential Transmission Facility Overloads Denoted in Green**

The Public Service Commission of Wisconsin has recently approved plans for ACT to construct two projects that will have an impact on serving load in Dane County. The first of these projects is a 345-kV line between Illinois and Southeastern Dane County that is intended to aid in importing power into the state [41]. The project is scheduled for completion in spring of 2010. The additional import capability will possibly reduce the amount of power generated by coal-fired and gas-fired plants in Southern Wisconsin, including those in Dane County. The second project is an additional 345-kV line that feeds the Western side of Dane County. This line will be placed in-service in 2013 and is expected to alleviate the potential for voltage collapse in the Dane County area following a critical transmission system outage. It will also play a role in reducing thermal overloads in the area [40].

The next chapter describes the initial impacts early penetration of PHEVs is likely to have on existing electric infrastructure, assuming that vehicle charging will remain largely uncontrolled during the early stages of market penetration. First, the potential to experience overloading on distribution infrastructure in explored. Due to the networked nature of the transmission system, it is likely that significant negative impacts will be delayed. However, the later section of the following chapter describes the potential impacts to transmission over an extended time frame, assuming the charging remains uncontrolled.

# 5 Initial Infrastructure Impacts of Plug-In Hybrid Electric Vehicles

## 5.1 Distribution Infrastructure Impacts

Initial penetration of PHEVs may present a new set of challenges to the reliability of the bulk electric system. The previous chapter outlined charging characteristics for different types of PHEVs. It also proposed two market penetration models that predict how many vehicles will be purchased over the next years. Additional factors that will aid in determining the magnitude of challenges posed by initial PHEV penetration include hourly load-use characteristics, spatial distribution of charging locations, and existing distribution equipment capacity.

### 5.1.1    Hourly Load-Use Characteristics in Dane County

Assuming that initial PHEV penetration precedes wide-spread installations of public charging stations, the majority of initial PHEV adopters will likely charge their vehicles at home. This necessitates knowledge of existing residential load-use patterns in order to determine whether PHEV charging will contribute to peak energy usage or off-peak energy usage. Due to certain common behaviors shared by the majority of residential customers, residential load-use patterns are very predictable. Prominent features of typical residential load curves include a small morning peak as individuals wake up in the morning and a much larger evening peak as individuals arrive home from work in the late afternoon or evening. However, regional climate differences can significantly change the magnitude of the two peaks experienced

during a typical day. An accurate assessment of distribution infrastructure impacts must take the regional differences in load-use patterns into account. Load-use patterns for Dane County, WI were obtained from a database of regional load profiles created by Itron Incorporated. Data from over 20,000 individual sites across the United States was compiled in order to develop the database [42]. The state of Wisconsin falls within the Central Industrial region. Other states included in the Central Industrial region are Illinois, Indiana, Michigan, and Ohio. Data is available for a variety of housing characteristics. The load-use patterns presented here assume gas heating and central air. Figure 14 shows typical winter and summer load curves for residential electricity demand in the Central Industrial region for 2005 [42]. The typical winter curve is calculated by averaging the hourly load data for all weekdays between December and February, excluding the three most extreme days. The typical summer curve is calculated by averaging the hourly load data for all weekdays between June and September, excluding the three most extreme days.
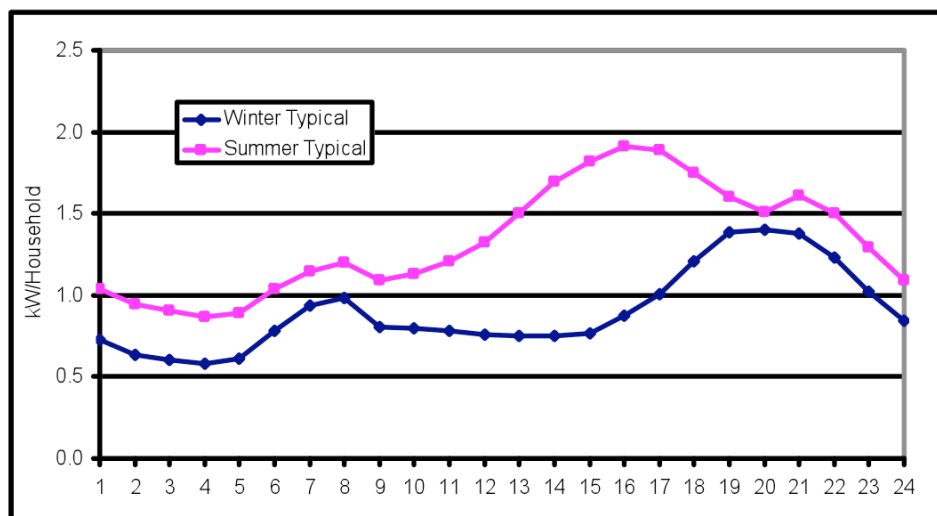


**Figure 14: Typical Household Electricity Usage as a Function of Time for a Single Household in the Central Industrial Region in 2005, Sampled on an Hourly Basis**

Although assessing the impact that PHEVs may have on distribution infrastructure on typical winter and summer days facilitates identification of potential trouble areas, owners of the distribution infrastructure are often more interested in peak loading scenarios. Distribution infrastructure must be built to withstand peak potential loading in order to prevent damage to equipment during extreme events. Figure 15 shows peak winter and summer load curves for residential electricity demand in the Central Industrial region for 2005 [42]. The peak winter curve is calculated by averaging the three most extreme weekdays between December and February. The peak summer curve is calculated by averaging the three most extreme weekdays between June and September.
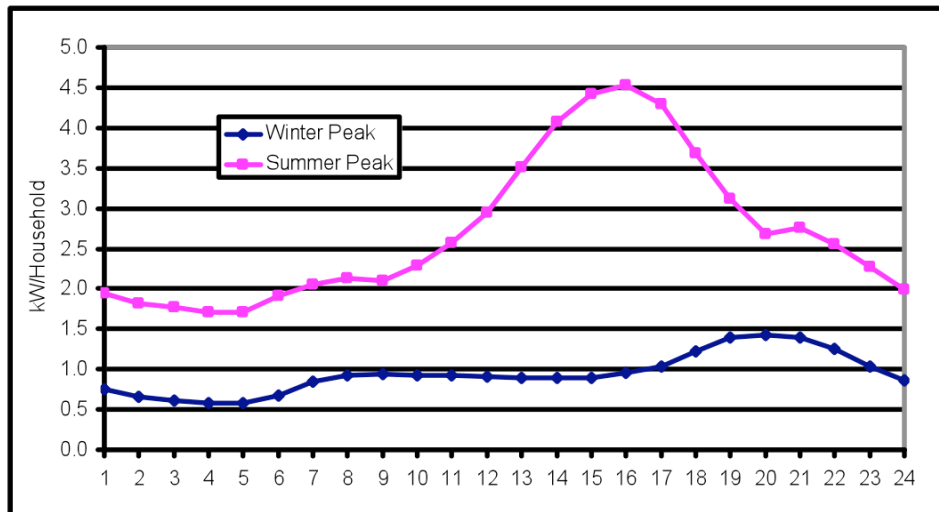


**Figure 15: Peak Household Electricity Usage as a Function of Time for a Single Household in the Central Industrial Region in 2005, Sampled on an Hourly Basis**

These load curves will be used as a baseline to evaluate changes in stress experienced by distribution infrastructure. Before assessing potential infrastructure impacts, certain assumptions need to be made about the number of PHEVs that will be electrically connected to pieces of equipment at any given time.

### 5.1.2    Assumed Spatial Distribution of PHEVs in Dane County

According to a study performed by Duke Energy, the most significant impacts of PHEV market penetration will likely be due to geographic clustering of the vehicles [43]. This means that certain localized areas may have much higher penetration of PHEVs than other areas. For example, areas with convenient charging locations and higher socio-economic statuses may have higher levels of PHEV market penetration. Most likely, the vast majority of early PHEV adopters will be single-family homeowners with attached garages [43]. PHEV owners will need to have access to a safe, secure charging location at home because it will take a great deal of time before charging locations are prevalently available in public places.

Due to the existing purchase premium associated with buying a PHEV over a conventional internal combustion engine vehicle, the rate of market penetration will likely be slow. Early adopters are likely to share certain characteristics including high incomes and/or high property values, access to a convenient and secure charging locations, and concerns with the United States' use of fossil fuels. It is very likely that individuals sharing these characteristics will live in close proximity to each other [43]. This means that even with relatively low rates of market penetration, equipment in certain areas might reach maximum rating very quickly if large numbers of vehicles are charged at the same time, coinciding with the pre-existing peak demand. Unfortunately, the most likely scenario in the early stages of PHEV penetration is individuals arriving home from work and immediately plugging in their vehicle for the sake of convenience.

During the initial period of PHEV penetration, it is likely that convenient access to a secure charging location will be a primary characteristic of PHEV owners. Using data obtained from the City of Madison, it is possible to identify land parcels that would likely provide PHEV owners with secure charging locations [44]. The characteristics of land parcels that are likely to have secure charging locations include residential, single-family, and attached garages. The parcels within the City of Madison that fit these characteristics are shown the lightest gray in Figure 16 [44].
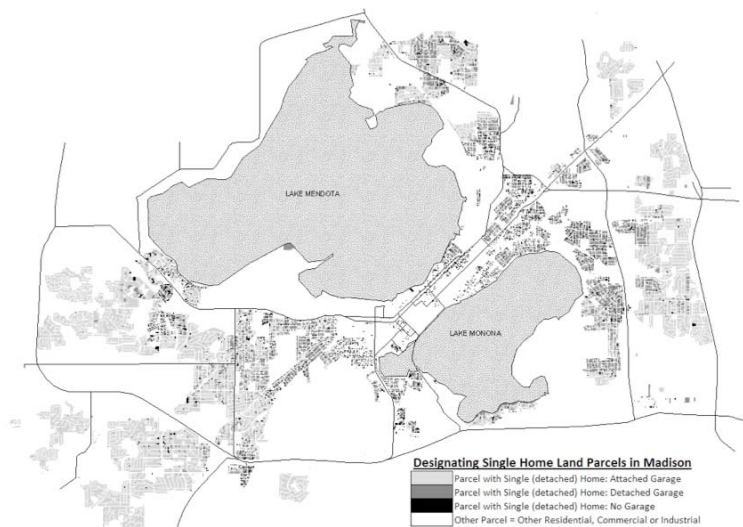


**Figure 16: Single Home Land Parcels in the City of Madison with Garage Type Specified by Shading**

A second common characteristic that is likely to be shared by initial PHEV adopters is high property values [43]. Figure 17 shows the spatial distribution of housing unit values for census tracts within the City of Madison [34].
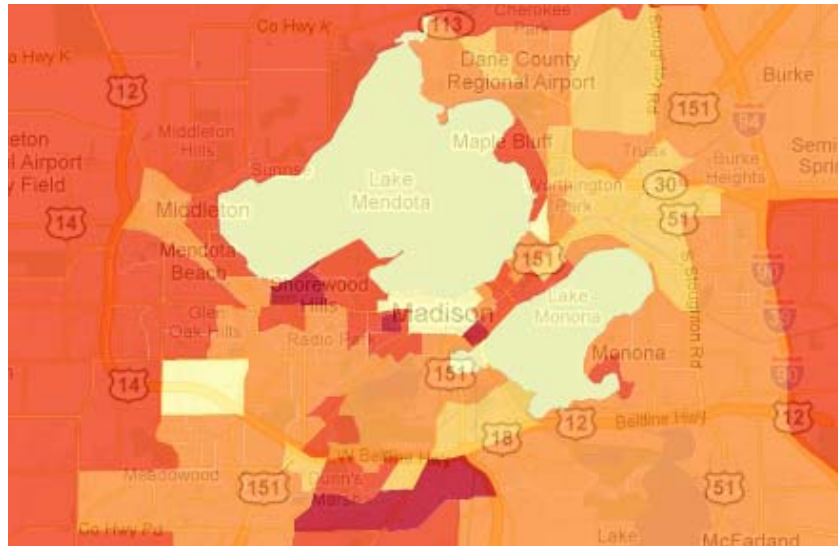
**Figure 17: Median Value of Housing Units in the City of Madison with Darker Shading Indicating a Higher Value and Lighter Shading Indicating a Lower Value**

As an example, Figure 18 overlays data concerning the median value of housing units over a map that shows single-family homes with attached garages [44, 34]. Households located in areas in which high housing unit values overlap with the desired housing characteristic are the most likely to purchase a PHEV in the near future.
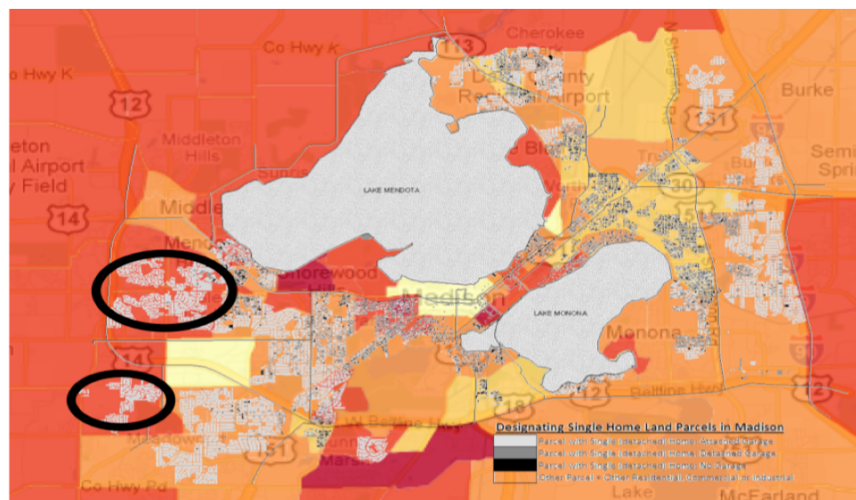


**Figure 18: Overlay of Single Home Land Parcels and Median Housing Unit Values**

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According to Figure 18, the greatest area of concern in the Madison area is on the far Western side of the city. There are a handful of potential problem areas more centrally located; however, these areas are not as densely filled with single family homes with attached garages.

### 5.1.3     Transformer Overload Analysis

From Figure 18, census tract 550250002052 was selected as a potential area that can expect to see large number of PHEVs during the initial penetration stage. It is located in an area that typically has high property values and the majority of parcels in the area are single family homes with attached garages. There are approximately 1,200 housing units in census tract 550250002052, corresponding to a population of 2,818. According to the penetration study performed by Duke Energy, energy customers that live in areas with higher property values are up to 3.5 times more likely to purchase PHEVs than energy customers that live in areas with average property values.

Figure 19 shows the upper and lower bounds of expected PHEV penetration in census tract 550250002052 assuming that residents are 3.5 time more likely to purchase PHEVs than the typical consumer. The shaded region between the two penetration scenarios presented in Figure 19 represents an infinite range of potential future PHEV penetration scenarios.
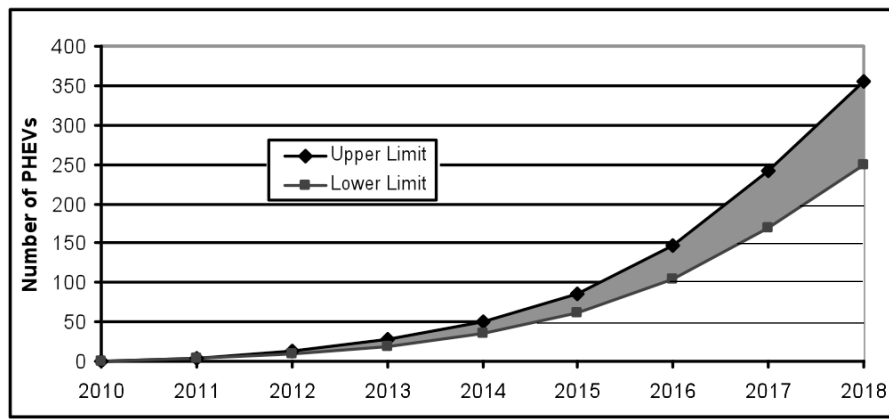


**Figure 19: Upper and Lower Limits on Expected PHEV Penetration
in Census Tract 550250002052**

The most immediate infrastructure impacts are likely to be observed at the distribution transformer level. As the electrical territory served by distribution equipment increases, there is a corresponding increase in the potential to rapidly accumulate customer outage hours following equipment failure. Thus, additional capacity is typically incorporated into the distribution equipment upstream of the transformers. In order to demonstrate the potential impact of PHEVs at the transformer distribution level, a single 50 kVA transformer located in census tract 550250002052 was selected for analysis. The selected transformer was assumed to serve eight households. Actual transformer ratings and numbers of customers served per transformer can differ significantly. The process outlined here can be utilized by

any utility that is interested in a more comprehensive analysis of equipment by modifying the assumed transformer rating and number of customers served. Figure 20 illustrates an upper and lower bound for the number of PHEVs that can be expected on the selected transformer through the year 2018. These numbers were determined by scaling the aggressive and non-aggressive penetration scenarios for census tract 550250002052 by the number of individuals residing in eight households.
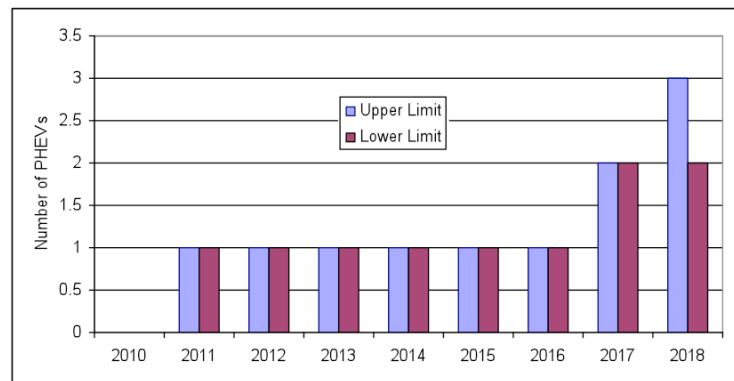


**Figure 20:  PHEV Penetration for a 50 kVA Distribution Transformer Serving Eight Customers**

Assuming that convenience will be the predominate factor in determining consumer charging behavior, the majority of initial PHEV adopters will likely elect to immediately charge their vehicle as they arrive home from work in the evening. Therefore, this assessment of initial penetration impacts assumes that all PHEV owners begin charging their vehicles at 5:00pm. Changes in charging behavior patterns that may result from various demand response program options will be discussed in more detail in the following chapter. The first step in assessing the initial impacts of PHEVs on distribution transformers was to scale the individual load curves presented earlier in this chapter to represent the total transformer load without PHEVs. The non-PHEV transformer load was assumed to remain constant over the

range of years studied; however, this likely underestimates the total transformer load for future years.

Secondly, the hourly power requirements for a single PHEV were multiplied by the total number of vehicles expected to be simultaneously charging from the selected 50 kVA transformer through the year 2018. A comprehensive set of scenarios were considered, including all combinations of the following characteristics:

- Summer and winter seasonal load curves
- Peak transformer loading and typical transformer loading curves
- Predominant installations of Level 1 and Level 2 charging infrastructure
- Aggressive and non-aggressive vehicle penetration models

Finally, the cumulative PHEV power requirements for each year were added to the total transformer load under each combination of the characteristics above, beginning at 5:00pm. An assumed residential power factor of 0.8 was used to calculate the apparent power seen by the selected 50 kVA transformer.

Figures 21 and 22 illustrate the impact that additional PHEV load will have on the selected transformer during peak loading periods assuming aggressive vehicle penetration and Level 1 charging infrastructure. After the cumulative addition of three PHEVs in year 2018, the summer peak transformer loading has increased from 90.7% to 96.5%. The winter peak transformer loading has increased from 28.5% to 39.0%. Under these conditions, the transformer does not become overloaded. However, reducing the transformer rating to 25 kVA causes the summer peak transformer loading to reach 193.0% and the winter peak transformer loading to reach
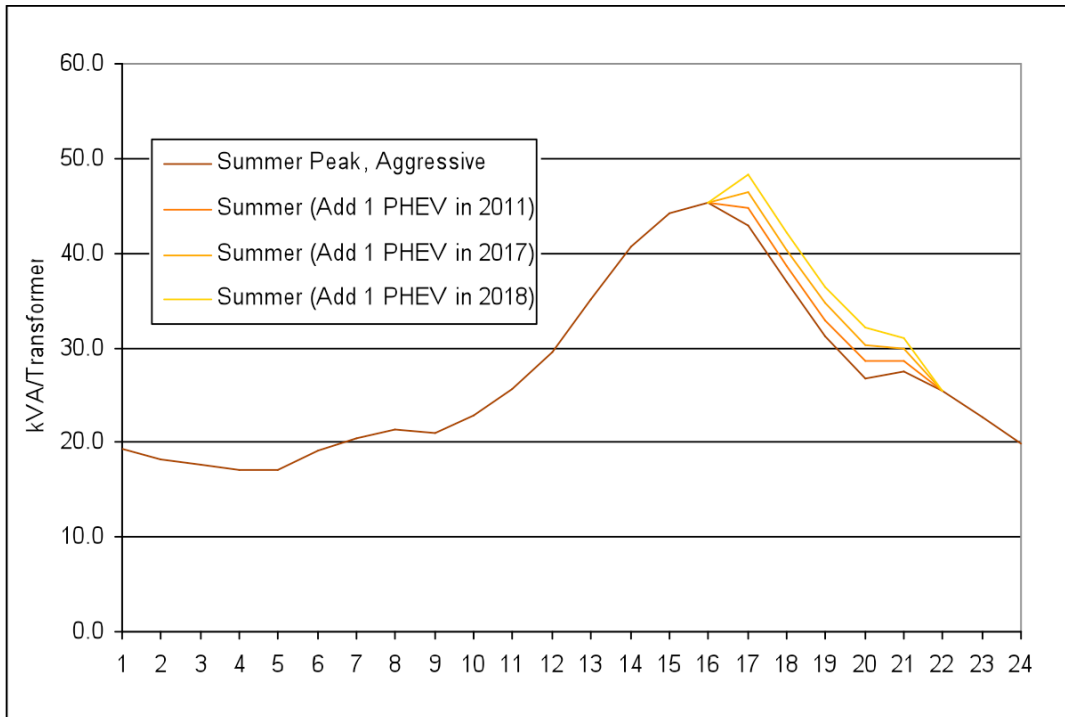
**Figure 21: Impact of Aggressive PHEV Penetration on Peak Summer Transformer Loads Assuming Predominance of Level 1 Charging Infrastructure with Charging Beginning at 5:00pm**
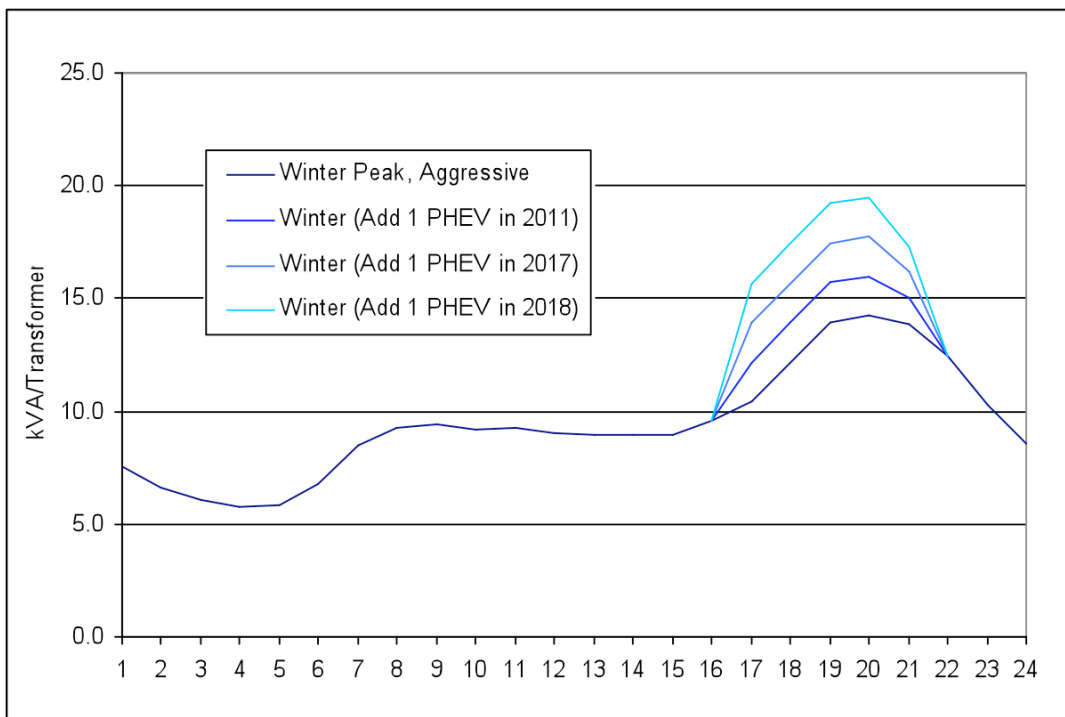


**Figure 22: Impact of Aggressive PHEV Penetration on Peak Winter Transformer Loads Assuming Predominance of Level 1 Charging Infrastructure with Charging Beginning at 5:00pm**

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78.0% by the year 2018. Under a typical transformer loading scenario, a 25 kVA transformer would cause the typical summer transformer loading to reach 96.6% by the year 2018, and the typical winter transformer loading to approach 77.1%. With no change in the number of vehicles added to the selected 50 kVA transformer, an additional two households would cause the summer peak transformer loading to increase from 96.5% to 118.0% by the year 2018. However, these additional households have a smaller impact on winter peak transformer loading, only causing the winter peak transformer loading to increase from 39.0% to 46.1%. Under the non-aggressive PHEV penetration scenario, a single PHEV will be added to the transformer load in 2011 and a second PHEV will be added to the transformer load in 2017. The additional transformer load added in the non-aggressive scenario is equivalent to year 2017 of the aggressive scenario.

The negative impacts on transformers will obviously be increased if Level 2 charging infrastructure becomes the preferred method of vehicle charging. Figures 23 and 24 illustrates the impact that additional PHEV will have on the selected transformer during peak loading periods assuming aggressive vehicle penetration and Level 2 charging infrastructure. In Figure 23, the selected 50 kVA transformer has clearly surpassed its rated value. In fact, after the cumulative addition of three PHEVs in year 2018, the summer peak transformer loading has increased from 90.7% to 131.0%. The summer peak transformer loading is already exceeding 100% after the addition of a single PHEV in the year 2011. Although the winter peak transformer rating does not exceed 100% through the year 2018, it does increase from 28.5% to
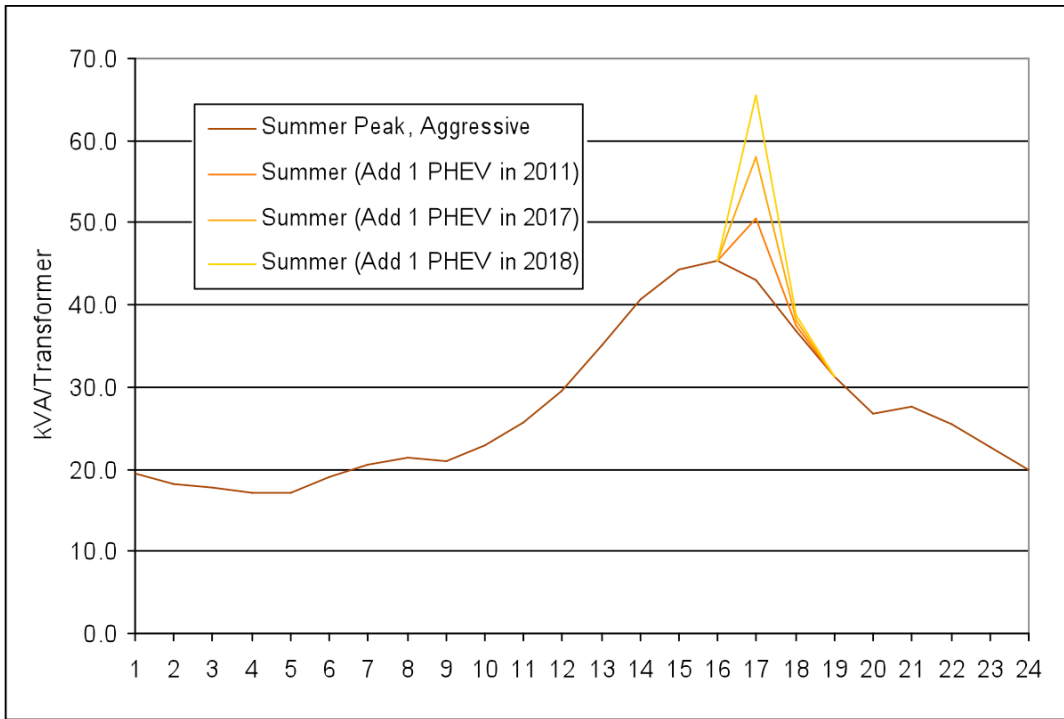
**Figure 23: Impact of Aggressive PHEV Penetration on Peak Summer Transformer Loads Assuming Predominance of Level 2 Charging Infrastructure with Charging Beginning at 5:00pm**
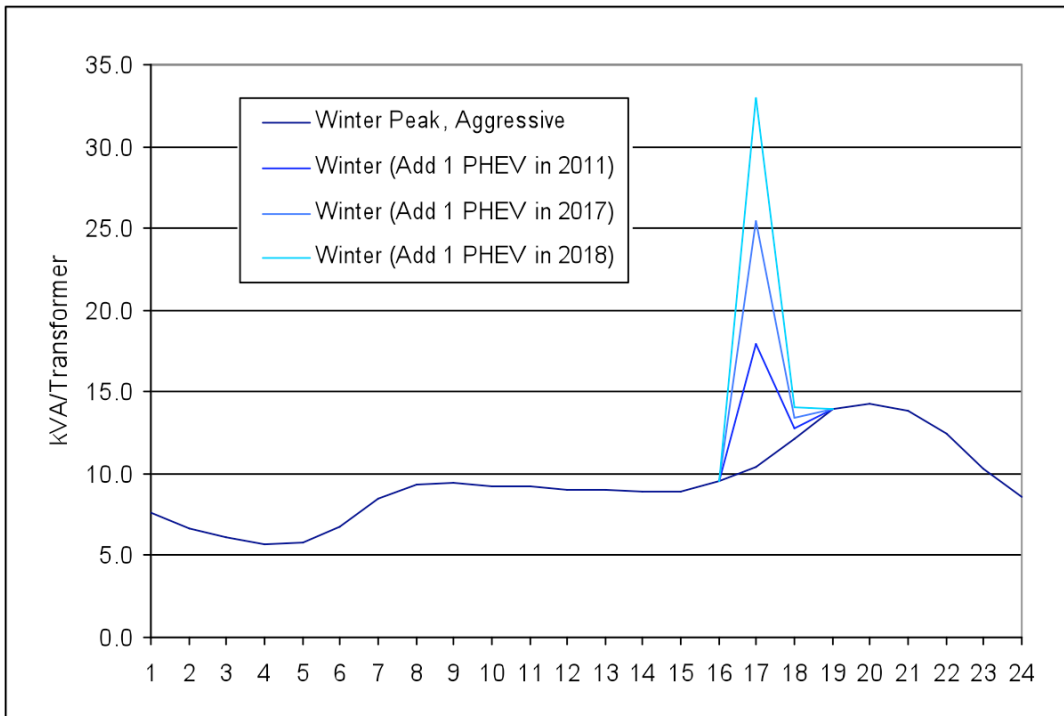


**Figure 24: Impact of Aggressive PHEV Penetration on Peak Winter Transformer Loads Assuming Predominance of Level 2 Charging Infrastructure with Charging Beginning at 5:00pm**

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65.8%. Under the scenario in which Level 2 charging is preferred, the transformer load factor diminishes rapidly as PHEVs are added. Prior to the addition of any PHEV load, the summer typical transformer load factor is 0.70 and the winter typical transformer load factor is 0.64. The values of load factor are 0.35 and 0.31, respectively, following the cumulative addition of three PHEVs in year 2018. In both cases, the values have approximately been cut in half.

With Level 2 charging, the cumulative addition of three PHEVs in the year 2018 results in a typical summer transformer loading of 82.8%, illustrated in Figure 25. For the same amount of PHEV penetration, the typical summer transformer loading was only 48.3% with Level 1 charging infrastructure. Under the same Level 2 charging conditions, the typical winter transformer loading is 65.1%.
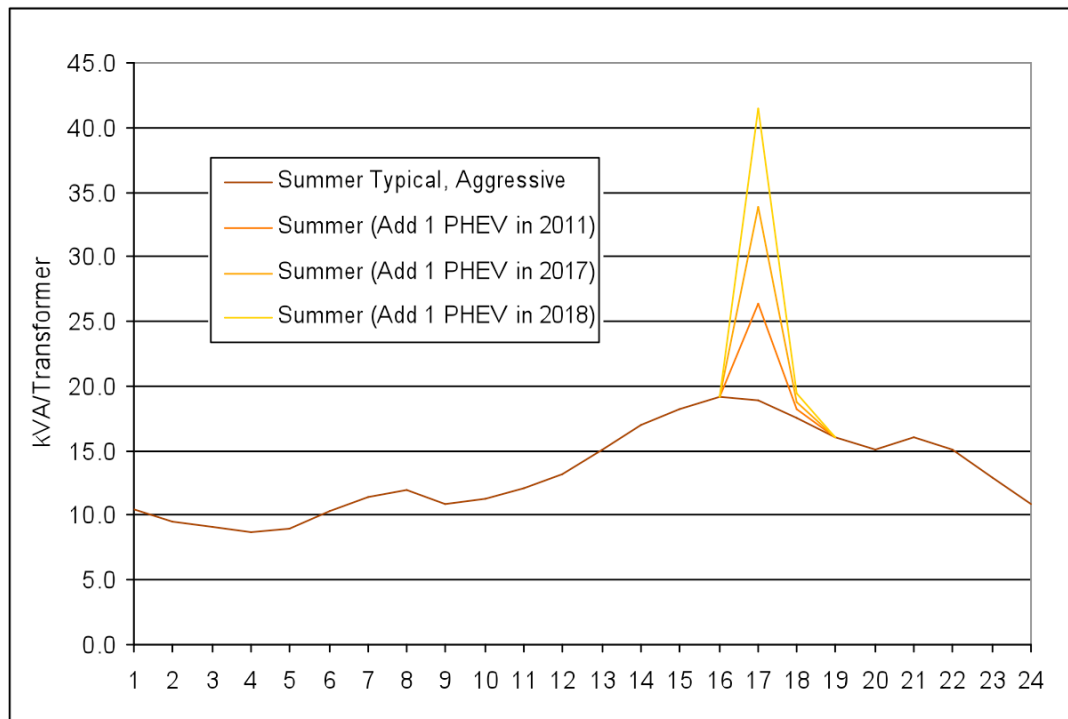


**Figure 25: Impact of Aggressive PHEV Penetration on Typical Summer Transformer Loads Assuming Predominance of Level 2 Charging Infrastructure with Charging Beginning at 5:00pm**

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The typical summer transformer loading on a 25 kVA transformer exceeds 100% of rated load after the addition of a single PHEV in the year 2011. Typical winter transformer loading exceeds 100% of rated load after the cumulative addition of two PHEVs in 2017. With no change in the number of vehicles to the 50 kVA transformer, the addition of two more households causes the summer peak transformer loading to reach 122.5% after the addition of a single PHEV in 2011. However, the addition of these households only increases winter peak transformer loading to 71.0% through the year 2018.

Figure 26 shows the changes in summer peak loading on the selected 50 kVA transformer assuming non-aggressive vehicle penetration and Level 2 charging infrastructure. As apparent in the figure, the cumulative addition of 2 PHEVs in the year 2017 results in a summer peak transformer loading of 116.0%.
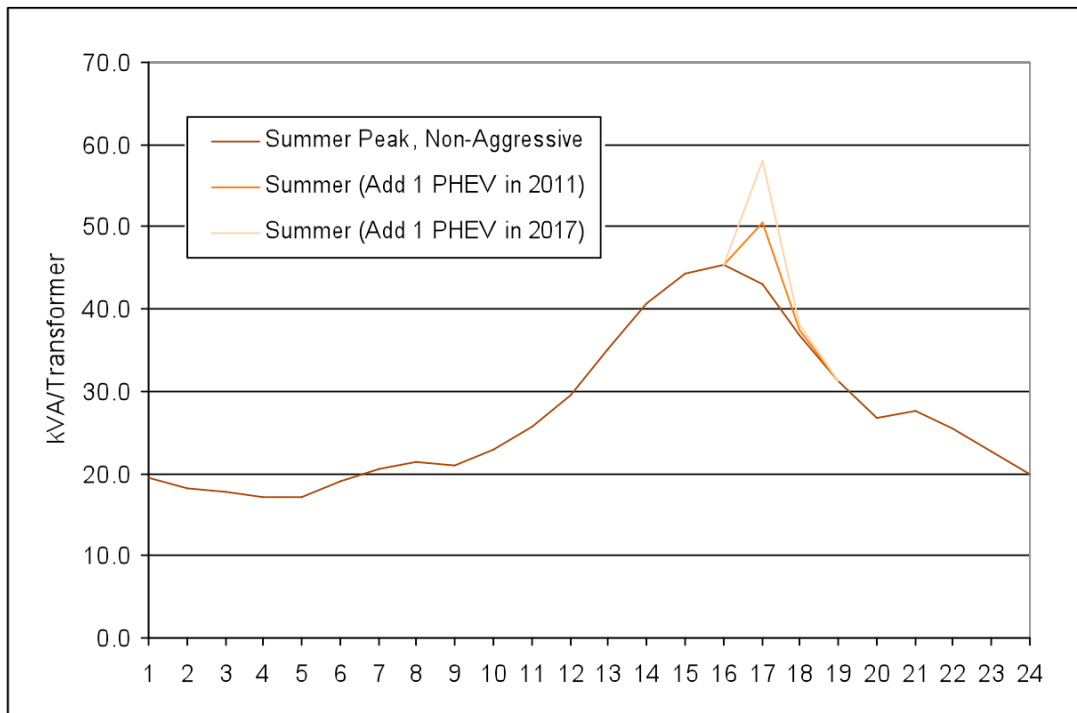


**Figure 26: Impact of Non-Aggressive PHEV Penetration on Peak Summer Transformer Loads Assuming Predominance of Level 2 Charging Infrastructure with Charging Beginning at 5:00pm**

## 5.2 Transmission Infrastructure Impacts

To a certain extent, the initial distribution impacts stemming from PHEV penetration are unavoidable due to the existing technology and policy environment. The automotive industry is outpacing the electric industry in development and implementation of PHEV technologies and policy. The majority of these distribution impacts will be able to be handled on a local level without significantly impacting reliability of the bulk electric system.

Failure of any given distribution transformer will be limited to a handful of houses. Utilities are fairly adept at responding quickly to the failure of these small transformers. However, if the electric industry is unable to devise policy mechanisms to control PHEV charging characteristics, extensive capital investments will be required in order to prevent the transmission system from becoming overly constrained.

### 5.2.1 Extended Plug-In Hybrid Electric Vehicle Adoption Model

Although some PHEV-related transmission constraints will surface prior to the year 2018, it is likely that existing equipment and near-future projects will be sufficient to adequately control most system constraints. In the Dane County area, this is likely to involve additional operation of generators including the Blount Power Plant and the West Campus Cogeneration Facility, potentially out of preferred economic order. Beyond 2018, significant problems requiring major infrastructure upgrades will begin to emerge unless the electric industry successfully implements policy to encourage and facilitate PHEV participation in demand response programs. In order to model the transmission constraints that occur in the years beyond 2018, the PHEV market share under aggressive penetration assumptions was assumed to increase by 1% annually through 2026. Each PHEV was assumed to have a ten-year lifespan. In an aggressive penetration scenario, this results in a PHEV market share of 33% by 2026. Under non-aggressive PHEV penetration assumptions, this results in a PHEV market share of 8.7% by 2026.

Figure 27 shows the extended PHEV penetration assumptions through the year 2026.
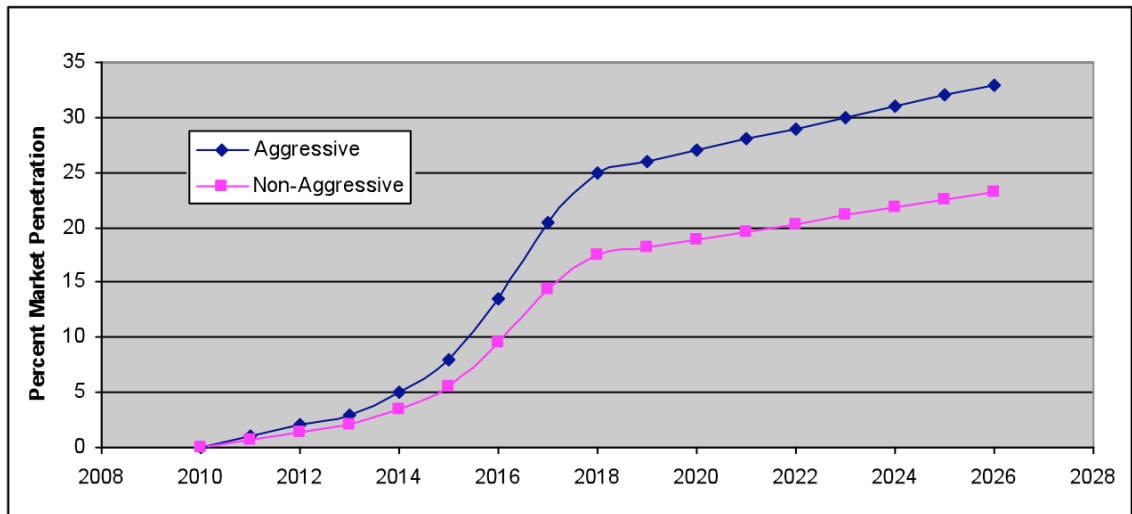


**Figure 27: Percent PHEV Market Penetration Expanded beyond 2018, through 2026**

Figure 28 illustrates the total number of PHEVs that are expected in Dane County per

year through the year 2026 under both aggressive and non-aggressive scenarios.
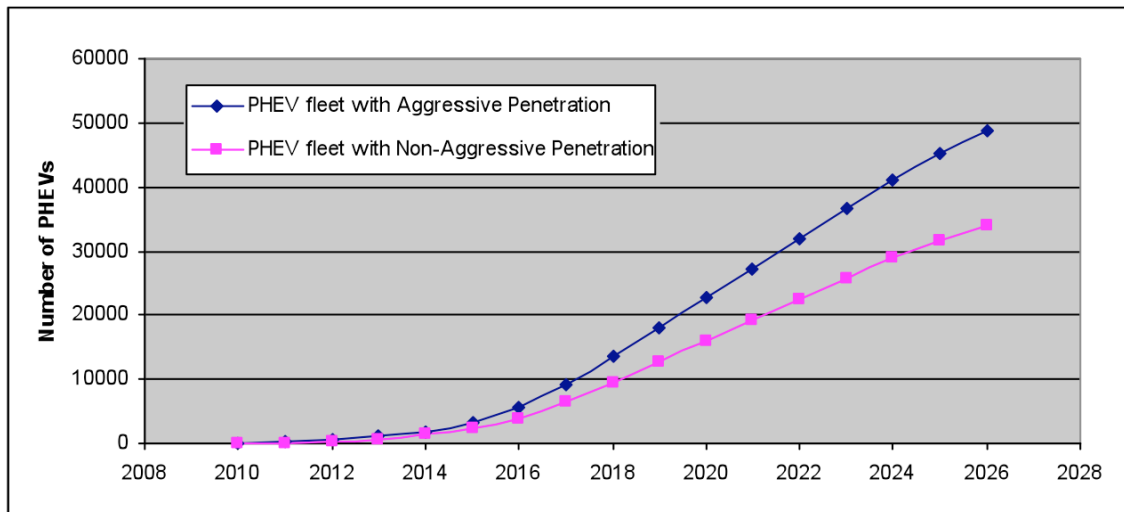


**Figure 28: Dane County Plug-In Hybrid Electric Vehicle Fleet
in Extended Penetration Scenarios**

### 5.2.2 Definition of Basecase Scenario and Modeling Assumptions

A single snapshot derived from the ATC Energy Management System was selected to determine potential PHEV-related transmission impacts. Criteria used to select the powerflow snapshot included an initial Dane County load exceeding 800 MW, absence of online Dane County generation, and system intact conditions in Dane County and the surrounding region. The total Dane County area load was modeled by summing the load at all MGE buses, in addition to all Alliant Energy buses that lie within the region defined by the Dane County interface tie lines, presented in the previous chapter. The initial Dane County load in the selected powerflow snapshot was 806.7 MW. Dane County area generation totals are modeled by summing the generation at all MGE buses. Alliant East has no generation within the region defined by the Dane County interface tie lines.

The voltage stability analysis uses a set of pre-defined transfer scenarios to stress the study model in small increments. Dane County area load and ATC generation (excluding Dane County generation) are both incremented in order to stress Dane County imports. A power flow is then performed at each step to solve the stressed case. Capacitor banks are not switched during this study. Changing the status of capacitor banks within Dane County could potentially allow additional load to be supported in the area. It would also shift the location of the lowest voltage buses. However, the impact of the capacitor banks will be much less than incrementing Dane County generation.

After the power flow has solved for each transfer level, a contingency analysis is performed for a pre-determined set of contingencies. If a contingency is found to cause voltage collapse or thermal overloading over 110%, the simulation is stopped and the results are reported. This process is repeated until a violation is found or the model reaches the set limits of load and generation scaling. The contingency set studied includes all on-line Dane County generators, all Dane County transmission lines greater than or equal to 69-kV, and all double circuit lines that feed the Dane County area. Major generators and transmission lines in the near vicinity of Dane County are also included in the contingency analysis.

Tables 4 and 5 summarize the voltage and thermal limits of the selected powerflow snapshot, respectively. Due to the susceptibility of the Dane County area to voltage instability following the loss of critical double circuit outages, separate studies were performed to monitor single circuit outages and double circuit outages.

**Table 4: Transmissions Peak Basecase Voltage Limits**

|  | Contingency | Pre-Ctg Limit | Load Margin |
|---|---|---|---|
| N-1 | ROE-WPTN 345-kV | 1471.7 MW | 665 MW |
| N-2 | COL-NMA 345-kV dbl ckt | 1016.7 MW | 210 MW |

**Table 5: Transmission Peak Basecase Thermal Limits and Violations**

|  | Contingency | Pre-Ctg Limit | Load Margin | Affected Lines | Percent Overload |
|---|---|---|---|---|---|
| N-1 | BLT-SYC 138-kV | 1191.7 MW | 385 MW | GWY-SYC 69-kV | 110.2% |
| N-2 | COL-NMA 345-kV dbl ckt | 806.7 MW | 0 MW | PTE-COL 69-kV | 134.1% |

The pre-contingent load limit represents the total load that can be supported in the Dane County area without collapsing the voltage or causing thermal overloading of greater than 110% following loss of the specified contingency. The load margin is defined as the additional amount of load that can be supported above and beyond the initial value of Dane County area load. As the load margin decreases, it becomes increasingly important to consider expansion of transmission infrastructure. An alternative to transmission infrastructure expansion is additional operation of Dane County area generation resources. However, this contributes to congestion and prevents appropriate operation of the Midwest ISO's security-constrained economic dispatch model. The affected lines listed in Table 5 are lines that experience thermal overloads following the loss of the specified contingency. Finally, the percent overload represents the overloading that the affected line will experience following loss of the specified contingency.

Figures 29 and 30 summarize the per unit behavior of voltages at the worst-case bus for the N-1 and N-2 basecase analyses, respectively. As shown in Figure 29, post-contingent thermal loading begins to exceed 110% of rated values at a Dane County import level of 1191.7 MW. In the N-1 basecase analysis, Dane County voltage does not approach the point of collapse until Dane County load reaches 1471.7 MW.

For the N-2 basecase analysis presented in Figure 30, post-contingent thermal overloads exist at the initial level of Dane County load. From the figure, it is clear that loss of either double circuit line feeding the Dane County area will cause a significant reduction on the total amount of load that can be supported. With post-

contingent voltage collapse occurring at 1016.7 MW, there is very little margin for additional PHEV load. Moreover, the worst-case Dane County bus voltages drops below 0.9 pu before Dane County imports reach 900 MW. This indicates that system upgrades will be necessary in order to protect Dane County equipment damage in the event of an N-2 contingency.
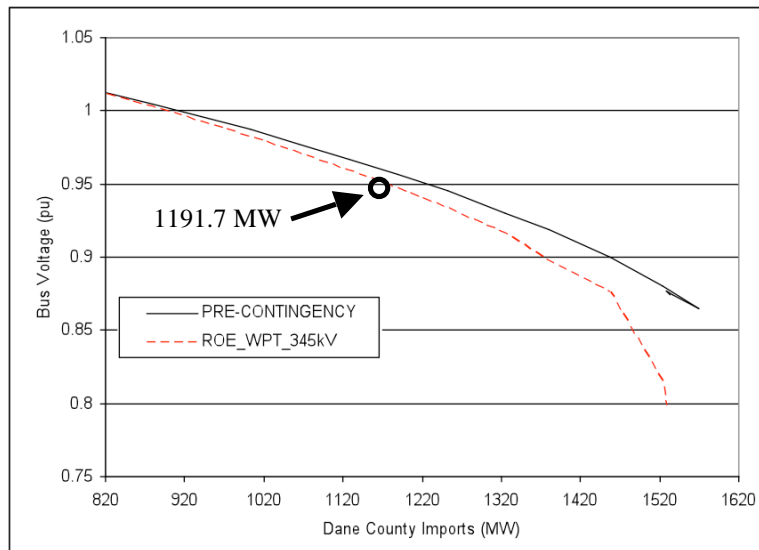


**Figure 29:  Transmission Peak Basecase Power-Voltage Characteristics for Loss of the Single Worst-Case N-1 Contingency**
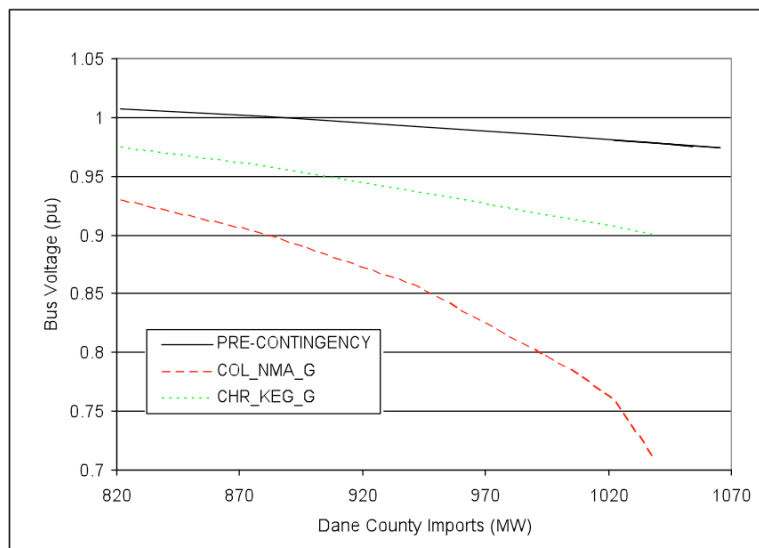


**Figure 30:  Transmission Peak Basecase Power-Voltage Characteristics for Loss of the Two Worst-Case N-2 Contingencies**

### 5.2.3 Voltage and Thermal Violation Analysis

In order to further determine the impact of PHEV penetration on the Dane County area transmission system, additional voltage stability analyses were performed for each of the eight scenarios considered. In lieu of knowledge pertaining to the end-use customer base served by each transmission bus, the percentage of residential load at each bus was used to determine the most probable locations to expect future PHEV load. The percentage of residential load at each pertinent bus is presented in Appendix A. Peak summer load forecasts for the years 2018 and 2026 were obtained from ATC.

These load forecasts were used in conjunction with the residential load percentages to assign actual values of PHEV load to transmission buses under the constraints of each penetration scenario. Table 6 presents the maximum instantaneous PHEV load values that are expected to result from uncontrolled PHEV charging in each of the studied scenarios. Hereafter, each PHEV penetration scenarios will be referred to by the ID number listed in Table 6.

**Table 6: Load Added to the Dane County Transmission System in Each of the Studied Scenarios**

| ID Number | Scenario Summary | PHEV Load |
|:---:|:---|:---:|
| 1 | 2018, Level 1 charging, Non-Aggressive penetration | 13.24 MW |
| 2 | 2018, Level 1 charging, Aggressive penetration | 50.32 MW |
| 3 | 2018, Level 2 charging, Non-Aggressive penetration | 56.75 MW |
| 4 | 2018, Level 2 charging, Aggressive penetration | 215.66 MW |
| 5 | 2026, Level 1 charging, Non-Aggressive penetration | 47.79 MW |
| 6 | 2026, Level 1 charging, Aggressive penetration | 68.10 MW |
| 7 | 2026, Level 2 charging, Non-Aggressive penetration | 204.82 MW |
| 8 | 2026, Level 2 charging, Aggressive penetration | 291.86 MW |

Figure 31 illustrates the N-1 and N-2 load margins calculated by the voltage stability program for each of the eight PHEV penetration scenarios. It also includes the load margins calculated in the N-1 and N-2 basecase analyses. From the previously presented basecase analyses, the N-1 load margin was identified as 665 MW and the N-2 load margin was identified as 210 MW.
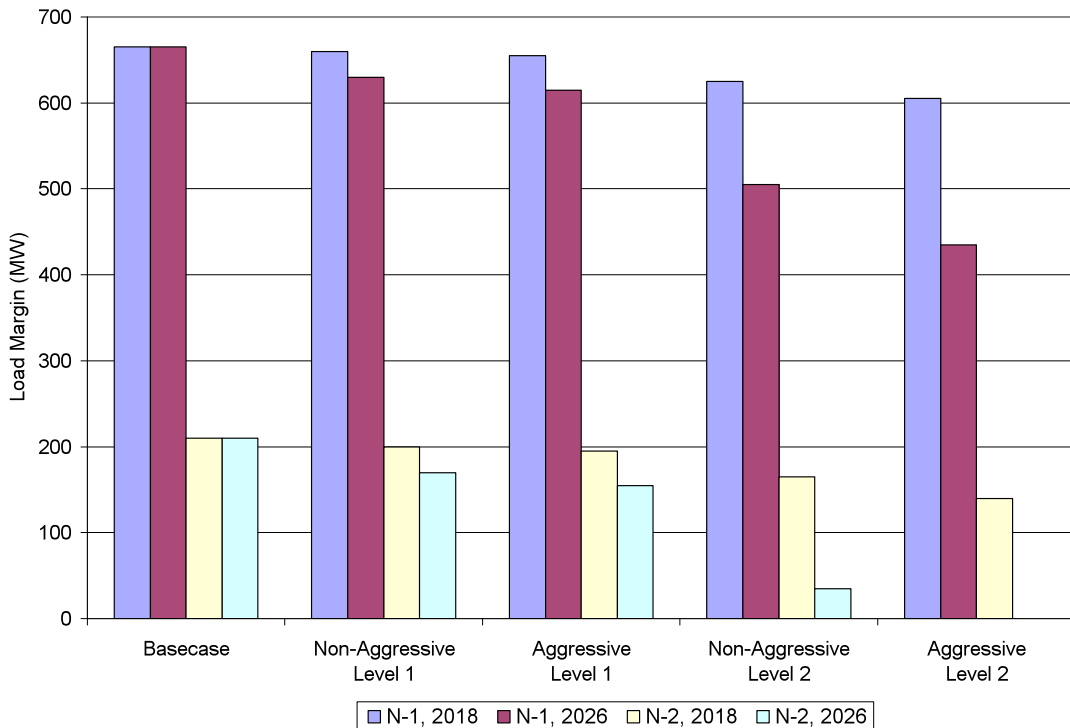


**Figure 31: Calculated Transmission Load Margin Following Addition of Peak PHEV Load**

From the figure, it is clear that the aggressive penetration and Level 2 charging characteristics of scenario 8 cannot be sustained through the year 2026 under N-2 conditions. Under these conditions, the voltage stability analysis program identified pre-contingent violations and was therefore unable to perform the contingency analysis. A considerable reduction in load margin is apparent in year 2026 assuming N-1 conditions and charging characteristics of scenario 8. In scenario 7, less

aggressive penetration still cause dramatic reductions in load margins by the year 2026 under both N-1 and N-2 conditions. Even through year 2018, significant reduction in load margin can be observed in both N-1 and N-2 analyses under scenario 8.

In the Dane County area, voltage violations are typically preceded by certain thermal violations. In fact, the voltage stability assessment identifies thermal overloads in excess of 110% occurring in the N-2 basecase, prior to any additional PHEV load. Emergency line ratings may enable the limited equipment to sustain high currents for short periods of time. Nonetheless, increasing levels of PHEV load adds a number of thermal constraints that must be closely monitored in the Dane County area, particularly under N-2 conditions. The susceptibility of the Dane County area to critical transmission outages precludes tolerance of thermal overloading. If any one of the interface tie lines that feeds Dane County were to unexpectedly fail, other interface tie lines with prior thermal overloads are likely to rapidly follow suit. The resulting damage to equipment will ultimately leave the Dane County area without sufficient import capacity to support the load until the damaged equipment can be replaced.

In the N-2 basecase analysis, the initial areas of thermal loading concern were limited to the 69-kV network just outside Dane County via the double circuit 345-kV lines between the North Madison and Columbia Substations. However, the addition of PHEV load under any of the proposed N-2 scenarios adds another point of concern on the Western Dane County interface tie line between the Spring Green and Arena

Substations. In addition to exacerbating the thermal concerns in Western Dane County, a third area of thermal concern surfaces in the Northwestern corner of Dane County between the Lodi and Dane Substations under N-2 PHEV penetration scenarios 4 and 7. The combination of N-2 conditions and scenario 8 charging characteristics leads to a situations in which voltage collapse precedes any thermal violations. In the N-1 analysis, thermal violations were located in the vicinity of the Sycamore and Fitchburg Power Plants. It is likely that these areas of concern would be electrically and geographically shifted depending on the online generation facilities within the Dane County area.

# 6   Benefits of Increased Demand Response Participation

6.1 **Infrastructure Benefits from PHEV Demand Response Participation**

From the previous Chapter, it is clear that there will need to be significant transmission infrastructure upgrades if an alternative method is not devised to otherwise control the charging of PHEVs. Figure 32 was obtained from a similar PHEV penetration study performed on the 1999 California ISO system [46]. The figure illustrates the changes to total California ISO system load due to evening charging of 1, 5, and 10 million PHEVs.
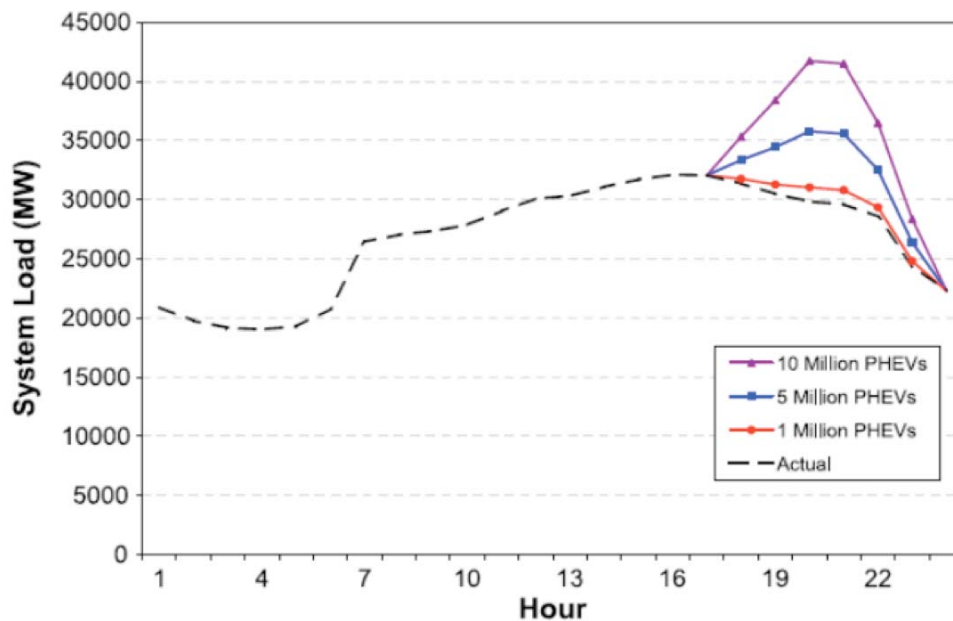


**Figure 32: California ISO System Load as a Function of Time with the Impacts of Uncontrolled PHEV Charging Superimposed**

A preferable scenario would be for PHEV owners to charge their vehicles during periods of low demand. This is sometimes referred to as 'load-leveling.' Transmission and distribution systems must be designed and built to withstand demand during peak loading periods. However, this results in a capacity surplus under normal operating conditions. Any addition

to peak load will likely require additional infrastructure; but large numbers of PHEVs can likely be added during off-peak periods without leading to a need for increased infrastructure. According to typical load curve patterns, the optimal time period during which to charge PHEVs is between the late evening and early morning, corresponding to the lowest system load. Figure 33 shows the impact of this controlled charging on total California ISO system load with the addition of 1, 5, and 10 PHEVs [46]. Controlled charging optimizes the use of existing equipment, thus increasing the overall load factor.
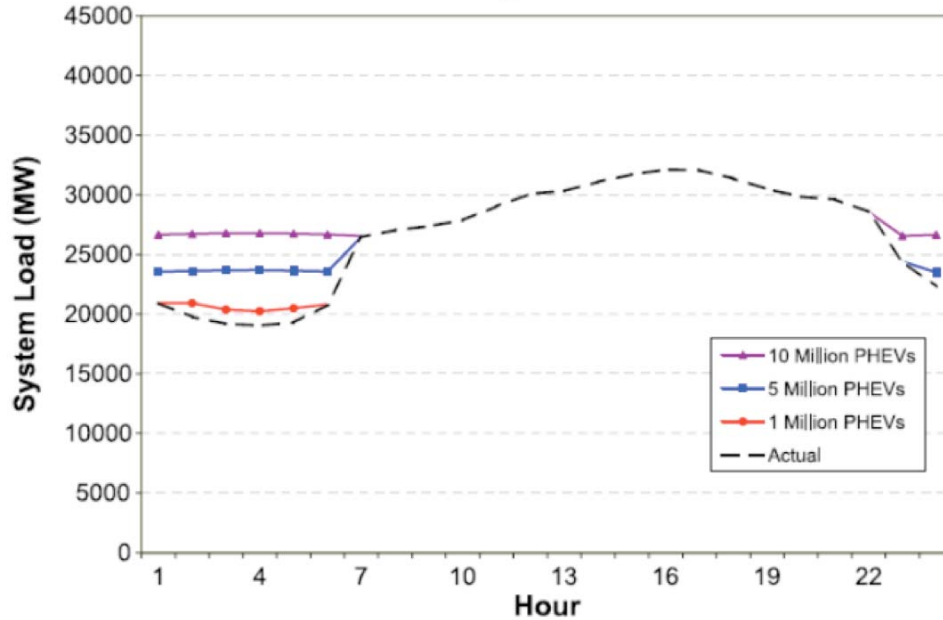


**Figure 33: California ISO System Load as a Function of Time with the Impacts of Controlled PHEV Charging Superimposed**

An important question to answer before PHEVs enter the automotive market is how the electric industry is going to ensure that the second charging scenario occurs. Enabling technologies such as basic timers will be very important. A timer would allow PHEV owners to plug in their vehicle immediately when arriving home from work, but would then postpone charging until a certain time. Without this technology it is likely that most customers would

select convenience over cost and charge immediately when arriving home from work anyways. If not, they might risk forgetting to charge the vehicle at all.

Beyond the enabling technology, certain rate structures could be used to provide an incentive for PHEV owners that take advantage of the enabling technology. Effective means for providing that incentive include time-sensitive pricing schemes such as time-of-use, critical peak pricing, and real-time pricing. Time-of-use pricing divides the day into different blocks of time and charges different unit prices for energy use during different blocks. This pricing strategy typically involves an on-peak and an off-peak price for energy [16]. Many commercial and industrial customers already participate in existing time-of-use pricing programs. Creating a time-of-use rate structure for residential PHEV owners would easily allow them to use timers to optimize energy use. The ability to participate in time-of-use rate structures might additionally encourage residential energy consumers to more carefully consider when they are using energy.

Critical peak pricing involves charging a pre-specified high rate for a pre-specified number of hours throughout the year. The hours are selected based on periods of high wholesale market prices or system events that impact reliability [16]. This pricing scheme is also widely used for commercial and industrial customers. However, opening this type of rate to residential customers would likely prove to be difficult. The regular pricing pattern that is known well in advance associated with time-of-use pricing would be much more convenient for residential customers. It would be very easy for a residential customer to forget that a critical peak period had been declared and then be upset by the corresponding increase in that month's electricity bill. Real-time pricing schemes allow the price of electricity to fluctuate

on a day-ahead or hour-ahead basis in order to reflect the wholesale price of electricity [16]. Similar to critical peak pricing, this pricing scheme places much of the burden on the individual residential customers.

Among these three time-sensitive pricing options, time-of-use pricing appears to place the smallest burden on the residential customer. As such, it is likely to receive the least amount of criticism from participants. Ideally, PHEV owners would be automatically enrolled in time-of-use programs due to the high potential that they have to contribute to equipment peaks. Other customers could choose to continue with their regular pricing scheme or switch over to the time-of-use pricing scheme. Many customers could likely save money on their monthly bill by switching over to the time-of-use pricing scheme and keeping a careful watch on when they use electricity. In the telecommunications industry, most companies provide free minutes to customers at night in order to reduce the number of calls made during peak hours. A time-of-use pricing scheme for electricity would be similar.

It is also possible that some early PHEV adopters will elect to participate in demand response programs. Based on the existing infrastructure, the most likely programs that will be available to PHEV owners will be direct load controlled programs. Many residential customers are currently participating in direct load control programs with air conditioners and water heaters. It would be a relatively simple matter to add PHEVs, however, more advanced forms of demand response participation by PHEV would likely take more time to introduce.

### 6.1.1 Distribution Infrastructure Benefits

Using the same assumptions for transformer loading and PHEV penetration presented in Chapter 5, a second distribution infrastructure impacts analysis was performed assuming controlled charging of PHEVs. Following the process outlined in Chapter 5, a single representative household load curve was scaled by the eight households expected to be fed by a single 50 kVA transformer. Representative data was obtained for peak summer transformer loading, peak winter transformer loading, typical summer transformer loading, and typical winter transformer loading. This non-PHEV transformer load was assumed to remain constant over the studied timeframe. Next, the total power requirement for a single PHEV was multiplied by the number of vehicles expected to be simultaneously charging from a 50 kVA transformer through year 2018, under both aggressive and non-aggressive PHEV penetration scenarios. Lastly, the cumulative PHEV power requirements for each year through 2018 were added to each of the representative transformer load curves. In order to simulate controlled charging characteristics, no PHEV charging was allowed to occur prior to 11:00pm. Between 11:00pm and 7:00am, the charging rate was fluctuated in an attempt to maintain a consistent level of transformer load, subject to the constraints of Level 1 and Level 2 charging infrastructure.

Figure 34 illustrates the impact that additional PHEV load will have on peak loading of a single 50 kVA transformer during off-peak loading periods, assuming aggressive vehicle penetration and Level 1 infrastructure. Even after the cumulative addition of three PHEVs in the year 2018, no additional peak load has been added to the

transformer. Summer and winter peak transformer loading remain constant at 91% and 28% respectively. However, the peak summer load factor of the transformer has improved from 0.60 in year 2010 to 0.62 in year 2018. This improvement is accentuated for the peak winter load factor, increasing from 0.66 in year 2010 to 0.71 in year 2018. The changes in transformer loading that result from replacing Level 1 infrastructure with Level 2 infrastructure are essentially negligible. The differences between Figures 34 and 35 are indicative of replacing Level 1 infrastructure with Level 2 infrastructure, assuming controlled PHEV charging. This is strikingly different from the significant impacts observed due to charging infrastructure in the uncontrolled PHEV charging analysis.
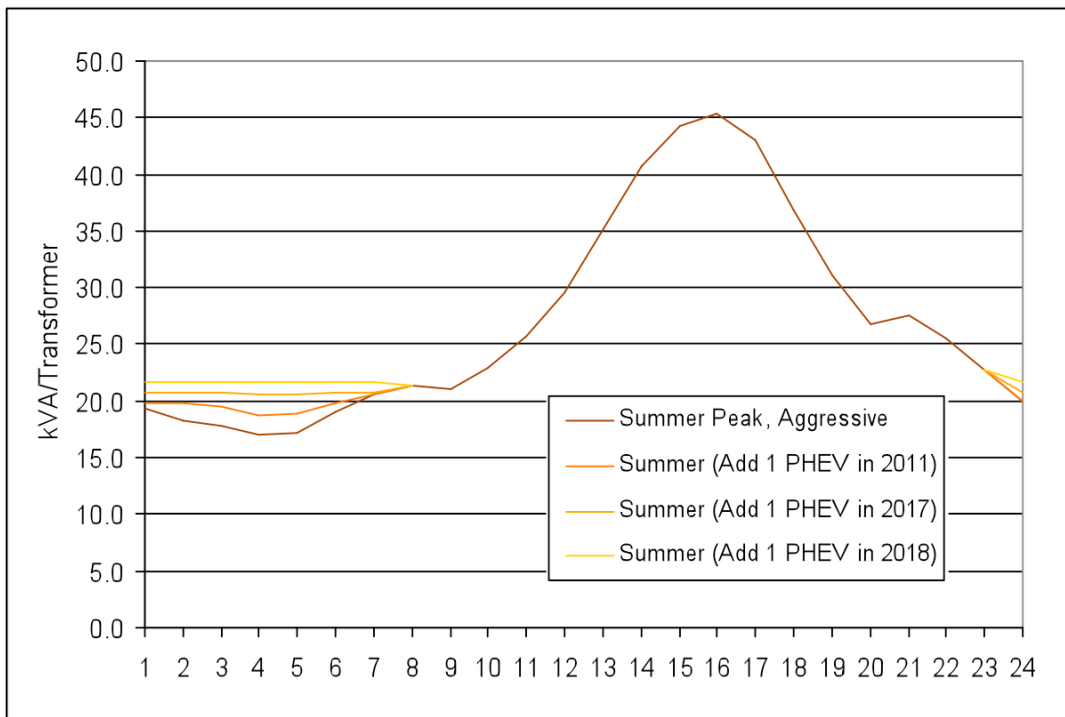


**Figure 34: Impact of Aggressive PHEV Penetration on Peak Summer Transformer Loads Assuming Level 1 Charging Infrastructure with Controlled Charging between 11pm and 7am**
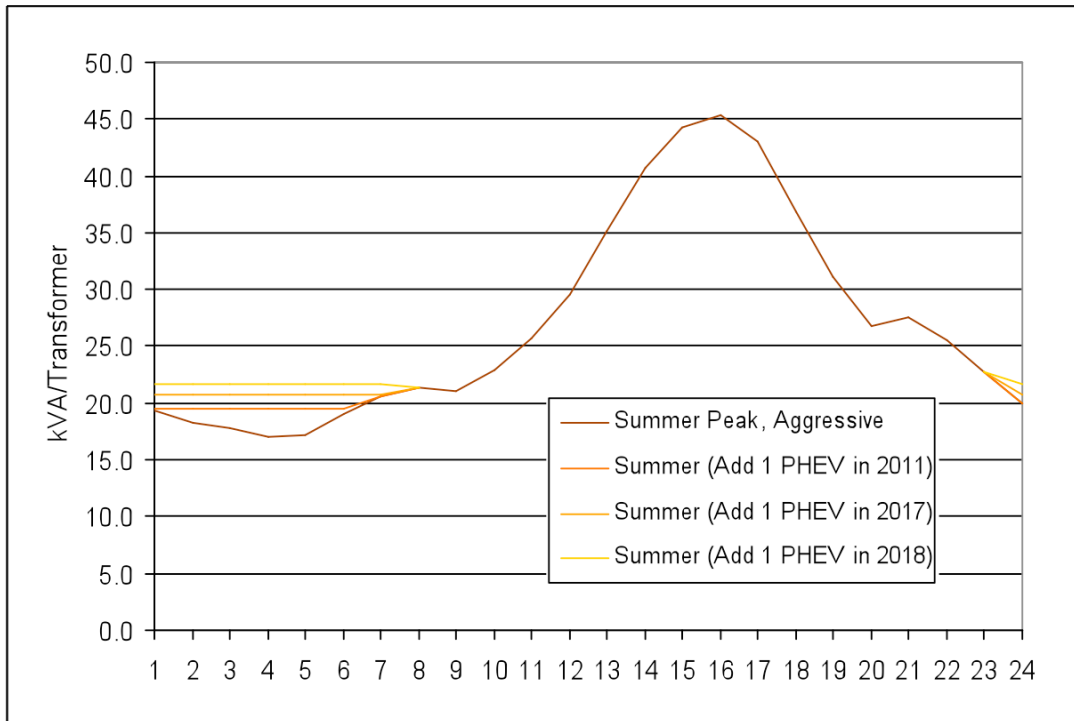
**Figure 35:  Impact of Aggressive PHEV Penetration on Peak Summer Transformer Loads Assuming Level 2 Charging Infrastructure with Controlled Charging Between 11pm and 7am**

Although the peak transformer demand is significantly reduced in typical transformer load curves, the cumulative addition of three PHEVs in year 2018 does not cause any increase in peak load.

Figure 36 illustrates the impact that additional PHEV load will have on typical loading of a single 50 kVA transformer during off-peak loading periods, assuming aggressive vehicle penetration and Level 1 infrastructure. Summer and winter typical transformer loading remain constant at 38% and 28%, respectively. With the cumulative addition of three PHEVs in year 2026, the typical summer load factor improves from an initial value of 0.70 to 0.75 and the typical winter load factor improves from an initial value of 0.64 to 0.71.
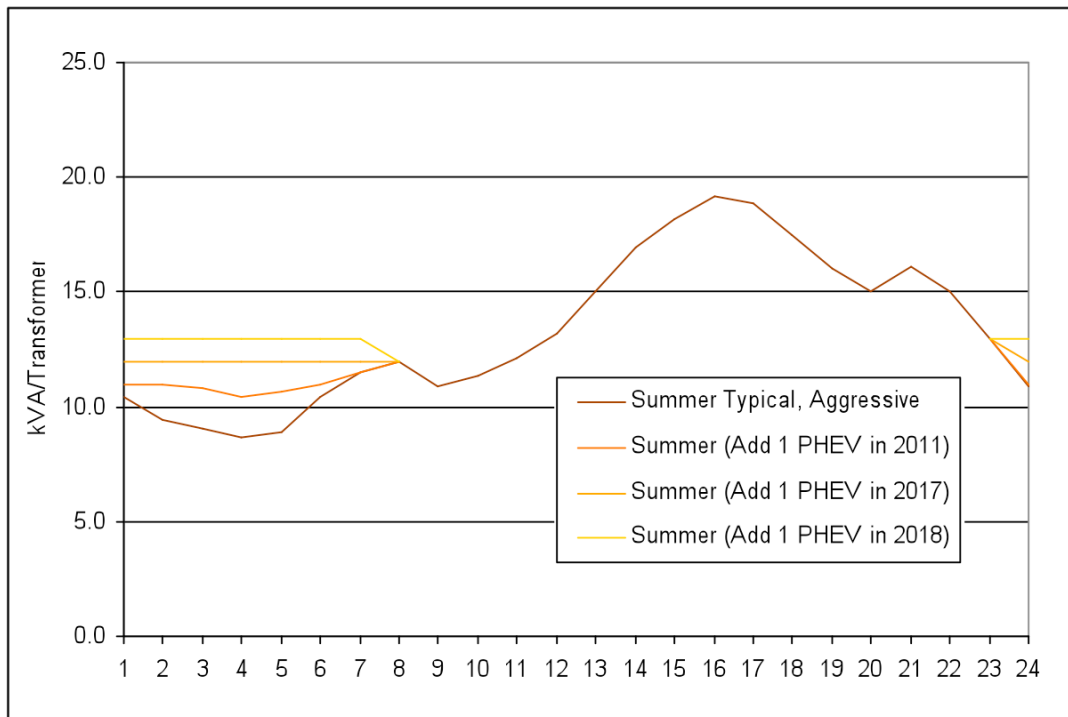


**Figure 36: Impact of Aggressive PHEV Penetration on Typical Summer Transformer Loads Assuming Level 1 Charging Infrastructure with Controlled Charging Between 11pm and 7am**

The improvements in load factor observed in the controlled charging analysis indicate increased utilization of existing distribution equipment. However, increasing transformer loading during off-peak hours will significantly diminish the amount of

cooling time that inherently exists for electric equipment due to typical energy consumer behavior. An increasing average operating temperature has the potential to ultimately reduce the longevity of equipment. However, much higher levels of PHEV penetration will be needed before equipment failure due to insufficient cooling period becomes an area of significant concern. Equipment failure due to increased peak loading of transformers is an area of much more immediate concern.

### 6.1.2    Transmission Infrastructure Benefits

A second transmission infrastructure impacts analysis was performed assuming all PHEV charging occurs during off-peak hours through the year 2026. The off-peak ATC Energy Management System snapshot was selected as the lowest Dane County load occurring between 11:00pm and 7:00am immediately following the selected peak snapshot that was used in the transmission analysis presented in Chapter 5. No significant changes in system configuration or generation dispatch occurred in the Dane County area during the period between the two snapshots. The initial Dane County load in the selected off-peak powerflow snapshot was 484.6 MW.

Using the same voltage stability analysis process described in Chapter 5, the N-1 and N-2 load margins were determined for each of the eight PHEV penetration scenarios presented in Table 6 (available in Chapter 5). Although ideal controlled charging will prevent the aggregate instantaneous PHEV demand from reaching the 1.4 MW and 6.0 MW maximums, these values will be used in this analysis as upper bounds based on charging infrastructure capabilities.

Tables 7 and 8 summarize the voltage and thermal limits of the selected off-peak powerflow snapshot, respectively. The N-1 basecase voltage stability load margin and the N-1 basecase thermal load margin have increased by 40.6% and 32.5%, respectively. More significantly, the N-2 basecase voltage stability load margin has more than doubled from 210 MW to 520 MW, an increase of 147.6%. In the peak Dane County load analysis presented in Chapter 5, N-2 basecase thermal violations occurred at the initial value of Dane County load resulting in an N-2 basecase thermal load margin of 0 MW. However, there is an N-2 basecase thermal load margin of 285 MW in the off-peak Dane County load analysis.

**Table 7: Transmission Off-Peak Basecase Voltage Limits**

|  | Contingency | Pre-Ctg Limit | Load Margin |
|---|---|---|---|
| N-1 | ROE-WPTN 345-kV | 1419.6 MW | 935 MW |
| N-2 | COL-NMA 345-kV dbl ckt | 1004.6 MW | 520 MW |

**Table 8: Transmission Off-Peak Basecase Thermal Limits and Violations**

|  | Contingency | Pre-Ctg Limit | Load Margin | Affected Lines | Percent Overload |
|---|---|---|---|---|---|
| N-1 | BLT-SYC 138-kV | 994.6 MW | 510 MW | GWY-SYC 69-kV | 110.0% |
| N-2 | COL-NMA 345-kV dbl ckt | 769.6 MW | 285 MW | PTE-COL 69-kV | 110.9% |

Figure 37 illustrates the N-1 and N-2 load margins calculated by the voltage stability program for each of the eight PHEV penetration scenarios shown in Table 6, assuming that PHEVs are charged off-peak. It also includes the load margins calculated in the N-1 and N-2 basecase analyses. Although there are still readily

apparent reductions in load margin as the amount of additional PHEV load increases, the lowest values are still greater than the basecase values of load margin identified in Figure 31.
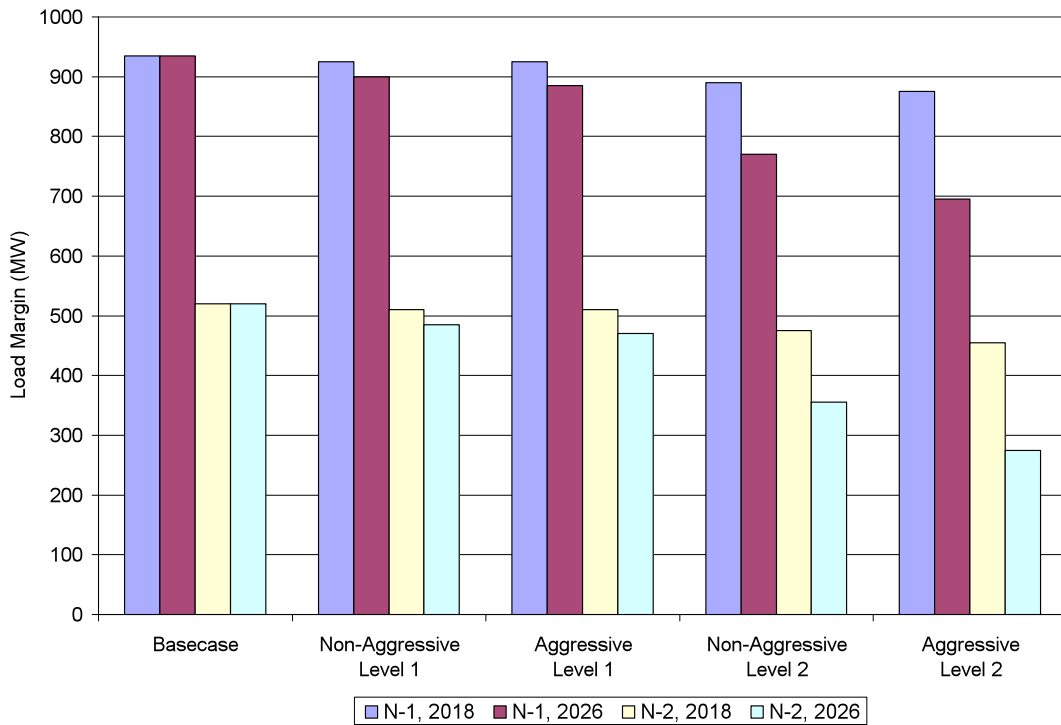


**Figure 37: Calculated Transmission Load Margin Following Addition Off-Peak of PHEV Load**

When PHEV load is added to off-peak Dane County area load, thermal overloads in excess of 110% do not occur at initial aggregate load levels in any of the eight PHEV penetration scenarios.  As post-contingent thermal loading limits are reached, N-2 thermal overloads are contained to the 69-kV network just outside Dane County via the double circuit 345-kV line between the North Madison and Columbia Substations.  N-1 thermal overloads are contained to the area immediately surrounding the Sycamore Power Plant.  Small changes to system configuration, such as operation of

Dane County capacitor banks, would likely mitigate thermal concerns until higher load levels.

## 6.2 **Existing Demand Response Programs Conducive to PHEV Participation**

This section describes the demand response options currently available to MGE residential customers. MGE then reserves these resources for use during local system emergencies or chooses to bid these resources into the Midwest ISO markets for system-wide economic and reliability use [47]. Based on the capabilities of the demand response resources, there are a number of different methods for MGE to participate in the Midwest ISO markets. However, in order for this system to work satisfactorily, MGE must select appropriate market bids to receive cost recovery for their aggregate resources.

MGE currently offers a direct load control program and a time-of-use metering program to residential customers. Participants in the direct load control program agree to allow MGE to remotely shut off air conditioners and/or water heaters when emergency power is needed. MGE periodically performs tests at different ambient temperatures in order to determine the actual achievable load reduction. This ensures that MGE is capable of accurately accounting for the capabilities of this resource in reliability calculations and/or bids submitted to the Midwest ISO markets [47]. Participants are compensated $8 per hour of interruption and can expect to be interrupted six hours over a ten-year period. The expected return for a single month's participation in the direct load control program is $0.40.

Individuals who participate in the time-of-use metering program pay a premium for electricity service during peak hours, but receive a significant rate reduction on electricity

service during off-peak hours. Peak hours are defined between 10am and 9pm on weekdays. Off-peak hours include weekends and weekdays between 9pm and 10am. Advanced metering infrastructure is required for individuals to participate in the time-of-use metering program. However, MGE has recently received stimulus grant money to install a network of 1,750 smart meters [48]. The installation of these meters will significantly increase the number of customers that are capable of participating in time-of-use metering programs.

Provided that certain metering requirements are met, MGE is able to bid these demand response resources into the Midwest ISO markets as Emergency Demand Response Resources (EDR), Type I Demand Response Resource (DRR-I), Type II Demand Response Resources (DRR-II), or Load Modifying Resources (LMR). At this time, MGE does not have any demand response resources that are capable of meeting the requirements for participation as DRR-I or DRR-II. It is possible that increasing penetration of advanced metering infrastructure and increased participation in demand response programs will ultimately MGE to bid DRR-I and DRR-II into the Midwest ISO markets [49].

EDR provide voluntary load reduction in response to price signals. During an energy emergency alert level 2 or 3, emergency demand response resources with offers below the locational marginal price are called on to reduce their demand. There are no penalties for failing to reduce demand; however, no compensation is received if the specified amount of load reduction is not achieved [49].

DRR-I are capable of supplying a specific quantity of energy to the market through physical load interruption. Generally, this means that the load is either on or off, with little to no controllable range. These resources can provide energy and reserve to the Midwest ISO

markets. They may also be designated as capacity resources, provided that they are able to meet the requirements listed in the tariff. Typically, DRR-I require significant notification time before being able to reduce load and are therefore less responsive to prices than DRR-II [49]. DRR-II are capable of supplying dispatchable energy to the market through behind-the-meter generation or controllable load. Unlike DRR-II, these resources are able to provide varying amounts of load reduction depending on the need. This enables DRR-II to provide regulation services, in addition to energy and reserve. If a DRR-II plans to offer regulation services into the market, there are additional metering requirements that it must meet. DRR-II are also able to meet capacity requirements. Typically, DRR-II are capable of responding quicker than DRR-I, and are thus more price responsive [49]. If DRR-I or DRR-II fail to respond after submitting bids into the Midwest ISO markets, they must pay the difference between the day-ahead and real-time locational marginal prices. Resources that reduce load by too much or too little may also be subject to excessive and deficient charges [49].

LMR provide capacity, and are thus the last resort during energy emergencies before firm load shed. These resources must meet the requirements listed in the Midwest ISO tariff to serve as capacity resources. Each LMR must meet its state's requirements in addition to being verified and accredited by the Midwest ISO. If an LMR fails to reduce demand by the required amount when called upon there are significant penalties up to and including decertification of that resource from serving as an LMR in the future [49].

6.3 **Benefits Accrued by Participants in Existing Demand Response Programs**

MGE offers a direct load control program and a time-of-use (TOU) rate program to residential customers within their service territory. Although the incentives to participate in

the critical peak pricing program are relatively high, lack of utilization reduces the actual expected return for participants. As described in Chapter 4, participants in MGE's critical peak pricing program only have an expected return of $0.40 per month [38]. Increased utilization of participating resources will result in higher expected returns, thus encouraging additional participation. However, at this point it is very difficult for MGE to financially justify increased use of these resources due to the difficulty of achieving cost recovery. As the Midwest ISO markets mature and evolve, MGE will likely be able to gradually increase utilization of the critical peak pricing program as they become more proficient at optimizing market bids.

TOU programs enable energy customers to sacrifice a certain degree of convenience in return for reduced monthly electricity bills [38]. As shown in Figure 9, a typical Midwestern household would likely be able to save a small amount of money on monthly electricity bills by switching to TOU rates. However, the savings are nearly negligible, particularly when coupled with the potential for unexpected peak electricity usage to result in exorbitant bills. Certain behavioral changes can be used to shift additional load off-peak, thus increasing the potential for savings.

**Table 9:  Typical Household Monthly Electricity Bills in Madison Gas and Electric's Service Territory**

|  | Standard Meter Summer | Time-of-Use Meter Summer | Standard Meter Winter | Time-of-Use Meter Winter |
|---|---|---|---|---|
| Monthly Usage | 1005 kWh | 1005 kWh | 665 kWh | 665 kWh |
| Monthly Bill | $139.42 | $136.04 | $85.01 | $80.95 |

PHEV charging load will significantly increase the monthly electricity consumption for a typical household. A PHEV20 owner that participates in a standard rate structure and travels an average of thirty miles per day will pay an additional $11.81 per month for vehicle charging. PHEV owners that charge their vehicles during peak hours after electing to participation in a TOU rate structure will pay $20.84 per month to charge the same vehicle. This is equivalent to a 76.5% increase over the price of charging the vehicle assuming standard electricity rates. Clearly, if unable to ensure that vehicles are charged during off-peak hours, it would be uneconomical for PHEV owners to participate in TOU programs. However, if controlled charging techniques are used to ensure that the vehicles are only charged during off-peak hours, the cost of charging the vehicle on a TOU rate structure drops to $5.71, or a reduction of 51.7% from the standard electricity rate.

Although there are clearly inherent cost savings, the current on-peak and off-peak prices in MGE's TOU programs are not necessarily designed to encourage PHEV participation. As shown previously in this chapter, controlled vehicle charging will enable the existing electric infrastructure to support expected numbers of PHEVs through year 2026. Thus, MGE will likely need to review the existing incentives, and potentially make changes and/or additions in order to most effectively control PHEV charging behavior. It is possible that some incentives will be governmentally-funded in an effort to successfully meet the PHEV penetrations goals set by the Obama administration. In order to determine the financial incentives necessary to entice PHEV owners to participate in TOU programs, the life-time fuel savings of a single vehicle will be compared to the purchase premium associated with PHEVs. The analysis will be conducted by calculating simple payback periods for various future policy options. In addition to a business-as-usual scenario in which no changes are made to the existing TOU program, this analysis will consider the impact of an additional upfront rebate following purchase of an electric vehicle and the impact of an additional reduction in off-peak electricity prices for the charging of PHEVs.

In order to determine the life-time fuel savings accrued by PHEVS, the amount of electricity required to charge each vehicle must be calculated. The amount of electricity required to charge a given PHEV is dependent on battery-size; and is thus a direct function of the number of all-electric miles that the vehicle can travel on a single charge [30]. The numbers shown previously assume that the vehicle can travel twenty electric miles prior to switching on the internal combustion engine.

Table 10 presents monthly cost data for charging a single PHEV in the summer if participating in standard electric rates, TOU electric rates with peak charging, and TOU electric rates with off-peak charging [50]. The cost data in Table 10 is presented for vehicles that are capable of traveling twenty, forty, and sixty all-electric miles. The electricity required to charge PHEVs is also a function of total miles driven per day. The data in Table 10 assumes thirty miles of driving per day. According to the 1995 National Personal Transportation Study approximately 50% of the population travels fewer than thirty miles per day [30].

**Table 10: Monthly Cost to Charge PHEVXX (Assumes Thirty Miles of Travel/Day)**

|  | PHEV20 | PHEV40 | PHEV60 |
|---|---|---|---|
| Energy Needs | 88.1 kWh | 152.6 kWh | 165.9 kWh |
| Elec. Consump. | 0.09 kWh/mi | 0.15 kWh/mi | 0.19 kWh/mi |
| Standard Meter | $12.22 | $21.18 | $23.01 |
| On-Peak Charging | $21.55 | $37.36 | $40.59 |
| Off-Peak Charging | $5.91 | $10.24 | $11.13 |

In addition to electricity, PHEVs require gasoline to operate. Thus, the total refueling expense for any given PHEV is the sum of electricity cost and gasoline cost. Table 11 describes the gasoline efficiency assumptions made in this analysis [50].

**Table 11: Gasoline Consumption Assumptions (Assumes Thirty Miles of Travel/Day)**

|  | CV | HEV | PHEV20 | PHEV40 | PHEV60 |
|---|---|---|---|---|---|
| Gasoline Consump. | 0.04 gal/mi | 0.03 gal/mi | 0.02 gal/mi | 0.02 gal/mi | 0.02 gal/mi |

Crude oil prices have been fairly unpredictable over the past few decades [51]. For this reason, a range of possible scenarios will be presented including low, medium, and high expected prices per gallon of gasoline. The price per gallon in each of these scenarios is $2.00, $4.00, and $6.00, respectively. After calculating the fuel expenses for an equivalently-sized internal combustion engine vehicle, the sum of monthly electricity costs and monthly gasoline costs can be scaled to determine the total life-time fuel savings expected for different PHEVs in different scenarios. As described earlier, it will be uneconomical for PHEV owners to participate in TOU programs and charge their vehicles during peak hours. Thus, no payback period will be calculated for this future scenario. Table 12 presents the assumed price for each vehicle included in the study [50].

**Table 12: Assumed Electric Vehicle Purchase Prices**

|  | CV | HEV | PHEV20 | PHEV40 | PHEV60 |
|---|---|---|---|---|---|
| Purchase price | $23,392 | $26,658 | $31,828 | $34,839 | $36,681 |

The color and shading convention defined in Figure 38 below is used throughout the remainder of this section to differentiate between the scenarios of interest.
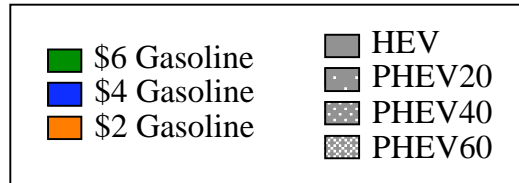


**Figure 38: Legend for Following Figures**

Figure 39 illustrates the number of years required to recoup the purchase premium of an electric vehicles for the range of scenarios studied. It assumes that no policy measures are enacted to encourage PHEV adoption of TOU program participation by PHEV owners. Assuming that gasoline prices reach or exceed $6 per gallon, the lifetime fuel savings of all vehicles included in this analysis would exceed the purchase premium of each respective vehicle. However, with gasoline prices in the vicinity of $4 per gallon, the only electric vehicle with a payback period of less than ten years is the HEV. With gasoline prices at or below $2 per gallon, none of the electric vehicles have payback periods of less than ten years.
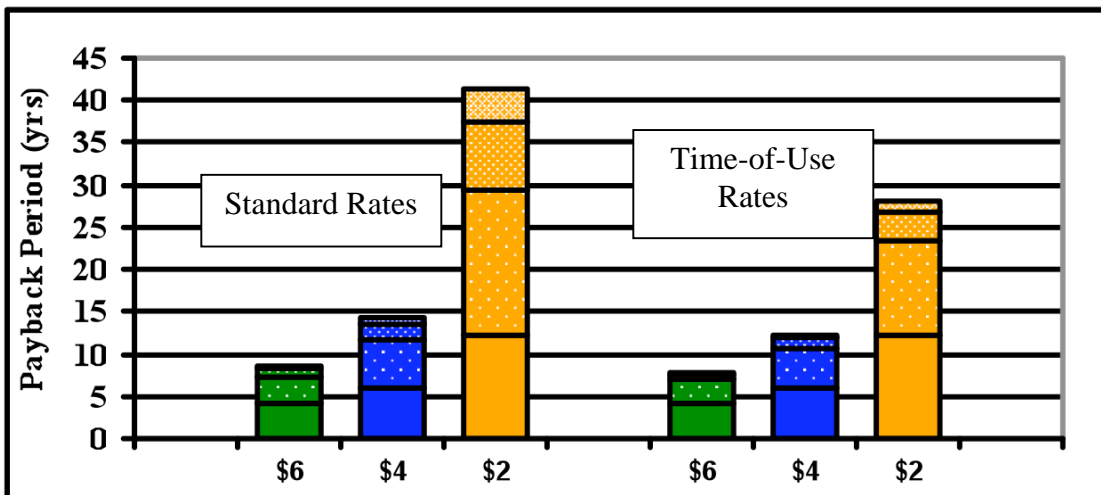


**Figure 39: Years to Repay Purchase Premium of HEV/PHEV over CV with no Additional Rebates or Incentives for Standard and TOU Rates**

Although it will be impossible for PHEV owners to recoup the entire purchase premium of PHEVs unless gas prices reach $6 per gallon, Figure 39 does indicate that PHEV owners who participate in TOU programs will pay significantly less than PHEV owners who choose to remain on the standard rate structure. This reduction in total refueling costs is more pronounced at lower gasoline prices.

## 6.4 **Incentives Necessary to Encourage Demand Response Participation**

In order to quantify the impact of possible future PHEV policy on the payback period of each vehicle, a sensitivity analysis was performed for two likely policy scenarios. The first policy option considered is an upfront rebate for any individual who purchases a PHEV. An example of a similar program is the upfront Californian rebate on PV installations of less than 100 kWp. Individuals that elect to install compliant PV systems are eligible for an upfront rebate of $2.50/Wp of installed capacity. In order to evaluate the effectiveness of this type of policy for PHEVs, upfront rebates of $2000, $4000, and $6000 were considered. In some cases, these upfront rebates actually reduce the initial upfront purchase price below that of a conventional internal combustion vehicle. Rather than displaying negative payback periods, the figures will indicate a payback period of zero in these situations.

Figure 40 compares the number of years required to payback vehicle purchase premiums for individuals that elect to participate in standard rates structures verses those that elect to participate in TOU rate structure. The assumed upfront financial incentive in Figure 40 is $4000.
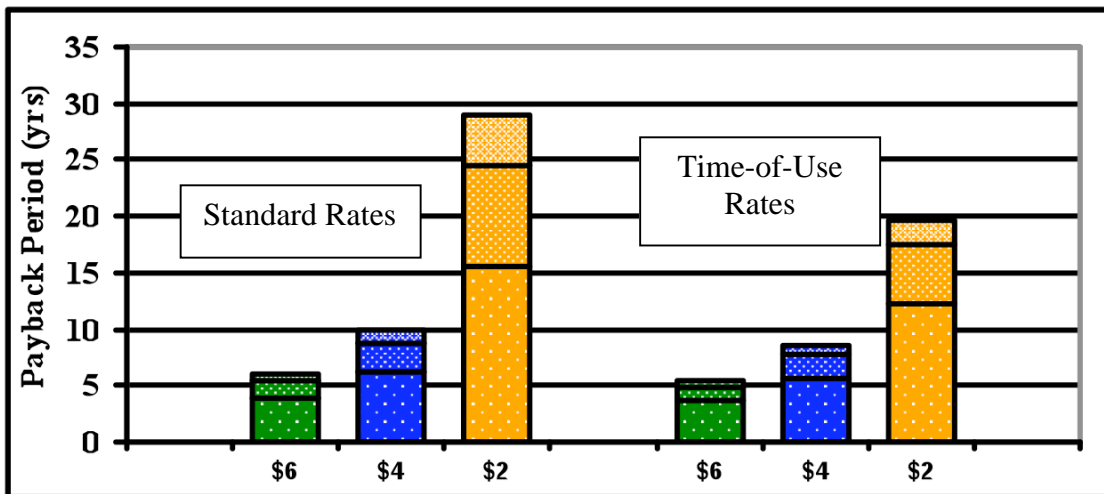


**Figure 40: Years to Repay Purchase Premium of HEV/PHEV over CV
with an Upfront Rebate of $4,000 on Electric Vehicle Purchases for Standard and TOU Rates**

With an upfront rebate of $4000, the lifetime fuel savings of all the vehicles considered will exceed the purchase premium of each respective vehicle when gasoline prices exceed $4 per gallon. However, if gasoline prices approach $2 per gallon, the upfront $4000 rebate will not be sufficient enough to recoup the purchase premium of any of the PHEV studied over their ten year lifespan. The upfront $4000 rebate actually reduces cost of HEVs below that of an equivalent conventional internal combustion engine vehicle in each of the scenarios presented. With the additional fuel savings over the lifespan of the vehicle, it would be difficult for individuals in the market to purchase a vehicle between $20,000 and $25,000 to economically justify the purchase of a conventional internal combustion engine vehicle.

Similarly to the business-as-usual scenario, the payback period for PHEV owners that participate in TOU programs is less than that for PHEV owners that participate in standard rate structures. Assuming that the majority of owners will elect TOU rates, Figure 41 illustrates the sensitivity of payback periods to the actual amount of upfront rebate. With an upfront rebate of $6000, it is possible that lifetime fuel savings will payback the purchase premium of a PHEV20 even with gasoline prices as low as $2 per gallon. However, with an upfront rebate of $2000, the HEVs no longer have negative payback periods for any of the considered gasoline prices.
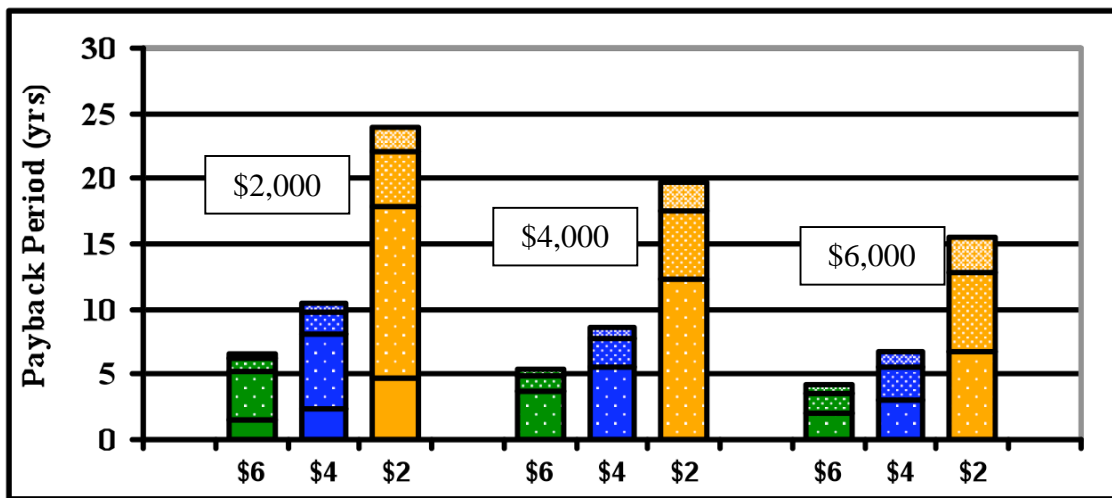


**Figure 41: Years to Repay Purchase Premium of HEV/PHEV over CV with Upfront Rebates of $2,000, $4,000, and $6,000 on Electric Vehicle Purchases for TOU Rates**

The second PHEV policy option considered is a reduction in the prices of electricity per kWh when charging the vehicle. Although not considered here, an additional stipulation to encourage off-peak charging of vehicles would be for the price reduction to only apply during off-peak hours. An example of a similar program is the Californian per kWh subsidy on PV installations. Participants receive a subsidy of $0.39 per kWh for all electricity produced. Subsidies of $0.02, $0.04, and $0.06 per kWh of electricity consumed during

charging were considered in order to evaluate the effectiveness of this type of policy for PHEVs.

Figure 42 shows the number of years required to payback vehicle purchase premiums assuming a rebate of $0.04 per kWh. The data is presented for both standard rate participants and TOU rate participants. With a rebate of $0.04 per kWh consumed in vehicle charging, all electric vehicles become economically viable if gasoline prices reach $6 per gallon. HEVs are the only vehicles that are economically viable for gasoline prices of less than $4 per gallon. Although the payback periods have been slightly reduced for each case considered, no additional vehicles beyond those identified in the business-as-usual scenario have become economically viable.
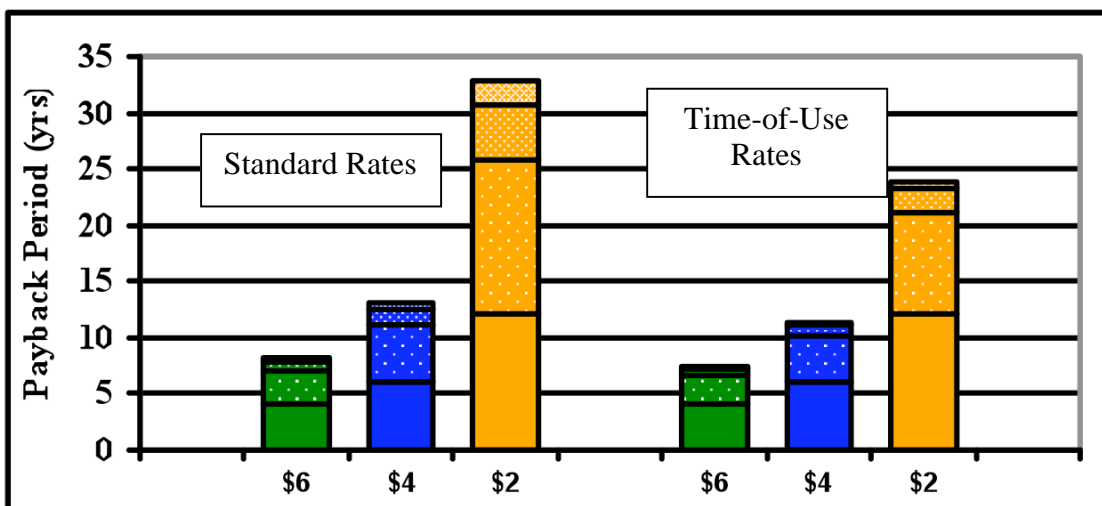


**Figure 42: Years to Repay Purchase Premium of HEV/PHEV over CV with Rebates of $0.04 per kWh on the Electricity Consumed during Electric Vehicle Charging for Standard and TOU Rates**

Again assuming that PHEV owners will elect to participate in TOU rates, Figure 43 shows the sensitivity of payback periods to the value per kWh subsidy. From the figure, it is clear that the payback period for electric vehicles is much less sensitive to the selected per kWh

subsidies as opposed to selected upfront vehicle rebates.  In fact, even if the subsidy on electricity consumed by PHEVs when charging is increased to $0.06 per kWh, the PHEV20 just barely becomes economically viable with gasoline prices at $4 per gallon.  With subsidies any higher than $0.06 per kWh, MGE would essentially be paying PHEV owning customers to charge their vehicles during off-peak hours.
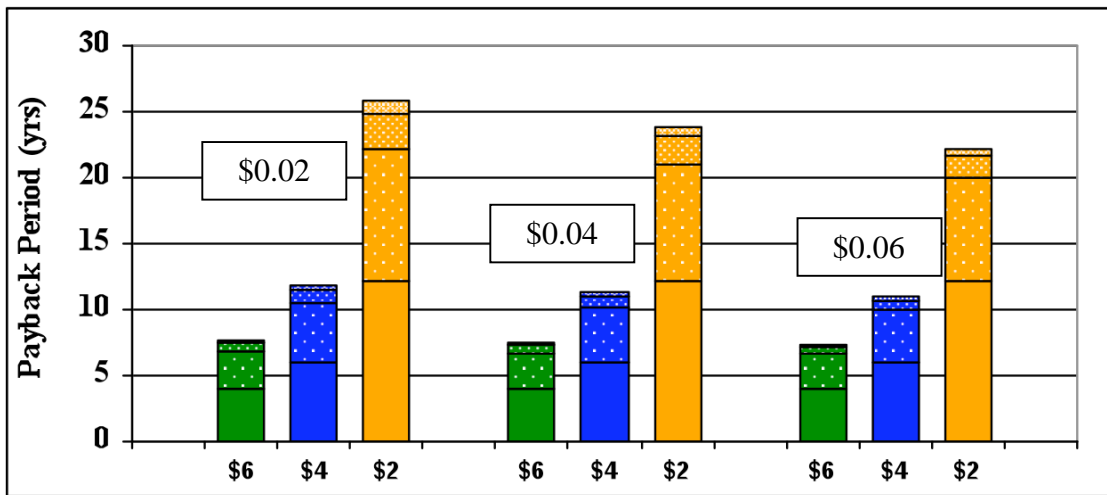


**Figure 43:  Years to Repay Purchase Premium of HEV/PHEV over CV with Rebates of $0.02, $0.04, and $0.06 per kWh on the Electricity Consumed during Electric Vehicle Charging for TOU Rates**

In all of the figures above that compare payback periods for standard rate participants and TOU rates participants, it is interesting to note that the payback periods for HEVs are independent of electric rate structure.  Electricity is not fed into these vehicles from an external source; thus, the per kWh rebate also has no impact on the payback period for HEVs.  Another point to be aware of is that the lower-ranged PHEVs typically pay themselves off more quickly than the higher-ranged PHEVS.  However, the additional payback period for each increment of PHEV battery capacity is less than the last.  For individuals with daily commutes greater than thirty miles per day, a vehicle with additional battery capacity might be more economically viable.

# 7  Potential Storage Opportunities with Vehicle-To-Grid Implementation

## 7.1  Comparison of National Energy Usage and PHEV Storage Capacity

Although PHEV participation in direct load control programs and time-of-use rate structures will reduce any negative impacts stemming from PHEV charging, V2G technology will provide an additional means for PHEV to participate as demand response resources. Bi-directional power flow will enable PHEVs to provide ancillary services such as reserve and regulation into energy markets. Such broader participation by vehicles in grid operations in a spatially distributed manner represents one enabling solution necessary for increased penetration of environmentally benign, but operationally challenging intermittent and variable generation, such as wind and solar energy resources.

One of the primary remaining barriers to increased renewable generation is energy storage technology. With target goals of over 25% electricity from renewable sources by 2025 [52], innovative storage solutions are necessary. Provided that there exists a method for PHEVs to participate as demand response resources in the future, and that V2G technology continues to develop, it is possible that these vehicles will help bridge the gap between consumer electricity demand and the existing capabilities of renewable generation technologies. Assuming that the majority of PHEV owners participate in a controlled charging program, and that night charging minimizes any negative infrastructure impacts, optimal vehicle charging periods are fortuitously aligned with the availability of underutilized wind resources.

Using the PHEV penetration scenarios presented previously, an initial study was performed in order to gauge the maximum storage potential of the PHEV fleet in each of the four geographical regions defined by the United States Census Bureau. Figure 44 illustrates the four regions as defined by the Census Bureau [53]. Different geographical areas have geographic and climate differences that can make the installation of certain types of renewable generation more or less effective. Renewable portfolio standards also differ in different regions throughout the United States. Geographic and climate differences also lead to a certain degree of variability in typical values of household electricity consumption, potentially requiring larger PHEV fleet to offset the same percentage of electricity use.
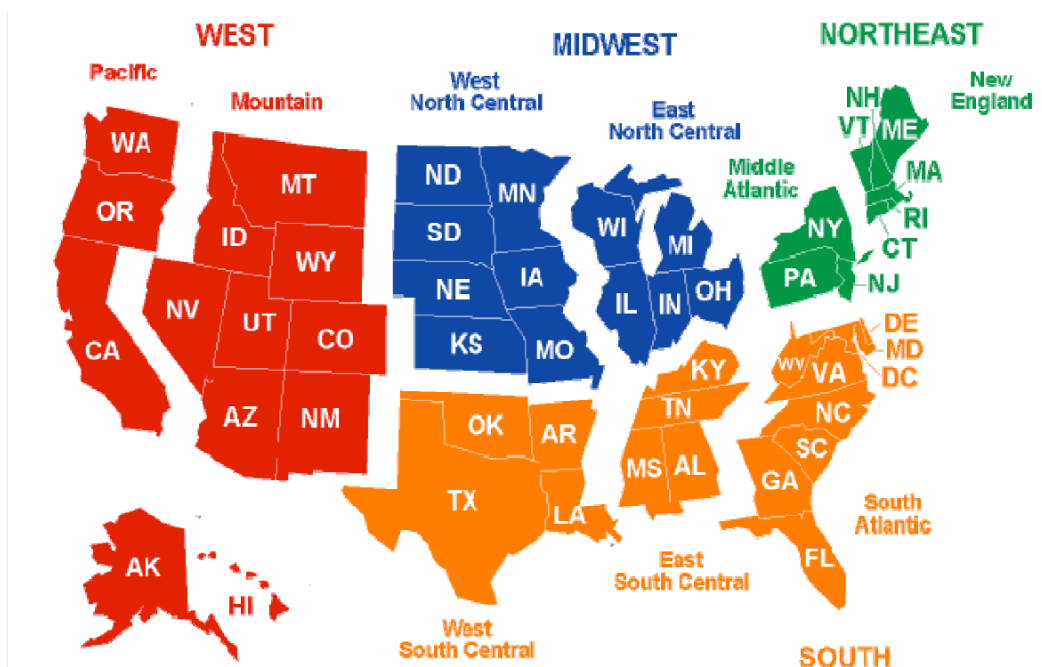


**Figure 44: Census Regions and Divisions in the United States**

As initially described in Chapter 4, PHEVs are typically classified by the number of pure electric miles that they can travel. The following section analyzes PHEV20, PHEV40, and PHEV60, which are capable of traveling twenty, forty, and sixty all-electric miles before

utilizing the internal combustion engine, respectively. Based on the battery energy and state-of-discharge window, the maximum possible storage capacity of a fully charged battery can be calculated. This storage capacity differs depending on the size of the battery, and thus the number of all-electric miles that a particular vehicle is capable of traveling before utilizing the internal combustion engine. Table 13 summarizes the maximum possible energy available for PHEV20, PHEV40, and PHEV60 [50]. For comparison, a typical household consumes approximately 32 kWh or electricity per day in the summer. Of these 32 kWh consumed on a typical summer day, 18 kWh will be consumed during peak hours [42].

**Table 13: Maximum Daily Energy Available From PHEVXX**

|                  | PHEV20   | PHEV40   | PHEV60   |
| ---------------- | -------- | -------- | -------- |
| Battery Energy   | 11.8 kWh | 19.0 kWh | 23.6 kWh |
| SOC Window       | 47%      | 59%      | 73%      |
| Available Energy | 5.55 kWh | 11.2 kWh | 17.2 kWh |

Assuming that each vehicle is entirely discharged during the day and then provided the opportunity to fully recharge every night, the daily available battery energy can be scaled by the number of days in a year to determine the annual storage capacity of a single PHEV. Table 14 presents this data for the three sizes of PHEVs considered in this analysis.

**Table 14: Maximum Annual Storage Capacity Available From PHEVXX**

|                          | PHEV20   | PHEV40   | PHEV60   |
| ------------------------ | -------- | -------- | -------- |
| Annual Available Energy  | 2024 kWh | 4092 kWh | 6288 kWh |

In order to determine the annual storage capacity for regional PHEV fleets, the same aggressive and non-aggressive PHEV penetration scenarios presented in earlier chapters were used. Based on the previously presented penetration scenarios, the number of PHEVs expected in years 2018 and 2026 were calculated. The total numbers of vehicles in each scenario were then divided among the four Census Regions according to the percentage of passenger vehicles that currently exist in each region. Interestingly, the percentage of vehicles owned corresponds closely to the population percentage in each region [54]. However, typical household electricity consumption in the Southern region is significantly higher than in any other region [55]. When scaled to account for the differences in population, the Southern region has a disproportionately high percentage of electricity consumed per year compared with the other three regions. This means that even though there are additional vehicles in the Southern region due to higher population levels, the energy storage of the PHEV fleet in this region will be a lesser percentage of total residential electricity consumption for the region. Table 15 describes the vehicle ownership percentages that were used to assign specific numbers of PHEVs to each region [56].

**Table 15: Existing Geographical Distribution of Vehicles in the United States**

| Household Census Region | Percent of Total U.S. Vehicles |
|---|---|
| Northeast | 16% |
| Midwest | 25% |
| South | 37% |
| West | 22% |

The total impact of the PHEVXX fleet in each region was then calculated by scaling the impact of a single PHEVXX by the total number of forecast PHEVXX in each region for each of the years of interest. Figure 45 defines the color and shading conventions used in Figure 46 to differentiate between scenarios and regions.



**Figure 45: Legend for Following Figures**

Figure 46 illustrates the potential aggregate regional battery storage capacity for each of the penetration scenarios studied. The three different axes represent PHEV20, PHEV40, and PHEV60, moving from the interior axis outwards.
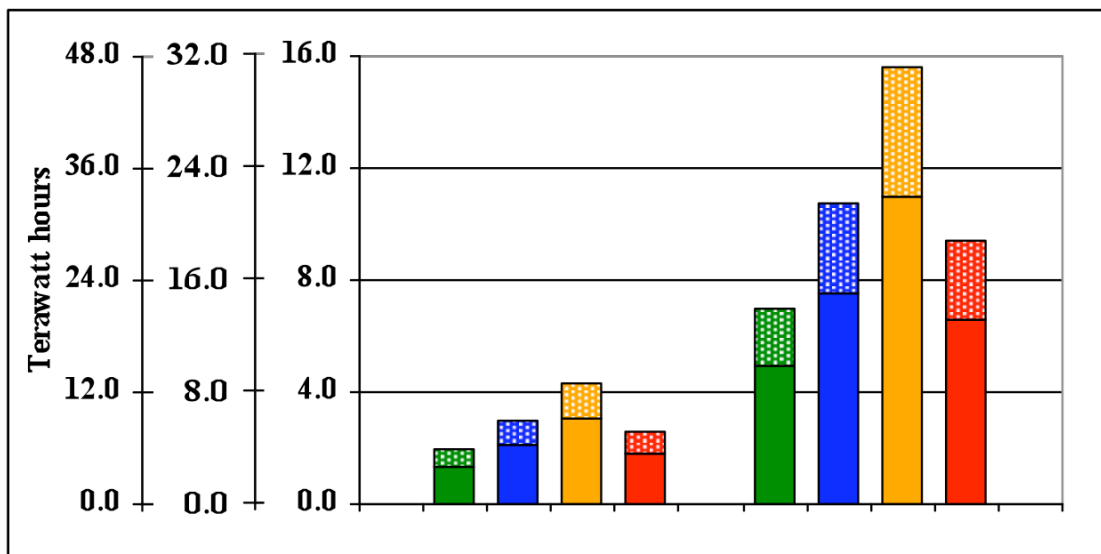


**Figure 46: National PHEV20 Storage Capacity by US Census Region**

The cumulative national level of potential aggregate regional battery storage capacity for each of the penetration scenarios studied is shown in Figure 47. As in the previous figure, the three different axes represent PHEV20, PHEV40, and PHEV60, moving outwards.
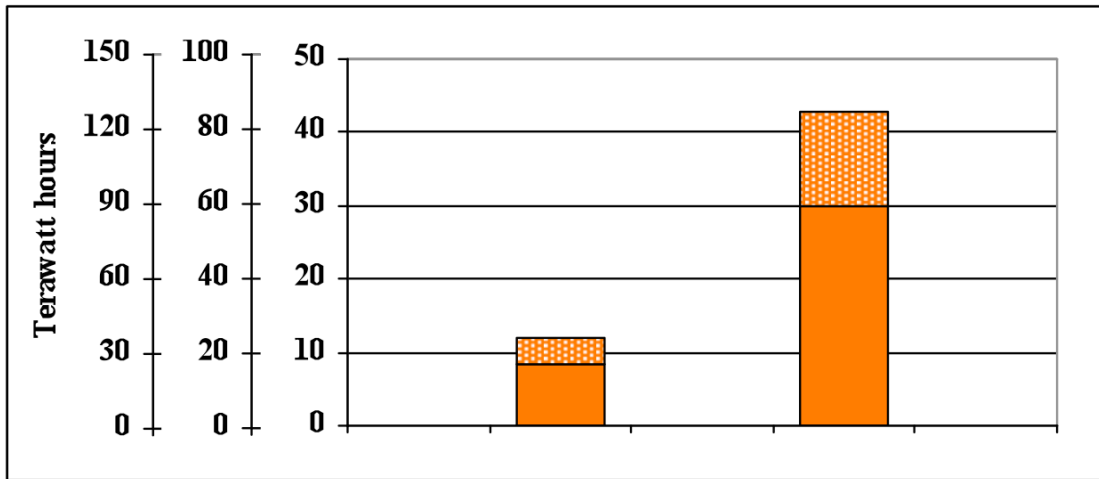


**Figure 47: National PHEV20 Storage Capacity**

In 2007, approximately 105,000 thousand Megawatt hours, or a little more than 2.5% of electricity generated in the United States was generated using renewable technologies (excluding conventional hydroelectric generation). The net renewable generation capacity in 2007 was just over 30,000 MW [57]. From Figure 47, it is apparent that an additional 30,000 thousand Megawatt hours from the total installed renewable generation capacity could be utilized assuming non-aggressive penetration of PHEV20 occurs through year 2026. With larger vehicles such as PHEV40 and PHEV60, and/or increased vehicle market penetration, utilization of installed capacity continues to increase. In the most aggressive scenario studied, with aggressive penetration of PHEV60 through year 2026, the existing renewable generation can potentially be more than doubled.

One additional item to consider is the geographical distribution of the technical feasibility of different types of renewable generation resources. For example, the Western region is particularly suited for solar renewable generation, while the Midwestern region is more suited towards wind renewable generation. As the total storage potential of regional PHEV fleets increases, it is possible that the total storage capacity will outstrip the availability of renewable resources. Certain areas in the Southern region are particularly susceptible to this due to the large number of vehicles and comparatively low likely installations of renewable generation resources. At this point, strengthening transmission interconnections between the regions will more aptly match renewable generation resources to storage resources.

## 7.2 **Ability for the PHEV Fleet to Complement Renewable Generation by Region**

At a more regional level, Figure 48 illustrates potential battery storage capacity for PHEV fleets in Wisconsin and Dane County, under the same set of scenarios presented in the previous section. The interior axis represents the storage capacity of a fleet composed of PHEV20, the central axis is scaled to represent a fleet composed of PHEV40, and the exterior axis is scaled to represent a fleet composed of PHEV60. As before, the solid bar indicates non-aggressive PHEV penetration and the shaded bar represents aggressive PHEV penetration. The color convention changes from the previous section. Green now represents battery storage potential in Dane County and blue represents battery storage potential in the state of Wisconsin. Relatively high levels of distributed generation resources in Dane County make the addition of regional storage resources of particular value.
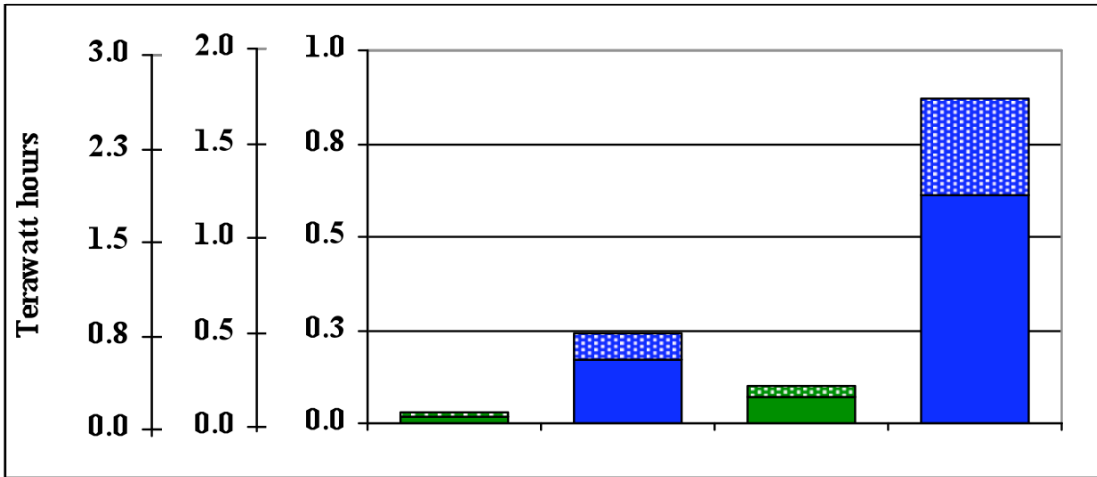
**Figure 48: PHEV20 Storage Capacity for Wisconsin and Dane County**

## 7.3 Comparison of Household Energy Usage and PHEV Storage Capacity

The daily electricity consumption of a typical Midwestern household is very much on par with the storage capacity of a single PHEV battery. In some cases, the vehicle battery actually has sufficient storage capacity to eliminate peak power usage between the hours of 10:00am and 9:00pm. Realistically, the majority of PHEVs will not be geographically located at home during these peak periods. However, there is the potential for PHEVs to plug-in at other locations in lieu of plugging in at home, thus creating the same net effect, but spatially corrected from home to work locations. Separate studies have been performed on the ability for PHEVs to support commercial office buildings during the work day [58].

Table 16 illustrates the percentage of total typically daily household electricity use that could be offset by PHEV20, PHEV40, and PHEV60. Table 17 illustrates the corresponding percentage of daily typical household electricity use that could be offset by PHEV20, PHEV40, and PHEV60 during peak hours.

**Table 16: Percentage of Typical Daily Household Electricity Offset by PHEVXX**

|  | PHEV20 | PHEV40 | PHEV60 |
|---|---|---|---|
| Winter Peak Day | 25% | 50% | 76% |
| Summer Peak Day | 9% | 17% | 27% |
| Winter Typical Day | 26% | 52% | 80% |
| Summer Typical Day | 17% | 35% | 54% |

**Table 17: Percentage of On-Peak Typical Household Electricity Offset by PHEVXX**

|  | PHEV20 | PHEV40 | PHEV60 |
|---|---|---|---|
| Winter Peak Day | 46% | 94% | 144% |
| Summer Peak Day | 14% | 29% | 45% |
| Winter Typical Day | 50% | 101% | 156% |
| Summer Typical Day | 31% | 63% | 97% |

Prior to implementation of such net metering programs, certain agreements and policies will need to be created between electric utilities in order to account for the eventuality of participating individuals who live in one electric service territory, but work in another. Dane County load is served by three unique electric service providers, making the likelihood of this occurring particularly high in this county. Metering and vehicle communications standards will also be essential in order to facilitate the interaction between utility and customer.

**Summary of Significant Results**   Assuming that current political and technological drivers remain constant in the coming years, a certain degree of PHEV penetration is inevitable. The methods used to incorporate PHEVs into the existing electric and automotive industries will dictate whether these vehicles are helpful or hurtful in the long run. Initial clustering of vehicles is assured to amplify the impact that initial PHEV penetration will have on existing distribution infrastructure. With level 2 charging, the addition of a single PHEV can cause peak summer transformer loading to exceed rated values. Although level 1 charging reduces the increased load placed on transformers, the addition of three PHEVs causes the peak summer transformer loading to approach rated values.

Early penetration of PHEVs is less likely to have a detrimental impact on larger equipment to higher amounts of installed capacity. However, if uncontrolled charging is allowed to continue over an extended timeframe, increasing peak demand will ultimately be reflected by an increasing frequency of voltage and thermal violations on transmission equipment. Under an aggressive PHEV penetration scenario and with level 2 charging, the additional PHEV load exceeds the Dane County area N-2 load margin by year 2018. Although less aggressive penetration scenarios and/or charging characteristics do not necessarily cause PHEV load to exceed load margins, they can significantly reduce load margin, thus reducing the robustness and flexibility of the bulk electric system.

Controlled charging techniques can be used to prevent PHEV load from contributing to peak electricity demand. This greatly extends the amount of time that will elapse before

reinforcements and/or additions are needed for the bulk electric system. Additionally, demand response can enable PHEV owners to reduce the cost required to charge their vehicles, thus creating a situation in which all stakeholders appear to benefit. However, the savings accrued by PHEV owners under existing demand response programs (e.g. direct load control and time-of-use pricing programs) are insufficient to convince PHEV to sacrifice convenience for financial savings. Additional rebates and incentives can be used to encourage PHEV owner participation. The metric used to ascertain the effectiveness of different rebates and incentives was the ratio of vehicle purchase premium to fuel cost savings over the ten year life of the vehicle. The effectiveness of each proposal was highly dependent on both gasoline prices and the electric range of the vehicle. In each of the cases considered in this analysis, upfront rebates were more effective than energy usage rebates. However, reductions in the upfront rebates and/or increased energy usage rebates could be used to make the two more equivalent.

Future implementation of V2G technology will enable PHEV to provide additional benefits to the bulk electric system, beyond mitigation of their own impacts. Unused battery capacity can be used to offset the variability inherent in renewable generation, thus resulting in an overall cleaner electrical system impact. Also, the aggregate PHEV fleet can be used to provide valuable ancillary services such as reserve and regulation. Currently, generation resources are the primary providers of these resources. Further opening this market to demand-side resources will enhance competition in energy markets. PHEV owners that decide to utilize their batteries as energy storage resources will be capable of shifting a significant percentage of their daily household energy usage to off-peak hours. Certain

batteries are actually capable of completely eliminating peak energy usage for a typical household.

**Future Work**   There is still a great deal of work that remains in order to ensure a smooth transition to an electrified automotive industry.  First of all, regional consumer surveys are needed to better identify characteristics that are indicative of likely PHEV adopters.  These surveys should be designed to such that they characterize both spatial and temporal aspects of PHEV adoption.  Additionally, these surveys can help determine the probability that early PHEV adopters will participate in existing demand response programs and/or evaluate which rebates and incentives are the most lucrative to potential vehicle owners.  After creating a regionally-accurate picture of future PHEV penetration, the initial distribution and transmission equipment impact assessment should be expanded to include all equipment in the region of interest, according to the spatial and temporal penetration characteristics. Finally, an analysis needs to be performed in order to evaluate whether or not the benefits recouped by electric utilities from PHEV participation in demand response programs are sufficient to achieve cost recovery for each of the proposed rebates and incentives.

**Conclusions**   Demand response is quickly evolving and playing a greater role in the electric industry.  PHEV have the potential to provide a significant amount of demand response through a variety of methods.  However, without careful development of demand response programs that benefit the consumer while maintaining system reliability, PHEVs have the potential to be part of the problem as opposed to part of the solution.

This report has presented a regional distribution and transmission impact analysis of initial PHEV penetration on electric infrastructure in Dane County, WI.  It has also offered an

outline of the different future possibilities of the ways in which PHEVs may participate as demand response resources with the currently available demand response programs, thus improving the reliability and robustness of the bulk electric system in Dane County. Furthermore, it has described a future vision that encourages PHEVs to participate in demand response programs that will be developed in order to take advantage of these vehicles' unique energy storage potential, thus enabling a higher penetration of intermittent and variable generation such as wind and solar energy resources.

It is clear that the current definition of linking demand response either to pricing of electricity or jeopardy of system reliability may be too restrictive in scope. A policy regime that recognizes the value of PHEVs for their energy storage and provides incentives for owners to enroll in an appropriate demand response program and receive additional compensation in exchange for use of their vehicles' participation in grid operations is worthy of exploration in light of its strong societal impact. Numerous technical, operational, economic, and logistic challenges need to be overcome before such a broad V2G visions can be realized. Thus, the remaining question is how to move forward and aptly utilize PHEV resources as they become available.

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# *Appendix A:  PHEV Penetration Tables*

Dane County, Non-Aggressive/Aggressive, 2011 – 2018

| | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|---|---|
| Non-Aggressive Annual Sales | 121 | 243 | 364 | 606 | 970 | 1637 | 2486 | 3032 |
| Non-Aggressive Cumulative Fleet | 121 | 364 | 728 | 1334 | 2304 | 3941 | 6427 | 9459 |
| Aggressive Annual Sales | 173 | 346 | 518 | 864 | 1,382 | 2,333 | 3,542 | 4,320 |
| Aggressive Cumulative Fleet | 173 | 518 | 1,037 | 1,901 | 3,283 | 5,616 | 9,159 | 13,479 |

Wisconsin, Non-Aggressive/Aggressive, 2011 – 2018

| | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|---|---|
| Non-Aggressive Annual Sales | 1073 | 2145 | 3218 | 5363 | 8582 | 14481 | 21990 | 26817 |
| Non-Aggressive Cumulative Fleet | 1073 | 3218 | 6436 | 11800 | 20381 | 34863 | 56853 | 83670 |
| Aggressive Annual Sales | 1529 | 3057 | 4586 | 7643 | 12229 | 20636 | 31336 | 38215 |
| Aggressive Cumulative Fleet | 1529 | 4586 | 9172 | 16814 | 29043 | 49679 | 81015 | 119230 |

United States, Non-Aggressive/Aggressive, 2011 – 2018

| | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|---|---|
| Non-Aggressive Annual Sales | 52632 | 105263 | 157895 | 263158 | 421053 | 710526 | 1078947 | 1315789 |
| Non-Aggressive Cumulative Fleet | 52632 | 157895 | 315789 | 578947 | 1000000 | 1710526 | 2789474 | 4105263 |
| Aggressive Annual Sales | 75000 | 150000 | 225000 | 375000 | 600000 | 1012500 | 1537500 | 1875000 |
| Aggressive Cumulative Fleet | 75000 | 225000 | 450000 | 825000 | 1425000 | 2437500 | 3975000 | 5850000 |

Dane County, Non-Aggressive/Aggressive, 2019 - 2026

| | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 |
|---|---|---|---|---|---|---|---|---|
| Non-Aggressive Annual Sales | 3153 | 3274 | 3395 | 3517 | 3638 | 3759 | 3880 | 4002 |
| Non-Aggressive Cumulative Fleet | 12612 | 15886 | 19160 | 22434 | 25708 | 28861 | 31771 | 34136 |
| Aggressive Annual Sales | 4493 | 4666 | 4838 | 5011 | 5184 | 5357 | 5530 | 5702 |
| Aggressive Cumulative Fleet | 17971 | 22637 | 27303 | 31968 | 36634 | 41127 | 45274 | 48644 |

Wisconsin, Non-Aggressive/Aggressive, 2019 – 2026

| | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 |
|---|---|---|---|---|---|---|---|---|
| Non-Aggressive Annual Sales | 27890 | 28963 | 30035 | 31108 | 32181 | 33254 | 34326 | 35399 |
| Non-Aggressive Cumulative Fleet | 111560 | 140523 | 169486 | 198448 | 227411 | 255301 | 281046 | 301963 |
| Aggressive Annual Sales | 39743 | 41272 | 42800 | 44329 | 45858 | 47386 | 48915 | 50443 |
| Aggressive Cumulative Fleet | 158973 | 200245 | 241517 | 282789 | 324061 | 363804 | 400490 | 430298 |

United States, Non-Aggressive/Aggressive, 2019 – 2026

| | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 |
|---|---|---|---|---|---|---|---|---|
| Non-Aggressive Annual Sales | 1368421 | 1421053 | 1473684 | 1526316 | 1578947 | 1631579 | 1684211 | 1736842 |
| Non-Aggressive Cumulative Fleet | 5473684 | 6894737 | 8315789 | 9736842 | 11157895 | 12526316 | 13789474 | 14815789 |
| Aggressive Annual Sales | 1950000 | 2025000 | 2100000 | 2175000 | 2250000 | 2325000 | 2400000 | 2475000 |
| Aggressive Cumulative Fleet | 7800000 | 9825000 | 11850000 | 13875000 | 15900000 | 17850000 | 19650000 | 21112500 |

# Appendix B: Distribution Impact Results (Without Demand Response)

Non-Aggressive/Aggressive, Level 1, 8 Households per Transformer (through 2018)

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1 PHEV** | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 7.6 | 6.6 | 6.1 | 5.7 | 5.8 | 6.7 | 8.5 | 9.3 | 9.4 | 9.2 | 9.2 | 9.0 | 9.0 | 8.9 | 8.9 | 9.6 | 12.2 | 13.9 | 15.7 | 16.0 | 15.0 | 12.5 | 10.3 | 8.6 |
| Summer Peak | 19.4 | 18.2 | 17.7 | 17.0 | 17.2 | 19.0 | 20.5 | 21.3 | 21.0 | 22.9 | 25.6 | 29.5 | 35.1 | 40.8 | 44.2 | 45.3 | 44.7 | 38.6 | 32.9 | 28.6 | 28.7 | 25.5 | 22.7 | 20.0 |
| Winter Typical | 7.3 | 6.4 | 6.0 | 5.8 | 6.1 | 7.8 | 9.3 | 9.8 | 8.1 | 7.9 | 7.8 | 7.6 | 7.5 | 7.5 | 7.7 | 8.7 | 11.8 | 13.8 | 15.6 | 15.8 | 14.9 | 12.3 | 10.2 | 8.4 |
| Summer Typical | 10.4 | 9.4 | 9.1 | 8.7 | 8.9 | 10.4 | 11.5 | 12.0 | 10.9 | 11.3 | 12.1 | 13.2 | 15.0 | 16.9 | 18.2 | 19.1 | 20.7 | 19.3 | 17.8 | 16.8 | 17.2 | 15.0 | 13.0 | 10.9 |
| **2 PHEV** | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 7.6 | 6.6 | 6.1 | 5.7 | 5.8 | 6.7 | 8.5 | 9.3 | 9.4 | 9.2 | 9.2 | 9.0 | 9.0 | 8.9 | 8.9 | 9.6 | 13.9 | 15.7 | 17.5 | 17.7 | 16.2 | 12.5 | 10.3 | 8.6 |
| Summer Peak | 19.4 | 18.2 | 17.7 | 17.0 | 17.2 | 19.0 | 20.5 | 21.3 | 21.0 | 22.9 | 25.6 | 29.5 | 35.1 | 40.8 | 44.2 | 45.3 | 46.5 | 40.4 | 34.7 | 30.3 | 29.8 | 25.5 | 22.7 | 20.0 |
| Winter Typical | 7.3 | 6.4 | 6.0 | 5.8 | 6.1 | 7.8 | 9.3 | 9.8 | 8.1 | 7.9 | 7.8 | 7.6 | 7.5 | 7.5 | 7.7 | 8.7 | 13.5 | 15.6 | 17.3 | 17.5 | 16.0 | 12.3 | 10.2 | 8.4 |
| Summer Typical | 10.4 | 9.4 | 9.1 | 8.7 | 8.9 | 10.4 | 11.5 | 12.0 | 10.9 | 11.3 | 12.1 | 13.2 | 15.0 | 16.9 | 18.2 | 19.1 | 22.4 | 21.0 | 19.5 | 18.6 | 18.4 | 15.0 | 13.0 | 10.9 |
| **3 PHEV** | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 7.6 | 6.6 | 6.1 | 5.7 | 5.8 | 6.7 | 8.5 | 9.3 | 9.4 | 9.2 | 9.2 | 9.0 | 9.0 | 8.9 | 8.9 | 9.6 | 15.7 | 17.4 | 19.2 | 19.5 | 17.3 | 12.5 | 10.3 | 8.6 |
| Summer Peak | 19.4 | 18.2 | 17.7 | 17.0 | 17.2 | 19.0 | 20.5 | 21.3 | 21.0 | 22.9 | 25.6 | 29.5 | 35.1 | 40.8 | 44.2 | 45.3 | 48.2 | 42.1 | 36.4 | 32.1 | 31.0 | 25.5 | 22.7 | 20.0 |
| Winter Typical | 7.3 | 6.4 | 6.0 | 5.8 | 6.1 | 7.8 | 9.3 | 9.8 | 8.1 | 7.9 | 7.8 | 7.6 | 7.5 | 7.5 | 7.7 | 8.7 | 15.3 | 17.3 | 19.1 | 19.3 | 17.2 | 12.3 | 10.2 | 8.4 |
| Summer Typical | 10.4 | 9.4 | 9.1 | 8.7 | 8.9 | 10.4 | 11.5 | 12.0 | 10.9 | 11.3 | 12.1 | 13.2 | 15.0 | 16.9 | 18.2 | 19.1 | 24.2 | 22.8 | 21.3 | 20.3 | 19.5 | 15.0 | 13.0 | 10.9 |

Non-Aggressive/Aggressive, Level 1, 10 Households per Transformer (through 2018)

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1 PHEV** | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 9.5 | 8.3 | 7.6 | 7.2 | 7.3 | 8.4 | 10.6 | 11.6 | 11.8 | 11.5 | 11.5 | 11.3 | 11.2 | 11.2 | 11.2 | 12.0 | 14.8 | 17.0 | 19.2 | 19.5 | 18.5 | 15.6 | 12.9 | 10.7 |
| Summer Peak | 24.3 | 22.8 | 22.2 | 21.3 | 21.5 | 23.8 | 25.6 | 26.7 | 26.2 | 28.6 | 32.0 | 36.9 | 43.9 | 51.0 | 55.3 | 56.7 | 55.5 | 47.9 | 40.7 | 35.3 | 35.6 | 31.9 | 28.4 | 25.0 |
| Winter Typical | 9.1 | 7.9 | 7.5 | 7.2 | 7.7 | 9.8 | 11.7 | 12.3 | 10.1 | 9.9 | 9.7 | 9.5 | 9.4 | 9.4 | 9.6 | 10.9 | 14.3 | 16.8 | 19.0 | 19.3 | 18.3 | 15.4 | 12.7 | 10.5 |
| Summer Typical | 13.0 | 11.8 | 11.4 | 10.8 | 11.2 | 13.0 | 14.4 | 15.0 | 13.6 | 14.2 | 15.1 | 16.5 | 18.8 | 21.2 | 22.7 | 23.9 | 25.4 | 23.6 | 21.8 | 20.6 | 21.2 | 18.8 | 16.2 | 13.6 |
| **2 PHEV** | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 9.5 | 8.3 | 7.6 | 7.2 | 7.3 | 8.4 | 10.6 | 11.6 | 11.8 | 11.5 | 11.5 | 11.3 | 11.2 | 11.2 | 11.2 | 12.0 | 16.5 | 18.7 | 20.9 | 21.3 | 19.6 | 15.6 | 12.9 | 10.7 |
| Summer Peak | 24.3 | 22.8 | 22.2 | 21.3 | 21.5 | 23.8 | 25.6 | 26.7 | 26.2 | 28.6 | 32.0 | 36.9 | 43.9 | 51.0 | 55.3 | 56.7 | 57.2 | 49.6 | 42.5 | 37.0 | 36.7 | 31.9 | 28.4 | 25.0 |
| Winter Typical | 9.1 | 7.9 | 7.5 | 7.2 | 7.7 | 9.8 | 11.7 | 12.3 | 10.1 | 9.9 | 9.7 | 9.5 | 9.4 | 9.4 | 9.6 | 10.9 | 16.1 | 18.6 | 20.8 | 21.0 | 19.5 | 15.4 | 12.7 | 10.5 |
| Summer Typical | 13.0 | 11.8 | 11.4 | 10.8 | 11.2 | 13.0 | 14.4 | 15.0 | 13.6 | 14.2 | 15.1 | 16.5 | 18.8 | 21.2 | 22.7 | 23.9 | 27.1 | 25.4 | 23.6 | 22.3 | 22.4 | 18.8 | 16.2 | 13.6 |
| **3 PHEV** | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 9.5 | 8.3 | 7.6 | 7.2 | 7.3 | 8.4 | 10.6 | 11.6 | 11.8 | 11.5 | 11.5 | 11.3 | 11.2 | 11.2 | 11.2 | 12.0 | 18.3 | 20.5 | 22.7 | 23.0 | 20.8 | 15.6 | 12.9 | 10.7 |
| Summer Peak | 24.3 | 22.8 | 22.2 | 21.3 | 21.5 | 23.8 | 25.6 | 26.7 | 26.2 | 28.6 | 32.0 | 36.9 | 43.9 | 51.0 | 55.3 | 56.7 | 59.0 | 51.4 | 44.2 | 38.8 | 37.8 | 31.9 | 28.4 | 25.0 |
| Winter Typical | 9.1 | 7.9 | 7.5 | 7.2 | 7.7 | 9.8 | 11.7 | 12.3 | 10.1 | 9.9 | 9.7 | 9.5 | 9.4 | 9.4 | 9.6 | 10.9 | 17.8 | 20.3 | 22.5 | 22.8 | 20.6 | 15.4 | 12.7 | 10.5 |
| Summer Typical | 13.0 | 11.8 | 11.4 | 10.8 | 11.2 | 13.0 | 14.4 | 15.0 | 13.6 | 14.2 | 15.1 | 16.5 | 18.8 | 21.2 | 22.7 | 23.9 | 28.9 | 27.1 | 25.3 | 24.1 | 23.5 | 18.8 | 16.2 | 13.6 |

Non-Aggressive/Aggressive, Level 2, 8 Households per Transformer (through 2018)

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 PHEV | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 7.6 | 6.6 | 6.1 | 5.7 | 5.8 | 6.7 | 8.5 | 9.3 | 9.4 | 9.2 | 9.2 | 9.0 | 9.0 | 8.9 | 8.9 | 9.6 | 17.9 | 12.8 | 14.0 | 14.2 | 13.9 | 12.5 | 10.3 | 8.6 |
| Summer Peak | 19.4 | 18.2 | 17.7 | 17.0 | 17.2 | 19.0 | 20.5 | 21.3 | 21.0 | 22.9 | 25.6 | 29.5 | 35.1 | 40.8 | 44.2 | 45.3 | 50.5 | 37.5 | 31.2 | 26.8 | 27.5 | 25.5 | 22.7 | 20.0 |
| Winter Typical | 7.3 | 6.4 | 6.0 | 5.8 | 6.1 | 7.8 | 9.3 | 9.8 | 8.1 | 7.9 | 7.8 | 7.6 | 7.5 | 7.5 | 7.7 | 8.7 | 17.5 | 12.7 | 13.8 | 14.0 | 13.8 | 12.3 | 10.2 | 8.4 |
| Summer Typical | 10.4 | 9.4 | 9.1 | 8.7 | 8.9 | 10.4 | 11.5 | 12.0 | 10.9 | 11.3 | 12.1 | 13.2 | 15.0 | 16.9 | 18.2 | 19.1 | 26.4 | 18.2 | 16.0 | 15.1 | 16.1 | 15.0 | 13.0 | 10.9 |
| 2 PHEV | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 7.6 | 6.6 | 6.1 | 5.7 | 5.8 | 6.7 | 8.5 | 9.3 | 9.4 | 9.2 | 9.2 | 9.0 | 9.0 | 8.9 | 8.9 | 9.6 | 25.4 | 13.5 | 14.0 | 14.2 | 13.9 | 12.5 | 10.3 | 8.6 |
| Summer Peak | 19.4 | 18.2 | 17.7 | 17.0 | 17.2 | 19.0 | 20.5 | 21.3 | 21.0 | 22.9 | 25.6 | 29.5 | 35.1 | 40.8 | 44.2 | 45.3 | 58.0 | 38.2 | 31.2 | 26.8 | 27.5 | 25.5 | 22.7 | 20.0 |
| Winter Typical | 7.3 | 6.4 | 6.0 | 5.8 | 6.1 | 7.8 | 9.3 | 9.8 | 8.1 | 7.9 | 7.8 | 7.6 | 7.5 | 7.5 | 7.7 | 8.7 | 25.0 | 13.3 | 13.8 | 14.0 | 13.8 | 12.3 | 10.2 | 8.4 |
| Summer Typical | 10.4 | 9.4 | 9.1 | 8.7 | 8.9 | 10.4 | 11.5 | 12.0 | 10.9 | 11.3 | 12.1 | 13.2 | 15.0 | 16.9 | 18.2 | 19.1 | 33.9 | 18.8 | 16.0 | 15.1 | 16.1 | 15.0 | 13.0 | 10.9 |
| 3 PHEV | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 7.6 | 6.6 | 6.1 | 5.7 | 5.8 | 6.7 | 8.5 | 9.3 | 9.4 | 9.2 | 9.2 | 9.0 | 9.0 | 8.9 | 8.9 | 9.6 | 32.9 | 14.1 | 14.0 | 14.2 | 13.9 | 12.5 | 10.3 | 8.6 |
| Summer Peak | 19.4 | 18.2 | 17.7 | 17.0 | 17.2 | 19.0 | 20.5 | 21.3 | 21.0 | 22.9 | 25.6 | 29.5 | 35.1 | 40.8 | 44.2 | 45.3 | 65.5 | 38.8 | 31.2 | 26.8 | 27.5 | 25.5 | 22.7 | 20.0 |
| Winter Typical | 7.3 | 6.4 | 6.0 | 5.8 | 6.1 | 7.8 | 9.3 | 9.8 | 8.1 | 7.9 | 7.8 | 7.6 | 7.5 | 7.5 | 7.7 | 8.7 | 32.5 | 14.0 | 13.8 | 14.0 | 13.8 | 12.3 | 10.2 | 8.4 |
| Summer Typical | 10.4 | 9.4 | 9.1 | 8.7 | 8.9 | 10.4 | 11.5 | 12.0 | 10.9 | 11.3 | 12.1 | 13.2 | 15.0 | 16.9 | 18.2 | 19.1 | 41.4 | 19.4 | 16.0 | 15.1 | 16.1 | 15.0 | 13.0 | 10.9 |

Non-Aggressive/Aggressive, Level 2, 10 Households per Transformer (through 2018)

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1 PHEV** | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 9.5 | 8.3 | 7.6 | 7.2 | 7.3 | 8.4 | 10.6 | 11.6 | 11.8 | 11.5 | 11.5 | 11.3 | 11.2 | 11.2 | 11.2 | 12.0 | 20.5 | 15.9 | 17.4 | 17.8 | 17.4 | 15.6 | 12.9 | 10.7 |
| Summer Peak | 24.3 | 22.8 | 22.2 | 21.3 | 21.5 | 23.8 | 25.6 | 26.7 | 26.2 | 28.6 | 32.0 | 36.9 | 43.9 | 51.0 | 55.3 | 56.7 | 61.2 | 46.8 | 39.0 | 33.5 | 34.4 | 31.9 | 28.4 | 25.0 |
| Winter Typical | 9.1 | 7.9 | 7.5 | 7.2 | 7.7 | 9.8 | 11.7 | 12.3 | 10.1 | 9.9 | 9.7 | 9.5 | 9.4 | 9.4 | 9.6 | 10.9 | 20.1 | 15.7 | 17.3 | 17.5 | 17.2 | 15.4 | 12.7 | 10.5 |
| Summer Typical | 13.0 | 11.8 | 11.4 | 10.8 | 11.2 | 13.0 | 14.4 | 15.0 | 13.6 | 14.2 | 15.1 | 16.5 | 18.8 | 21.2 | 22.7 | 23.9 | 31.1 | 22.5 | 20.1 | 18.8 | 20.1 | 18.8 | 16.2 | 13.6 |
| **2 PHEV** | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 9.5 | 8.3 | 7.6 | 7.2 | 7.3 | 8.4 | 10.6 | 11.6 | 11.8 | 11.5 | 11.5 | 11.3 | 11.2 | 11.2 | 11.2 | 12.0 | 28.0 | 16.5 | 17.4 | 17.8 | 17.4 | 15.6 | 12.9 | 10.7 |
| Summer Peak | 24.3 | 22.8 | 22.2 | 21.3 | 21.5 | 23.8 | 25.6 | 26.7 | 26.2 | 28.6 | 32.0 | 36.9 | 43.9 | 51.0 | 55.3 | 56.7 | 68.7 | 47.4 | 39.0 | 33.5 | 34.4 | 31.9 | 28.4 | 25.0 |
| Winter Typical | 9.1 | 7.9 | 7.5 | 7.2 | 7.7 | 9.8 | 11.7 | 12.3 | 10.1 | 9.9 | 9.7 | 9.5 | 9.4 | 9.4 | 9.6 | 10.9 | 27.6 | 16.3 | 17.3 | 17.5 | 17.2 | 15.4 | 12.7 | 10.5 |
| Summer Typical | 13.0 | 11.8 | 11.4 | 10.8 | 11.2 | 13.0 | 14.4 | 15.0 | 13.6 | 14.2 | 15.1 | 16.5 | 18.8 | 21.2 | 22.7 | 23.9 | 38.6 | 23.2 | 20.1 | 18.8 | 20.1 | 18.8 | 16.2 | 13.6 |
| **3 PHEV** | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 9.5 | 8.3 | 7.6 | 7.2 | 7.3 | 8.4 | 10.6 | 11.6 | 11.8 | 11.5 | 11.5 | 11.3 | 11.2 | 11.2 | 11.2 | 12.0 | 35.5 | 17.1 | 17.4 | 17.8 | 17.4 | 15.6 | 12.9 | 10.7 |
| Summer Peak | 24.3 | 22.8 | 22.2 | 21.3 | 21.5 | 23.8 | 25.6 | 26.7 | 26.2 | 28.6 | 32.0 | 36.9 | 43.9 | 51.0 | 55.3 | 56.7 | 76.2 | 48.0 | 39.0 | 33.5 | 34.4 | 31.9 | 28.4 | 25.0 |
| Winter Typical | 9.1 | 7.9 | 7.5 | 7.2 | 7.7 | 9.8 | 11.7 | 12.3 | 10.1 | 9.9 | 9.7 | 9.5 | 9.4 | 9.4 | 9.6 | 10.9 | 35.1 | 17.0 | 17.3 | 17.5 | 17.2 | 15.4 | 12.7 | 10.5 |
| Summer Typical | 13.0 | 11.8 | 11.4 | 10.8 | 11.2 | 13.0 | 14.4 | 15.0 | 13.6 | 14.2 | 15.1 | 16.5 | 18.8 | 21.2 | 22.7 | 23.9 | 46.1 | 23.8 | 20.1 | 18.8 | 20.1 | 18.8 | 16.2 | 13.6 |

# Appendix C: Transmission Bus Loading (Without Demand Response)

Non-Aggressive/Aggressive, Level 1/2, 2018/2026

| | Non-Aggressive Level 1 2018 | Non-Aggressive Level 2 2018 | Aggressive Level 1 2018 | Aggressive Level 2 2018 | Non-Aggressive Level 1 2026 | Non-Aggressive Level 2 2026 | Aggressive Level 1 2026 | Aggressive Level 2 2026 |
|---|---|---|---|---|---|---|---|---|
| AMN | 0.07 | 0.31 | 0.10 | 0.45 | 0.26 | 1.13 | 0.37 | 1.61 |
| AMN | 0.10 | 0.41 | 0.14 | 0.59 | 0.38 | 1.65 | 0.55 | 2.35 |
| BKE | 0.04 | 0.19 | 0.06 | 0.27 | 0.14 | 0.59 | 0.20 | 0.84 |
| BLE | 0.07 | 0.28 | 0.09 | 0.40 | 0.25 | 1.06 | 0.35 | 1.50 |
| BLH | 0.21 | 0.88 | 0.29 | 1.26 | 0.64 | 2.73 | 0.91 | 3.88 |
| BLH | 0.23 | 1.00 | 0.33 | 1.43 | 0.72 | 3.11 | 1.03 | 4.43 |
| BLT | 0.03 | 0.12 | 0.04 | 0.17 | 0.09 | 0.38 | 0.13 | 0.54 |
| BLT | 0.07 | 0.29 | 0.10 | 0.42 | 0.21 | 0.91 | 0.30 | 1.30 |
| BLT | 0.28 | 1.22 | 0.40 | 1.73 | 0.88 | 3.77 | 1.25 | 5.37 |
| BLT | 0.31 | 1.34 | 0.45 | 1.91 | 0.97 | 4.15 | 1.38 | 5.92 |
| BPK | 0.04 | 0.16 | 0.05 | 0.23 | 0.12 | 0.52 | 0.17 | 0.74 |
| BRD | 0.23 | 0.97 | 0.32 | 1.38 | 0.72 | 3.10 | 1.03 | 4.42 |
| BYN | 0.17 | 0.75 | 0.25 | 1.07 | 0.69 | 2.97 | 0.99 | 4.24 |
| CCS | 0.08 | 0.35 | 0.11 | 0.49 | 0.38 | 1.62 | 0.54 | 2.31 |
| CCS | 0.49 | 2.08 | 0.69 | 2.96 | 2.28 | 9.75 | 3.24 | 13.90 |
| CDO | 0.18 | 0.78 | 0.26 | 1.10 | 0.58 | 2.48 | 0.82 | 3.53 |
| COD | 0.08 | 0.35 | 0.12 | 0.50 | 0.31 | 1.32 | 0.44 | 1.88 |
| COGT | 0.19 | 0.81 | 0.27 | 1.15 | 0.80 | 3.42 | 1.14 | 4.87 |
| CRP | 0.14 | 0.59 | 0.20 | 0.84 | 0.47 | 2.01 | 0.67 | 2.87 |
| DAN | 0.05 | 0.22 | 0.07 | 0.32 | 0.22 | 0.93 | 0.31 | 1.33 |
| DEF | 0.09 | 0.37 | 0.12 | 0.53 | 0.34 | 1.46 | 0.49 | 2.09 |
| DEF | 0.10 | 0.43 | 0.14 | 0.61 | 0.39 | 1.69 | 0.56 | 2.41 |
| ECA | 0.01 | 0.04 | 0.01 | 0.06 | 0.03 | 0.13 | 0.04 | 0.19 |
| ECA | 0.15 | 0.65 | 0.22 | 0.93 | 0.49 | 2.09 | 0.69 | 2.97 |
| ECA | 0.19 | 0.81 | 0.27 | 1.16 | 0.60 | 2.56 | 0.85 | 3.64 |
| ECA | 0.35 | 1.48 | 0.49 | 2.11 | 1.09 | 4.66 | 1.55 | 6.64 |
| ETN | 0.07 | 0.30 | 0.10 | 0.42 | 0.27 | 1.16 | 0.39 | 1.65 |
| ETN | 0.11 | 0.46 | 0.15 | 0.66 | 0.41 | 1.77 | 0.59 | 2.53 |
| FCH | 0.28 | 1.21 | 0.40 | 1.73 | 1.03 | 4.42 | 1.47 | 6.30 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| FCH | 0.43 | 1.86 | 0.62 | 2.65 | 1.63 | 7.01 | 2.33 | 9.98 |
| FEM | 0.06 | 0.24 | 0.08 | 0.34 | 0.22 | 0.96 | 0.32 | 1.36 |
| FEM | 0.07 | 0.29 | 0.10 | 0.42 | 0.24 | 1.04 | 0.34 | 1.48 |
| GAST | 0.21 | 0.89 | 0.29 | 1.26 | 0.97 | 4.16 | 1.38 | 5.93 |
| GWY | 0.04 | 0.19 | 0.06 | 0.27 | 0.14 | 0.60 | 0.20 | 0.85 |
| HKP | 0.14 | 0.59 | 0.20 | 0.84 | 0.43 | 1.85 | 0.61 | 2.63 |
| HKP | 0.18 | 0.79 | 0.26 | 1.13 | 0.58 | 2.47 | 0.82 | 3.52 |
| MAZ | 0.10 | 0.44 | 0.15 | 0.63 | 0.40 | 1.70 | 0.57 | 2.42 |
| MCF | 0.20 | 0.84 | 0.28 | 1.19 | 0.73 | 3.13 | 1.04 | 4.46 |
| MHL | 0.00 | 0.01 | 0.00 | 0.02 | 0.01 | 0.04 | 0.01 | 0.05 |
| MOH | 0.01 | 0.04 | 0.01 | 0.06 | 0.03 | 0.14 | 0.05 | 0.20 |
| MOH | 0.04 | 0.19 | 0.06 | 0.27 | 0.14 | 0.58 | 0.19 | 0.83 |
| MOH | 0.08 | 0.36 | 0.12 | 0.51 | 0.31 | 1.31 | 0.44 | 1.87 |
| NSP | 0.11 | 0.47 | 0.16 | 0.67 | 0.41 | 1.74 | 0.58 | 2.48 |
| NSP | 0.24 | 1.03 | 0.34 | 1.47 | 0.88 | 3.77 | 1.25 | 5.38 |
| NSTT | 0.06 | 0.28 | 0.09 | 0.40 | 0.20 | 0.86 | 0.28 | 1.22 |
| NSTT | 0.08 | 0.34 | 0.11 | 0.49 | 0.25 | 1.05 | 0.35 | 1.50 |
| OKG | 0.28 | 1.21 | 0.40 | 1.73 | 1.10 | 4.70 | 1.56 | 6.70 |
| ORE | 0.07 | 0.31 | 0.10 | 0.44 | 0.30 | 1.27 | 0.42 | 1.80 |
| ORE | 0.11 | 0.48 | 0.16 | 0.69 | 0.47 | 2.00 | 0.67 | 2.85 |
| PFL | 0.04 | 0.16 | 0.05 | 0.23 | 0.12 | 0.50 | 0.17 | 0.72 |
| PFL | 0.20 | 0.87 | 0.29 | 1.25 | 0.74 | 3.17 | 1.05 | 4.51 |
| PHB | 0.26 | 1.12 | 0.37 | 1.60 | 0.87 | 3.74 | 1.24 | 5.33 |
| PHB | 0.28 | 1.18 | 0.39 | 1.68 | 0.94 | 4.02 | 1.34 | 5.73 |
| PLV | 0.02 | 0.08 | 0.03 | 0.12 | 0.08 | 0.36 | 0.12 | 0.51 |
| PLV | 0.04 | 0.17 | 0.06 | 0.24 | 0.15 | 0.64 | 0.21 | 0.90 |
| PLV | 0.08 | 0.36 | 0.12 | 0.51 | 0.30 | 1.29 | 0.43 | 1.84 |
| RKN | 0.15 | 0.62 | 0.21 | 0.89 | 0.49 | 2.08 | 0.69 | 2.97 |
| RKN | 0.21 | 0.92 | 0.30 | 1.31 | 0.71 | 3.05 | 1.01 | 4.35 |
| RYS | 0.06 | 0.24 | 0.08 | 0.34 | 0.17 | 0.73 | 0.24 | 1.04 |
| RYS | 0.17 | 0.71 | 0.24 | 1.01 | 0.53 | 2.27 | 0.76 | 3.24 |
| SPR | 0.30 | 1.26 | 0.42 | 1.80 | 1.24 | 5.30 | 1.76 | 7.56 |
| SPR | 0.37 | 1.57 | 0.52 | 2.23 | 1.46 | 6.24 | 2.07 | 8.89 |
| ST1 | 0.03 | 0.12 | 0.04 | 0.17 | 0.09 | 0.37 | 0.12 | 0.53 |
| ST1 | 0.04 | 0.18 | 0.06 | 0.26 | 0.13 | 0.56 | 0.19 | 0.80 |
| ST2 | 0.06 | 0.25 | 0.08 | 0.35 | 0.18 | 0.76 | 0.25 | 1.08 |
| ST2 | 0.07 | 0.29 | 0.10 | 0.41 | 0.21 | 0.89 | 0.30 | 1.27 |
| STO | 0.06 | 0.27 | 0.09 | 0.38 | 0.26 | 1.11 | 0.37 | 1.58 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| SUP | 0.08 | 0.33 | 0.11 | 0.47 | 0.25 | 1.05 | 0.35 | 1.50 |
| SUP | 0.09 | 0.37 | 0.12 | 0.53 | 0.28 | 1.19 | 0.40 | 1.70 |
| SUP | 0.13 | 0.56 | 0.18 | 0.79 | 0.52 | 2.24 | 0.74 | 3.19 |
| SYC | 0.08 | 0.35 | 0.12 | 0.50 | 0.30 | 1.30 | 0.43 | 1.85 |
| SYC | 0.19 | 0.83 | 0.28 | 1.19 | 0.72 | 3.11 | 1.03 | 4.43 |
| SYN | 0.13 | 0.57 | 0.19 | 0.81 | 0.50 | 2.13 | 0.71 | 3.04 |
| TBL | 0.13 | 0.56 | 0.18 | 0.79 | 0.49 | 2.09 | 0.69 | 2.97 |
| TKY | 0.12 | 0.49 | 0.16 | 0.70 | 0.36 | 1.56 | 0.52 | 2.22 |
| TOC | 0.15 | 0.66 | 0.22 | 0.93 | 0.54 | 2.30 | 0.77 | 3.28 |
| VER | 0.06 | 0.25 | 0.08 | 0.35 | 0.25 | 1.06 | 0.35 | 1.51 |
| VER | 0.14 | 0.60 | 0.20 | 0.86 | 0.66 | 2.82 | 0.94 | 4.02 |
| WE1 | 0.00 | 0.01 | 0.00 | 0.01 | 0.01 | 0.02 | 0.01 | 0.03 |
| WE3 | 0.14 | 0.58 | 0.19 | 0.83 | 0.44 | 1.88 | 0.63 | 2.68 |
| WGA | 0.13 | 0.57 | 0.19 | 0.82 | 0.49 | 2.09 | 0.70 | 2.98 |
| WGA | 0.22 | 0.93 | 0.31 | 1.33 | 0.76 | 3.28 | 1.09 | 4.67 |
| WLT | 0.11 | 0.48 | 0.16 | 0.69 | 0.37 | 1.57 | 0.52 | 2.24 |
| WLT | 0.19 | 0.84 | 0.28 | 1.19 | 0.60 | 2.59 | 0.86 | 3.69 |
| WLT | 0.31 | 1.31 | 0.44 | 1.87 | 1.00 | 4.31 | 1.43 | 6.14 |
| WMD | 0.05 | 0.20 | 0.07 | 0.28 | 0.20 | 0.85 | 0.28 | 1.21 |
| WMD | 0.22 | 0.96 | 0.32 | 1.37 | 0.86 | 3.70 | 1.23 | 5.27 |
| WPK | 0.17 | 0.75 | 0.25 | 1.07 | 0.57 | 2.43 | 0.81 | 3.46 |
| WPT | 0.34 | 1.47 | 0.49 | 2.10 | 1.38 | 5.91 | 1.96 | 8.42 |
| WTN | 0.13 | 0.56 | 0.19 | 0.80 | 0.48 | 2.05 | 0.68 | 2.92 |
| WTN | 0.20 | 0.85 | 0.28 | 1.21 | 0.68 | 2.91 | 0.97 | 4.14 |
| WTN | 0.33 | 1.42 | 0.47 | 2.03 | 1.11 | 4.76 | 1.58 | 6.78 |
| YAR | 0.04 | 0.16 | 0.05 | 0.22 | 0.15 | 0.65 | 0.21 | 0.92 |

# Appendix D: Transmission Impact Results (*Without Demand Response*)

N-2, Non-Aggressive/Aggressive, Level 1/2, 2018

| | Voltage Contingency | Voltage Load Margin | Worst-Case Bus | Thermal Contingency | Overloaded Equipment | Percent Overload | Thermal Load Margin |
|---|---|---|---|---|---|---|---|
| Basecase | COL-NMA dbl ckt | 210 | 696 WLT | COL-NMA dbl ckt | PTE-COL 69-kV | 134.1% | 0 |
| Non-Aggressive Level 1 | COL-NMA dbl ckt | 200 | 696 WLT | COL-NMA dbl ckt | ARE-SPG 69-kV<br>PTE-COL 69-kV | 111.8%<br>136.3% | 0 |
| Aggressive Level 1 | COL-NMA dbl ckt | 195 | 696 WLT | COL-NMA dbl ckt | ARE-SPG 69-kV<br>PTE-COL 69-kV | 112.6%<br>137.3% | 0 |
| Non-Aggressive Level 2 | COL-NMA dbl ckt | 165 | 696 WLT | COL-NMA dbl ckt | DHT-OKE 69-kV<br>ARE-SPG 69-kV<br>PTE-COL 69-kV | 111.9%<br>118.0%<br>144.0% | 0 |
| Aggressive Level 2 | COL-NMA dbl ckt | 140 | 696 WLT | COL-NMA dbl ckt | DHT-OKE 69-kV<br>ARE-SPG 69-kV<br>PTE-COL 69-kV | 117.2%<br>122.7%<br>149.4% | 0 |

N-1, Non-Aggressive/Aggressive, Level 1/2, 2018

| | Voltage Contingency | Voltage Load Margin | Worst-Case Bus | Thermal Contingency | Overloaded Equipment | Percent Overload | Thermal Load Margin |
|---|---|---|---|---|---|---|---|
| Basecase | ROE-WPT ckt | 665 | 709 NSP | BLT-SYC ckt | GWY-SYC 69-kV | 110.20% | 385 |
| Non-Aggressive Level 1 | ROE-WPT ckt | 660 | 709 NSP | BLT-SYC ckt | GWY-SYC 69-kV | 110.50% | 375 |
| Aggressive Level 1 | ROE-WPT ckt | 655 | 709 NSP | BLT-SYC ckt | GWY-SYC 69-kV | 110.60% | 370 |
| Non-Aggressive Level 2 | ROE-WPT ckt | 625 | 709 NSP | BLT-SYC ckt | GWY-SYC 69-kV | 110.00% | 330 |
| Aggressive Level 2 | ROE-WPT ckt | 605 | 709 NSP | BLT-SYC ckt | GWY-SYC 69-kV | 110.20% | 310 |

N-2, Non-Aggressive/Aggressive, Level 1/2, 2026

| | Voltage Contingency | Voltage Load Margin | Worst-Case Bus | Thermal Contingency | Overloaded Equipment | Percent Overload | Thermal Load Margin |
|---|---|---|---|---|---|---|---|
| Basecase | COL-NMA dbl ckt | 210 | 696 WLT | COL-NMA dbl ckt | PTE-COL 69-kV | 134.1% | 0 |
| Non-Aggressive Level 1 | COL-NMA dbl ckt | 170 | 696 WLT | COL-NMA dbl ckt | DHT-OKE 69-kV<br>ARE-SPG 69-kV<br>PTE-COL 69-kV | 110.4%<br>116.7%<br>142.4% | 0 |
| Aggressive Level 1 | COL-NMA dbl ckt | 155 | 696 WLT | COL-NMA dbl ckt | DHT-OKE 69-kV<br>ARE-SPG 69-kV<br>PTE-COL 69-kV | 113.8%<br>119.9%<br>146.1% | 0 |
| Non-Aggressive Level 2 | COL-NMA dbl ckt | 35 | 696 WLT | COL-NMA dbl ckt | DHT-OKE 69-kV<br>ARE-SPG 69-kV<br>MZI-ARE 69-kV<br>PTE-COL 69-kV<br>LOD-DAN 69-kV | 148.3%<br>150.2%<br>114.3%<br>183.0%<br>117.6% | 0 |
| Aggressive Level 2 | COL-NMA dbl ckt | 0 | 696 WLT | N/A | Insecure Basecase | N/A | N/A |

N-1, Non-Aggressive/Aggressive, Level 1/2, 2026

| | Voltage Contingency | Voltage Load Margin | Worst-Case Bus | Thermal Contingency | Overloaded Equipment | Percent Overload | Thermal Load Margin |
|---|---|---|---|---|---|---|---|
| Basecase | ROE-WPT ckt | 665 | 709 NSP | BLT-SYC ckt | GWY-SYC 69-kV | 110.20% | 385 |
| Non-Aggressive Level 1 | ROE-WPT ckt | 630 | 709 NSP | RYS-RYS ckt | SYN-FCH 69-kV | 110.10% | 345 |
| Aggressive Level 1 | ROE-WPT ckt | 615 | 709 NSP | BLT-SYC ckt | GWY-SYC 69-kV | 110.20% | 330 |
| Non-Aggressive Level 2 | ROE-WPT ckt | 505 | 709 NSP | RYS-RYS ckt | SYN-FCH 69-kV | 110.10% | 205 |
| Aggressive Level 2 | ROE-WPT ckt | 435 | 709 NSP | RYS-RYS ckt | SYN-FCH 69-kV | 110.10% | 125 |

# Appendix E: Distribution Impact Results (With Demand Response)

Non-Aggressive/Aggressive, Level 1, 8 Households per Transformer (through 2018)

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1 PHEV** | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 7.9 | 7.9 | 7.8 | 7.5 | 7.6 | 7.9 | 8.5 | 9.3 | 9.4 | 9.2 | 9.2 | 9.0 | 9.0 | 8.9 | 8.9 | 9.6 | 10.4 | 12.2 | 14.0 | 14.2 | 13.9 | 12.5 | 10.3 | 8.6 |
| Summer Peak | 19.9 | 19.9 | 19.5 | 18.8 | 18.9 | 19.9 | 20.5 | 21.3 | 21.0 | 22.9 | 25.6 | 29.5 | 35.1 | 40.8 | 44.2 | 45.3 | 43.0 | 36.9 | 31.2 | 26.8 | 27.5 | 25.5 | 22.7 | 20.0 |
| Winter Typical | 8.1 | 8.1 | 7.8 | 7.5 | 7.9 | 8.1 | 9.3 | 9.8 | 8.1 | 7.9 | 7.8 | 7.6 | 7.5 | 7.5 | 7.7 | 8.7 | 10.0 | 12.1 | 13.8 | 14.0 | 13.8 | 12.3 | 10.2 | 8.4 |
| Summer Typical | 11.0 | 11.0 | 10.8 | 10.4 | 10.7 | 11.0 | 11.5 | 12.0 | 10.9 | 11.3 | 12.1 | 13.2 | 15.0 | 16.9 | 18.2 | 19.1 | 18.9 | 17.5 | 16.0 | 15.1 | 16.1 | 15.0 | 13.0 | 11.0 |
| **2 PHEV** | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.3 | 9.4 | 9.2 | 9.2 | 9.0 | 9.0 | 8.9 | 8.9 | 9.6 | 10.4 | 12.2 | 14.0 | 14.2 | 13.9 | 12.5 | 10.3 | 9.0 |
| Summer Peak | 20.7 | 20.7 | 20.7 | 20.5 | 20.7 | 20.7 | 20.7 | 21.3 | 21.0 | 22.9 | 25.6 | 29.5 | 35.1 | 40.8 | 44.2 | 45.3 | 43.0 | 36.9 | 31.2 | 26.8 | 27.5 | 25.5 | 22.7 | 20.7 |
| Winter Typical | 9.2 | 9.2 | 9.2 | 9.2 | 9.2 | 9.2 | 9.3 | 9.8 | 8.1 | 7.9 | 7.8 | 7.6 | 7.5 | 7.5 | 7.7 | 8.7 | 10.0 | 12.1 | 13.8 | 14.0 | 13.8 | 12.3 | 10.2 | 9.2 |
| Summer Typical | 11.9 | 11.9 | 11.9 | 11.9 | 11.9 | 11.9 | 11.9 | 12.0 | 10.9 | 11.3 | 12.1 | 13.2 | 15.0 | 16.9 | 18.2 | 19.1 | 18.9 | 17.5 | 16.0 | 15.1 | 16.1 | 15.0 | 13.0 | 11.9 |
| **3 PHEV** | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 9.3 | 9.4 | 9.2 | 9.2 | 9.0 | 9.0 | 8.9 | 8.9 | 9.6 | 10.4 | 12.2 | 14.0 | 14.2 | 13.9 | 12.5 | 10.3 | 10.0 |
| Summer Peak | 21.7 | 21.7 | 21.7 | 21.7 | 21.7 | 21.7 | 21.7 | 21.3 | 21.0 | 22.9 | 25.6 | 29.5 | 35.1 | 40.8 | 44.2 | 45.3 | 43.0 | 36.9 | 31.2 | 26.8 | 27.5 | 25.5 | 22.7 | 21.7 |
| Winter Typical | 10.2 | 10.2 | 10.2 | 10.2 | 10.2 | 10.2 | 10.2 | 9.8 | 8.1 | 7.9 | 7.8 | 7.6 | 7.5 | 7.5 | 7.7 | 8.7 | 10.0 | 12.1 | 13.8 | 14.0 | 13.8 | 12.3 | 10.2 | 10.2 |
| Summer Typical | 13.0 | 13.0 | 13.0 | 13.0 | 13.0 | 13.0 | 13.0 | 12.0 | 10.9 | 11.3 | 12.1 | 13.2 | 15.0 | 16.9 | 18.2 | 19.1 | 18.9 | 17.5 | 16.0 | 15.1 | 16.1 | 15.0 | 13.0 | 13.0 |

Non-Aggressive/Aggressive, Level 1, 10 Households per Transformer (through 2018)

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1 PHEV** | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 9.8 | 9.6 | 9.4 | 8.9 | 9.0 | 9.6 | 10.6 | 11.6 | 11.8 | 11.5 | 11.5 | 11.3 | 11.2 | 11.2 | 11.2 | 12.0 | 13.0 | 15.2 | 17.4 | 17.8 | 17.4 | 15.6 | 12.9 | 10.7 |
| Summer Peak | 24.7 | 24.4 | 23.9 | 23.0 | 23.2 | 24.6 | 25.6 | 26.7 | 26.2 | 28.6 | 32.0 | 36.9 | 43.9 | 51.0 | 55.3 | 56.7 | 53.7 | 46.1 | 39.0 | 33.5 | 34.4 | 31.9 | 28.4 | 25.0 |
| Winter Typical | 9.9 | 9.7 | 9.3 | 9.0 | 9.4 | 10.1 | 11.7 | 12.3 | 10.1 | 9.9 | 9.7 | 9.5 | 9.4 | 9.4 | 9.6 | 10.9 | 12.6 | 15.1 | 17.3 | 17.5 | 17.2 | 15.4 | 12.7 | 10.5 |
| Summer Typical | 13.6 | 13.4 | 13.1 | 12.6 | 12.9 | 13.6 | 14.4 | 15.0 | 13.6 | 14.2 | 15.1 | 16.5 | 18.8 | 21.2 | 22.7 | 23.9 | 23.6 | 21.9 | 20.1 | 18.8 | 20.1 | 18.8 | 16.2 | 13.7 |
| **2 PHEV** | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 10.9 | 10.6 | 10.5 | 10.4 | 10.4 | 10.7 | 11.1 | 11.6 | 11.8 | 11.5 | 11.5 | 11.3 | 11.2 | 11.2 | 11.2 | 12.0 | 13.0 | 15.2 | 17.4 | 17.8 | 17.4 | 15.6 | 12.9 | 11.1 |
| Summer Peak | 25.5 | 25.3 | 25.1 | 24.8 | 25.0 | 25.5 | 25.8 | 26.7 | 26.2 | 28.6 | 32.0 | 36.9 | 43.9 | 51.0 | 55.3 | 56.7 | 53.7 | 46.1 | 39.0 | 33.5 | 34.4 | 31.9 | 28.4 | 25.7 |
| Winter Typical | 11.0 | 10.7 | 10.7 | 10.6 | 10.7 | 11.1 | 11.7 | 12.3 | 10.1 | 9.9 | 9.7 | 9.5 | 9.4 | 9.4 | 9.6 | 10.9 | 12.6 | 15.1 | 17.3 | 17.5 | 17.2 | 15.4 | 12.7 | 11.3 |
| Summer Typical | 14.5 | 14.3 | 14.2 | 14.1 | 14.2 | 14.5 | 14.8 | 15.0 | 13.6 | 14.2 | 15.1 | 16.5 | 18.8 | 21.2 | 22.7 | 23.9 | 23.6 | 21.9 | 20.1 | 18.8 | 20.1 | 18.8 | 16.2 | 14.7 |
| **3 PHEV** | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 11.9 | 11.7 | 11.5 | 11.4 | 11.5 | 11.7 | 12.1 | 11.6 | 11.8 | 11.5 | 11.5 | 11.3 | 11.2 | 11.2 | 11.2 | 12.0 | 13.0 | 15.2 | 17.4 | 17.8 | 17.4 | 15.6 | 12.9 | 12.1 |
| Summer Peak | 26.5 | 26.2 | 26.1 | 25.9 | 26.0 | 26.4 | 26.8 | 26.7 | 26.2 | 28.6 | 32.0 | 36.9 | 43.9 | 51.0 | 55.3 | 56.7 | 53.7 | 46.1 | 39.0 | 33.5 | 34.4 | 31.9 | 28.4 | 26.7 |
| Winter Typical | 12.0 | 11.8 | 11.7 | 11.6 | 11.7 | 12.1 | 12.5 | 12.3 | 10.1 | 9.9 | 9.7 | 9.5 | 9.4 | 9.4 | 9.6 | 10.9 | 12.6 | 15.1 | 17.3 | 17.5 | 17.2 | 15.4 | 12.7 | 12.3 |
| Summer Typical | 15.6 | 15.3 | 15.2 | 15.1 | 15.2 | 15.6 | 15.8 | 15.0 | 13.6 | 14.2 | 15.1 | 16.5 | 18.8 | 21.2 | 22.7 | 23.9 | 23.6 | 21.9 | 20.1 | 18.8 | 20.1 | 18.8 | 16.2 | 15.7 |

Non-Aggressive/Aggressive, Level 2, 8 Households per Transformer (through 2018)

|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1 PHEV** | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 7.8 | 7.8 | 7.8 | 7.8 | 7.8 | 7.8 | 8.5 | 9.3 | 9.4 | 9.2 | 9.2 | 9.0 | 9.0 | 8.9 | 8.9 | 9.6 | 10.4 | 12.2 | 14.0 | 14.2 | 13.9 | 12.5 | 10.3 | 8.6 |
| Summer Peak | 19.5 | 19.5 | 19.5 | 19.5 | 19.5 | 19.5 | 20.5 | 21.3 | 21.0 | 22.9 | 25.6 | 29.5 | 35.1 | 40.8 | 44.2 | 45.3 | 43.0 | 36.9 | 31.2 | 26.8 | 27.5 | 25.5 | 22.7 | 20.0 |
| Winter Typical | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 | 9.3 | 9.8 | 8.1 | 7.9 | 7.8 | 7.6 | 7.5 | 7.5 | 7.7 | 8.7 | 10.0 | 12.1 | 13.8 | 14.0 | 13.8 | 12.3 | 10.2 | 8.4 |
| Summer Typical | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 11.5 | 12.0 | 10.9 | 11.3 | 12.1 | 13.2 | 15.0 | 16.9 | 18.2 | 19.1 | 18.9 | 17.5 | 16.0 | 15.1 | 16.1 | 15.0 | 13.0 | 10.9 |
| **2 PHEV** | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.3 | 9.4 | 9.2 | 9.2 | 9.0 | 9.0 | 8.9 | 8.9 | 9.6 | 10.4 | 12.2 | 14.0 | 14.2 | 13.9 | 12.5 | 10.3 | 9.0 |
| Summer Peak | 20.7 | 20.7 | 20.7 | 20.7 | 20.7 | 20.7 | 20.7 | 21.3 | 21.0 | 22.9 | 25.6 | 29.5 | 35.1 | 40.8 | 44.2 | 45.3 | 43.0 | 36.9 | 31.2 | 26.8 | 27.5 | 25.5 | 22.7 | 20.7 |
| Winter Typical | 9.2 | 9.2 | 9.2 | 9.2 | 9.2 | 9.2 | 9.3 | 9.8 | 8.1 | 7.9 | 7.8 | 7.6 | 7.5 | 7.5 | 7.7 | 8.7 | 10.0 | 12.1 | 13.8 | 14.0 | 13.8 | 12.3 | 10.2 | 9.2 |
| Summer Typical | 11.9 | 11.9 | 11.9 | 11.9 | 11.9 | 11.9 | 11.9 | 12.0 | 10.9 | 11.3 | 12.1 | 13.2 | 15.0 | 16.9 | 18.2 | 19.1 | 18.9 | 17.5 | 16.0 | 15.1 | 16.1 | 15.0 | 13.0 | 11.9 |
| **3 PHEV** | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 9.3 | 9.4 | 9.2 | 9.2 | 9.0 | 9.0 | 8.9 | 8.9 | 9.6 | 10.4 | 12.2 | 14.0 | 14.2 | 13.9 | 12.5 | 10.3 | 10.0 |
| Summer Peak | 21.7 | 21.7 | 21.7 | 21.7 | 21.7 | 21.7 | 21.7 | 21.3 | 21.0 | 22.9 | 25.6 | 29.5 | 35.1 | 40.8 | 44.2 | 45.3 | 43.0 | 36.9 | 31.2 | 26.8 | 27.5 | 25.5 | 22.7 | 21.7 |
| Winter Typical | 10.2 | 10.2 | 10.2 | 10.2 | 10.2 | 10.2 | 10.2 | 9.8 | 8.1 | 7.9 | 7.8 | 7.6 | 7.5 | 7.5 | 7.7 | 8.7 | 10.0 | 12.1 | 13.8 | 14.0 | 13.8 | 12.3 | 10.2 | 10.2 |
| Summer Typical | 13.0 | 13.0 | 13.0 | 13.0 | 13.0 | 13.0 | 13.0 | 12.0 | 10.9 | 11.3 | 12.1 | 13.2 | 15.0 | 16.9 | 18.2 | 19.1 | 18.9 | 17.5 | 16.0 | 15.1 | 16.1 | 15.0 | 13.0 | 13.0 |

Non-Aggressive/Aggressive, Level 2, 10 Households per Transformer (through 2018)

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1 PHEV** | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 9.7 | 9.4 | 9.3 | 9.2 | 9.2 | 9.5 | 10.6 | 11.6 | 11.8 | 11.5 | 11.5 | 11.3 | 11.2 | 11.2 | 11.2 | 12.0 | 13.0 | 15.2 | 17.4 | 17.8 | 17.4 | 15.6 | 12.9 | 10.7 |
| Summer Peak | 24.3 | 24.0 | 23.9 | 23.7 | 23.7 | 24.2 | 25.6 | 26.7 | 26.2 | 28.6 | 32.0 | 36.9 | 43.9 | 51.0 | 55.3 | 56.7 | 53.7 | 46.1 | 39.0 | 33.5 | 34.4 | 31.9 | 28.4 | 25.0 |
| Winter Typical | 9.7 | 9.5 | 9.4 | 9.4 | 9.5 | 9.9 | 11.7 | 12.3 | 10.1 | 9.9 | 9.7 | 9.5 | 9.4 | 9.4 | 9.6 | 10.9 | 12.6 | 15.1 | 17.3 | 17.5 | 17.2 | 15.4 | 12.7 | 10.5 |
| Summer Typical | 13.4 | 13.2 | 13.1 | 13.0 | 13.1 | 13.4 | 14.4 | 15.0 | 13.6 | 14.2 | 15.1 | 16.5 | 18.8 | 21.2 | 22.7 | 23.9 | 23.6 | 21.9 | 20.1 | 18.8 | 20.1 | 18.8 | 16.2 | 13.6 |
| **2 PHEV** | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 10.9 | 10.6 | 10.5 | 10.4 | 10.4 | 10.7 | 11.1 | 11.6 | 11.8 | 11.5 | 11.5 | 11.3 | 11.2 | 11.2 | 11.2 | 12.0 | 13.0 | 15.2 | 17.4 | 17.8 | 17.4 | 15.6 | 12.9 | 11.1 |
| Summer Peak | 25.5 | 25.2 | 25.1 | 24.9 | 25.0 | 25.4 | 25.8 | 26.7 | 26.2 | 28.6 | 32.0 | 36.9 | 43.9 | 51.0 | 55.3 | 56.7 | 53.7 | 46.1 | 39.0 | 33.5 | 34.4 | 31.9 | 28.4 | 25.7 |
| Winter Typical | 11.0 | 10.7 | 10.7 | 10.6 | 10.7 | 11.1 | 11.7 | 12.3 | 10.1 | 9.9 | 9.7 | 9.5 | 9.4 | 9.4 | 9.6 | 10.9 | 12.6 | 15.1 | 17.3 | 17.5 | 17.2 | 15.4 | 12.7 | 11.3 |
| Summer Typical | 14.5 | 14.3 | 14.2 | 14.1 | 14.2 | 14.5 | 14.8 | 15.0 | 13.6 | 14.2 | 15.1 | 16.5 | 18.8 | 21.2 | 22.7 | 23.9 | 23.6 | 21.9 | 20.1 | 18.8 | 20.1 | 18.8 | 16.2 | 14.7 |
| **3 PHEV** | | | | | | | | | | | | | | | | | | | | | | | | |
| Winter Peak | 11.9 | 11.7 | 11.5 | 11.4 | 11.5 | 11.7 | 12.1 | 11.6 | 11.8 | 11.5 | 11.5 | 11.3 | 11.2 | 11.2 | 11.2 | 12.0 | 13.0 | 15.2 | 17.4 | 17.8 | 17.4 | 15.6 | 12.9 | 12.1 |
| Summer Peak | 26.5 | 26.2 | 26.1 | 25.9 | 26.0 | 26.4 | 26.8 | 26.7 | 26.2 | 28.6 | 32.0 | 36.9 | 43.9 | 51.0 | 55.3 | 56.7 | 53.7 | 46.1 | 39.0 | 33.5 | 34.4 | 31.9 | 28.4 | 26.7 |
| Winter Typical | 12.0 | 11.8 | 11.7 | 11.6 | 11.7 | 12.1 | 12.5 | 12.3 | 10.1 | 9.9 | 9.7 | 9.5 | 9.4 | 9.4 | 9.6 | 10.9 | 12.6 | 15.1 | 17.3 | 17.5 | 17.2 | 15.4 | 12.7 | 12.3 |
| Summer Typical | 15.6 | 15.3 | 15.2 | 15.1 | 15.2 | 15.6 | 15.8 | 15.0 | 13.6 | 14.2 | 15.1 | 16.5 | 18.8 | 21.2 | 22.7 | 23.9 | 23.6 | 21.9 | 20.1 | 18.8 | 20.1 | 18.8 | 16.2 | 15.7 |

*Appendix F: Transmission Bus Loading (With Demand Response)*

Non-Aggressive/Aggressive, Level 1/2, 2018/2026

| | Non-Aggressive Level 1 2018 | Non-Aggressive Level 2 2018 | Aggressive Level 1 2018 | Aggressive Level 2 2018 | Non-Aggressive Level 1 2026 | Non-Aggressive Level 2 2026 | Aggressive Level 1 2026 | Aggressive Level 2 2026 |
|---|---|---|---|---|---|---|---|---|
| AMN | 0.07 | 0.31 | 0.10 | 0.45 | 0.26 | 1.13 | 0.37 | 1.61 |
| AMN | 0.10 | 0.41 | 0.14 | 0.59 | 0.38 | 1.65 | 0.55 | 2.35 |
| BKE | 0.04 | 0.19 | 0.06 | 0.27 | 0.14 | 0.59 | 0.20 | 0.84 |
| BLE | 0.07 | 0.28 | 0.09 | 0.40 | 0.25 | 1.06 | 0.35 | 1.50 |
| BLH | 0.21 | 0.88 | 0.29 | 1.26 | 0.64 | 2.73 | 0.91 | 3.88 |
| BLH | 0.23 | 1.00 | 0.33 | 1.43 | 0.72 | 3.11 | 1.03 | 4.43 |
| BLT | 0.03 | 0.12 | 0.04 | 0.17 | 0.09 | 0.38 | 0.13 | 0.54 |
| BLT | 0.07 | 0.29 | 0.10 | 0.42 | 0.21 | 0.91 | 0.30 | 1.30 |
| BLT | 0.28 | 1.22 | 0.40 | 1.73 | 0.88 | 3.77 | 1.25 | 5.37 |
| BLT | 0.31 | 1.34 | 0.45 | 1.91 | 0.97 | 4.15 | 1.38 | 5.92 |
| BPK | 0.04 | 0.16 | 0.05 | 0.23 | 0.12 | 0.52 | 0.17 | 0.74 |
| BRD | 0.23 | 0.97 | 0.32 | 1.38 | 0.72 | 3.10 | 1.03 | 4.42 |
| BYN | 0.17 | 0.75 | 0.25 | 1.07 | 0.69 | 2.97 | 0.99 | 4.24 |
| CCS | 0.08 | 0.35 | 0.11 | 0.49 | 0.38 | 1.62 | 0.54 | 2.31 |
| CCS | 0.49 | 2.08 | 0.69 | 2.96 | 2.28 | 9.75 | 3.24 | 13.90 |
| CDO | 0.18 | 0.78 | 0.26 | 1.10 | 0.58 | 2.48 | 0.82 | 3.53 |
| COD | 0.08 | 0.35 | 0.12 | 0.50 | 0.31 | 1.32 | 0.44 | 1.88 |
| COGT | 0.19 | 0.81 | 0.27 | 1.15 | 0.80 | 3.42 | 1.14 | 4.87 |
| CRP | 0.14 | 0.59 | 0.20 | 0.84 | 0.47 | 2.01 | 0.67 | 2.87 |
| DAN | 0.05 | 0.22 | 0.07 | 0.32 | 0.22 | 0.93 | 0.31 | 1.33 |
| DEF | 0.09 | 0.37 | 0.12 | 0.53 | 0.34 | 1.46 | 0.49 | 2.09 |
| DEF | 0.10 | 0.43 | 0.14 | 0.61 | 0.39 | 1.69 | 0.56 | 2.41 |
| ECA | 0.01 | 0.04 | 0.01 | 0.06 | 0.03 | 0.13 | 0.04 | 0.19 |
| ECA | 0.15 | 0.65 | 0.22 | 0.93 | 0.49 | 2.09 | 0.69 | 2.97 |
| ECA | 0.19 | 0.81 | 0.27 | 1.16 | 0.60 | 2.56 | 0.85 | 3.64 |
| ECA | 0.35 | 1.48 | 0.49 | 2.11 | 1.09 | 4.66 | 1.55 | 6.64 |
| ETN | 0.07 | 0.30 | 0.10 | 0.42 | 0.27 | 1.16 | 0.39 | 1.65 |
| ETN | 0.11 | 0.46 | 0.15 | 0.66 | 0.41 | 1.77 | 0.59 | 2.53 |
| FCH | 0.28 | 1.21 | 0.40 | 1.73 | 1.03 | 4.42 | 1.47 | 6.30 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| FCH | 0.43 | 1.86 | 0.62 | 2.65 | 1.63 | 7.01 | 2.33 | 9.98 |
| FEM | 0.06 | 0.24 | 0.08 | 0.34 | 0.22 | 0.96 | 0.32 | 1.36 |
| FEM | 0.07 | 0.29 | 0.10 | 0.42 | 0.24 | 1.04 | 0.34 | 1.48 |
| GAST | 0.21 | 0.89 | 0.29 | 1.26 | 0.97 | 4.16 | 1.38 | 5.93 |
| GWY | 0.04 | 0.19 | 0.06 | 0.27 | 0.14 | 0.60 | 0.20 | 0.85 |
| HKP | 0.14 | 0.59 | 0.20 | 0.84 | 0.43 | 1.85 | 0.61 | 2.63 |
| HKP | 0.18 | 0.79 | 0.26 | 1.13 | 0.58 | 2.47 | 0.82 | 3.52 |
| MAZ | 0.10 | 0.44 | 0.15 | 0.63 | 0.40 | 1.70 | 0.57 | 2.42 |
| MCF | 0.20 | 0.84 | 0.28 | 1.19 | 0.73 | 3.13 | 1.04 | 4.46 |
| MHL | 0.00 | 0.01 | 0.00 | 0.02 | 0.01 | 0.04 | 0.01 | 0.05 |
| MOH | 0.01 | 0.04 | 0.01 | 0.06 | 0.03 | 0.14 | 0.05 | 0.20 |
| MOH | 0.04 | 0.19 | 0.06 | 0.27 | 0.14 | 0.58 | 0.19 | 0.83 |
| MOH | 0.08 | 0.36 | 0.12 | 0.51 | 0.31 | 1.31 | 0.44 | 1.87 |
| NSP | 0.11 | 0.47 | 0.16 | 0.67 | 0.41 | 1.74 | 0.58 | 2.48 |
| NSP | 0.24 | 1.03 | 0.34 | 1.47 | 0.88 | 3.77 | 1.25 | 5.38 |
| NSTT | 0.06 | 0.28 | 0.09 | 0.40 | 0.20 | 0.86 | 0.28 | 1.22 |
| NSTT | 0.08 | 0.34 | 0.11 | 0.49 | 0.25 | 1.05 | 0.35 | 1.50 |
| OKG | 0.28 | 1.21 | 0.40 | 1.73 | 1.10 | 4.70 | 1.56 | 6.70 |
| ORE | 0.07 | 0.31 | 0.10 | 0.44 | 0.30 | 1.27 | 0.42 | 1.80 |
| ORE | 0.11 | 0.48 | 0.16 | 0.69 | 0.47 | 2.00 | 0.67 | 2.85 |
| PFL | 0.04 | 0.16 | 0.05 | 0.23 | 0.12 | 0.50 | 0.17 | 0.72 |
| PFL | 0.20 | 0.87 | 0.29 | 1.25 | 0.74 | 3.17 | 1.05 | 4.51 |
| PHB | 0.26 | 1.12 | 0.37 | 1.60 | 0.87 | 3.74 | 1.24 | 5.33 |
| PHB | 0.28 | 1.18 | 0.39 | 1.68 | 0.94 | 4.02 | 1.34 | 5.73 |
| PLV | 0.02 | 0.08 | 0.03 | 0.12 | 0.08 | 0.36 | 0.12 | 0.51 |
| PLV | 0.04 | 0.17 | 0.06 | 0.24 | 0.15 | 0.64 | 0.21 | 0.90 |
| PLV | 0.08 | 0.36 | 0.12 | 0.51 | 0.30 | 1.29 | 0.43 | 1.84 |
| RKN | 0.15 | 0.62 | 0.21 | 0.89 | 0.49 | 2.08 | 0.69 | 2.97 |
| RKN | 0.21 | 0.92 | 0.30 | 1.31 | 0.71 | 3.05 | 1.01 | 4.35 |
| RYS | 0.06 | 0.24 | 0.08 | 0.34 | 0.17 | 0.73 | 0.24 | 1.04 |
| RYS | 0.17 | 0.71 | 0.24 | 1.01 | 0.53 | 2.27 | 0.76 | 3.24 |
| SPR | 0.30 | 1.26 | 0.42 | 1.80 | 1.24 | 5.30 | 1.76 | 7.56 |
| SPR | 0.37 | 1.57 | 0.52 | 2.23 | 1.46 | 6.24 | 2.07 | 8.89 |
| ST1 | 0.03 | 0.12 | 0.04 | 0.17 | 0.09 | 0.37 | 0.12 | 0.53 |
| ST1 | 0.04 | 0.18 | 0.06 | 0.26 | 0.13 | 0.56 | 0.19 | 0.80 |
| ST2 | 0.06 | 0.25 | 0.08 | 0.35 | 0.18 | 0.76 | 0.25 | 1.08 |
| ST2 | 0.07 | 0.29 | 0.10 | 0.41 | 0.21 | 0.89 | 0.30 | 1.27 |
| STO | 0.06 | 0.27 | 0.09 | 0.38 | 0.26 | 1.11 | 0.37 | 1.58 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| SUP | 1.50 | 0.35 | 1.05 | 0.25 | 0.47 | 0.11 | 0.33 | 0.08 |
| SUP | 1.70 | 0.40 | 1.19 | 0.28 | 0.53 | 0.12 | 0.37 | 0.09 |
| SUP | 3.19 | 0.74 | 2.24 | 0.52 | 0.79 | 0.18 | 0.56 | 0.13 |
| SYC | 1.85 | 0.43 | 1.30 | 0.30 | 0.50 | 0.12 | 0.35 | 0.08 |
| SYC | 4.43 | 1.03 | 3.11 | 0.72 | 1.19 | 0.28 | 0.83 | 0.19 |
| SYN | 3.04 | 0.71 | 2.13 | 0.50 | 0.81 | 0.19 | 0.57 | 0.13 |
| TBL | 2.97 | 0.69 | 2.09 | 0.49 | 0.79 | 0.18 | 0.56 | 0.13 |
| TKY | 2.22 | 0.52 | 1.56 | 0.36 | 0.70 | 0.16 | 0.49 | 0.12 |
| TOC | 3.28 | 0.77 | 2.30 | 0.54 | 0.93 | 0.22 | 0.66 | 0.15 |
| VER | 1.51 | 0.35 | 1.06 | 0.25 | 0.35 | 0.08 | 0.25 | 0.06 |
| VER | 4.02 | 0.94 | 2.82 | 0.66 | 0.86 | 0.20 | 0.60 | 0.14 |
| WE1 | 0.03 | 0.01 | 0.02 | 0.01 | 0.01 | 0.00 | 0.01 | 0.00 |
| WE3 | 2.68 | 0.63 | 1.88 | 0.44 | 0.83 | 0.19 | 0.58 | 0.14 |
| WGA | 2.98 | 0.70 | 2.09 | 0.49 | 0.82 | 0.19 | 0.57 | 0.13 |
| WGA | 4.67 | 1.09 | 3.28 | 0.76 | 1.33 | 0.31 | 0.93 | 0.22 |
| WLT | 2.24 | 0.52 | 1.57 | 0.37 | 0.69 | 0.16 | 0.48 | 0.11 |
| WLT | 3.69 | 0.86 | 2.59 | 0.60 | 1.19 | 0.28 | 0.84 | 0.19 |
| WLT | 6.14 | 1.43 | 4.31 | 1.00 | 1.87 | 0.44 | 1.31 | 0.31 |
| WMD | 1.21 | 0.28 | 0.85 | 0.20 | 0.28 | 0.07 | 0.20 | 0.05 |
| WMD | 5.27 | 1.23 | 3.70 | 0.86 | 1.37 | 0.32 | 0.96 | 0.22 |
| WPK | 3.46 | 0.81 | 2.43 | 0.57 | 1.07 | 0.25 | 0.75 | 0.17 |
| WPT | 8.42 | 1.96 | 5.91 | 1.38 | 2.10 | 0.49 | 1.47 | 0.34 |
| WTN | 2.92 | 0.68 | 2.05 | 0.48 | 0.80 | 0.19 | 0.56 | 0.13 |
| WTN | 4.14 | 0.97 | 2.91 | 0.68 | 1.21 | 0.28 | 0.85 | 0.20 |
| WTN | 6.78 | 1.58 | 4.76 | 1.11 | 2.03 | 0.47 | 1.42 | 0.33 |
| YAR | 0.92 | 0.21 | 0.65 | 0.15 | 0.22 | 0.05 | 0.16 | 0.04 |

# Appendix G: Transmission Impact Results (With Demand Response)

N-2, Non-Aggressive/Aggressive, Level 1/2, 2018

|  | Voltage Contingency | Voltage Load Margin | Worst-Case Bus | Thermal Contingency | Overloaded Equipment | Percent Overload | Thermal Load Margin |
|---|---|---|---|---|---|---|---|
| Basecase | COL-NMA dbl ckt | 520 | 696 WLT | COL-NMA dbl ckt | PTE-COL 69-kV | 110.90% | 285 |
| Non-Aggressive Level 1 | COL-NMA dbl ckt | 510 | 696 WLT | COL-NMA dbl ckt | PTE-COL 69-kV | 110.40% | 270 |
| Aggressive Level 1 | COL-NMA dbl ckt | 510 | 696 WLT | COL-NMA dbl ckt | PTE-COL 69-kV | 110.40% | 265 |
| Non-Aggressive Level 2 | COL-NMA dbl ckt | 475 | 696 WLT | COL-NMA dbl ckt | PTE-COL 69-kV | 110.60% | 230 |
| Aggressive Level 2 | COL-NMA dbl ckt | 455 | 696 WLT | COL-NMA dbl ckt | PTE-COL 69-kV | 110.20% | 205 |

N-1, Non-Aggressive/Aggressive, Level 1/2, 2018

|  | Voltage Contingency | Voltage Load Margin | Worst-Case Bus | Thermal Contingency | Overloaded Equipment | Percent Overload | Thermal Load Margin |
|---|---|---|---|---|---|---|---|
| Basecase | ROE-WPT ckt | 935 | 709 NSP | BLT-SYC ckt | GWY-SYC 69-kV | 110.00% | 510 |
| Non-Aggressive Level 1 | ROE-WPT ckt | 925 | 709 NSP | BLT-SYC ckt | GWY-SYC 69-kV | 110.50% | 505 |
| Aggressive Level 1 | ROE-WPT ckt | 925 | 709 NSP | BLT-SYC ckt | GWY-SYC 69-kV | 110.40% | 500 |
| Non-Aggressive Level 2 | ROE-WPT ckt | 890 | 709 NSP | BLT-SYC ckt | GWY-SYC 69-kV | 110.10% | 470 |
| Aggressive Level 2 | ROE-WPT ckt | 875 | 709 NSP | BLT-SYC ckt | GWY-SYC 69-kV | 110.40% | 455 |

N-2, Non-Aggressive/Aggressive, Level 1/2, 2026

|  | Voltage Contingency | Voltage Load Margin | Worst-Case Bus | Thermal Contingency | Overloaded Equipment | Percent Overload | Thermal Load Margin |
|---|---|---|---|---|---|---|---|
| Basecase | COL-NMA dbl ckt | 520 | 696 WLT | COL-NMA dbl ckt | PTE-COL 69-kV | 110.90% | 285 |
| Non-Aggressive Level 1 | COL-NMA dbl ckt | 485 | 696 WLT | COL-NMA dbl ckt | PTE-COL 69-kV | 110.80% | 240 |
| Aggressive Level 1 | COL-NMA dbl ckt | 470 | 696 WLT | COL-NMA dbl ckt | PTE-COL 69-kV | 110.60% | 220 |
| Non-Aggressive Level 2 | COL-NMA dbl ckt | 355 | 696 WLT | COL-NMA dbl ckt | PTE-COL 69-kV | 110.50% | 90 |
| Aggressive Level 2 | COL-NMA dbl ckt | 275 | 696 WLT | COL-NMA dbl ckt | PTE-COL 69-kV | 110.20% | 5 |

N-1, Non-Aggressive/Aggressive, Level 1/2, 2026

|  | Voltage Contingency | Voltage Load Margin | Worst-Case Bus | Thermal Contingency | Overloaded Equipment | Percent Overload | Thermal Load Margin |
|---|---|---|---|---|---|---|---|
| Basecase | ROE-WPT ckt | 935 | 709 NSP | BLT-SYC ckt | GWY-SYC 69-kV | 110.00% | 510 |
| Non-Aggressive Level 1 | ROE-WPT ckt | 900 | 709 NSP | BLT-SYC ckt | GWY-SYC 69-kV | 110.10% | 485 |
| Aggressive Level 1 | ROE-WPT ckt | 885 | 709 NSP | BLT-SYC ckt | GWY-SYC 69-kV | 110.30% | 475 |
| Non-Aggressive Level 2 | ROE-WPT ckt | 770 | 709 NSP | BLT-SYC ckt | GWY-SYC 69-kV | 110.00% | 385 |
| Aggressive Level 2 | ROE-WPT ckt | 695 | 709 NSP | ROE-WPT ckt | ARE-SPG 69-kV | 110.50% | 315 |

# Appendix H: Simple Payback Period Results (With Demand Response)

PHEV Electricity Requirements

|  | 10 mi/day | on-peak cost | typical cost | off-peak cost | 30 mi/day | on-peak cost | typical cost | off-peak cost | 70 mi/day | on-peak cost | typical cost | off-peak cost |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CV |  |  |  |  |  |  |  |  |  |  |  |  |
| HEV |  |  |  |  |  |  |  |  |  |  |  |  |
| PHEV10 | 15.66 kWh | $3.83 | $2.17 | $1.05 | 46.97 kWh | $11.50 | $6.52 | $3.15 | 109.59 kWh | $26.82 | $15.20 | $7.35 |
| PHEV20 | 28.38 kWh | $6.95 | $3.94 | $1.90 | 85.13 kWh | $20.84 | $11.81 | $5.71 | 198.63 kWh | $48.62 | $27.56 | $13.33 |
| PHEV30 | 38.16 kWh | $9.34 | $5.29 | $2.56 | 114.48 kWh | $28.02 | $15.88 | $7.68 | 267.13 kWh | $65.38 | $37.06 | $17.92 |
| PHEV40 | 46.97 kWh | $11.50 | $6.52 | $3.15 | 140.90 kWh | $34.49 | $19.55 | $9.45 | 328.77 kWh | $80.47 | $45.61 | $22.06 |
| PHEV50 | 52.84 kWh | $12.93 | $7.33 | $3.55 | 158.51 kWh | $38.80 | $21.99 | $10.64 | 369.87 kWh | $90.53 | $51.31 | $24.82 |
| PHEV60 | 58.71 kWh | $14.37 | $8.14 | $3.94 | 176.13 kWh | $43.11 | $24.43 | $11.82 | 410.96 kWh | $100.59 | $57.01 | $27.58 |

PHEV Gasoline Requirements

|  | 10 mi/day | high cost ($6) | medium cost ($4) | low cost ($2) | 30 mi/day | high cost ($6) | medium cost ($4) | low cost ($2) | 70 mi/day | high cost ($6) | medium cost ($4) | low cost ($2) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CV | 13.31 gal | $79.87 | $53.25 | $26.62 | 39.94 gal | $239.62 | $159.75 | $79.87 | 93.18 gal | $559.11 | $372.74 | $186.37 |
| HEV | 9.56 gal | $57.38 | $38.26 | $19.13 | 28.69 gal | $172.15 | $114.77 | $57.38 | 66.95 gal | $401.69 | $267.79 | $133.90 |
| PHEV10 | 8.40 gal | $50.41 | $33.60 | $16.80 | 25.20 gal | $151.22 | $100.81 | $50.41 | 58.81 gal | $352.84 | $235.22 | $117.61 |
| PHEV20 | 7.37 gal | $44.20 | $29.47 | $14.73 | 22.10 gal | $132.60 | $88.40 | $44.20 | 51.57 gal | $309.41 | $206.27 | $103.14 |
| PHEV30 | 6.46 gal | $38.77 | $25.85 | $12.92 | 19.39 gal | $116.32 | $77.55 | $38.77 | 45.24 gal | $271.41 | $180.94 | $90.47 |
| PHEV40 | 5.82 gal | $34.90 | $23.26 | $11.63 | 17.45 gal | $104.69 | $69.79 | $34.90 | 40.71 gal | $244.27 | $162.85 | $81.42 |
| PHEV50 | 5.30 gal | $31.79 | $21.20 | $10.60 | 15.90 gal | $95.38 | $63.59 | $31.79 | 37.09 gal | $222.56 | $148.37 | $74.19 |
| PHEV60 | 4.78 gal | $28.69 | $19.13 | $9.56 | 14.35 gal | $86.08 | $57.38 | $28.69 | 33.47 gal | $200.84 | $133.90 | $66.95 |

PHEV Total Fuel Requirements, Assuming 10 miles of travel per day

| | on-peak and high cost | on-peak and medium cost | on-peak and low cost | typical and high cost | typical and medium cost | typical and low cost | off-peak and high cost | off-peak and medium cost | off-peak and low cost |
|---|---|---|---|---|---|---|---|---|---|
| CV | $79.87 | $53.25 | $26.62 | $79.87 | $53.25 | $26.62 | $79.87 | $53.25 | $26.62 |
| HEV | $57.38 | $38.26 | $19.13 | $57.38 | $38.26 | $19.13 | $57.38 | $38.26 | $19.13 |
| PHEV10 | $54.24 | $37.44 | $20.63 | $52.58 | $35.78 | $18.97 | $51.46 | $34.65 | $17.85 |
| PHEV20 | $51.15 | $36.41 | $21.68 | $48.14 | $33.40 | $18.67 | $46.11 | $31.37 | $16.64 |
| PHEV30 | $48.11 | $35.19 | $22.26 | $44.07 | $31.14 | $18.22 | $41.33 | $28.41 | $15.48 |
| PHEV40 | $46.39 | $34.76 | $23.13 | $41.41 | $29.78 | $18.15 | $38.05 | $26.42 | $14.78 |
| PHEV50 | $44.73 | $34.13 | $23.53 | $39.12 | $28.53 | $17.93 | $35.34 | $24.74 | $14.14 |
| PHEV60 | $43.06 | $33.50 | $23.93 | $36.84 | $27.27 | $17.71 | $32.63 | $23.07 | $13.50 |

PHEV Total Fuel Requirements, Assuming 30 miles of travel per day

| | on-peak and high cost | on-peak and medium cost | on-peak and low cost | typical and high cost | typical and medium cost | typical and low cost | off-peak and high cost | off-peak and medium cost | off-peak and low cost |
|---|---|---|---|---|---|---|---|---|---|
| CV | $239.62 | $159.75 | $79.87 | $239.62 | $159.75 | $79.87 | $239.62 | $159.75 | $79.87 |
| HEV | $172.15 | $114.77 | $57.38 | $172.15 | $114.77 | $57.38 | $172.15 | $114.77 | $57.38 |
| PHEV10 | $162.71 | $112.31 | $61.90 | $157.73 | $107.33 | $56.92 | $154.37 | $103.96 | $53.56 |
| PHEV20 | $153.44 | $109.24 | $65.04 | $144.41 | $100.21 | $56.01 | $138.32 | $94.11 | $49.91 |
| PHEV30 | $144.34 | $105.57 | $66.79 | $132.20 | $93.43 | $54.66 | $124.00 | $85.23 | $46.45 |
| PHEV40 | $139.17 | $104.28 | $69.38 | $124.23 | $89.34 | $54.44 | $114.14 | $79.25 | $44.35 |
| PHEV50 | $134.18 | $102.39 | $70.59 | $117.37 | $85.58 | $53.78 | $106.02 | $74.22 | $42.43 |
| PHEV60 | $129.19 | $100.49 | $71.80 | $110.51 | $81.82 | $53.13 | $97.89 | $69.20 | $40.51 |

PHEV Total Fuel Requirements, Assuming 70 miles of travel per day

| | on-peak and high cost | on-peak and medium cost | on-peak and low cost | typical and high cost | typical and medium cost | typical and low cost | off-peak and high cost | off-peak and medium cost | off-peak and low cost |
|---|---|---|---|---|---|---|---|---|---|
| CV | $559.11 | $372.74 | $186.37 | $559.11 | $372.74 | $186.37 | $559.11 | $372.74 | $186.37 |
| HEV | $401.69 | $267.79 | $133.90 | $401.69 | $267.79 | $133.90 | $401.69 | $267.79 | $133.90 |
| PHEV10 | $379.66 | $262.05 | $144.43 | $388.04 | $250.43 | $132.82 | $360.19 | $242.58 | $124.97 |
| PHEV20 | $358.03 | $254.89 | $151.75 | $336.97 | $233.83 | $130.69 | $322.74 | $219.60 | $116.46 |
| PHEV30 | $336.79 | $246.32 | $155.85 | $308.47 | $218.00 | $127.53 | $289.34 | $198.87 | $108.39 |
| PHEV40 | $324.74 | $243.32 | $161.89 | $289.88 | $208.46 | $127.03 | $266.33 | $184.91 | $103.48 |
| PHEV50 | $313.09 | $238.90 | $164.71 | $273.87 | $199.68 | $125.50 | $247.38 | $173.19 | $99.00 |
| PHEV60 | $301.43 | $234.48 | $167.54 | $257.86 | $190.91 | $123.96 | $228.42 | $161.47 | $94.52 |

No Policy, Years required to repay the purchase premium of HEV/PHEV over CV

## Assuming 10 miles of travel per day

| | on-peak and high cost | on-peak and medium cost | on-peak and low cost | typical and high cost | typical and medium cost | typical and low cost | off-peak and high cost | off-peak and medium cost | off-peak and low cost |
|---|---|---|---|---|---|---|---|---|---|
| HEV | 12.1 | 18.2 | 36.3 | 12.1 | 18.2 | 36.3 | 12.1 | 18.2 | 36.3 |
| PHEV10 | 20.5 | 33.2 | 87.7 | 19.2 | 30.1 | 68.7 | 18.5 | 28.3 | 59.9 |
| PHEV20 | 24.5 | 41.8 | 142.2 | 22.2 | 35.4 | 88.4 | 20.8 | 32.1 | 70.4 |
| PHEV30 | 26.6 | 46.8 | 193.8 | 23.6 | 38.2 | 100.5 | 21.9 | 34.0 | 75.9 |
| PHEV40 | 28.5 | 51.6 | 272.8 | 24.8 | 40.6 | 112.5 | 22.8 | 35.6 | 80.6 |
| PHEV50 | 29.6 | 54.3 | 335.8 | 25.5 | 42.0 | 119.5 | 23.3 | 36.4 | 83.2 |
| PHEV60 | 30.1 | 56.1 | 411.6 | 25.7 | 42.6 | 124.2 | 23.4 | 36.7 | 84.4 |

## Assuming 30 miles of travel per day

| | on-peak and high cost | on-peak and medium cost | on-peak and low cost | typical and high cost | typical and medium cost | typical and low cost | off-peak and high cost | off-peak and medium cost | off-peak and low cost |
|---|---|---|---|---|---|---|---|---|---|
| HEV | 4.0 | 6.1 | 12.1 | 4.0 | 6.1 | 12.1 | 4.0 | 6.1 | 12.1 |
| PHEV10 | 6.8 | 11.1 | 29.2 | 6.4 | 10.0 | 22.9 | 6.2 | 9.4 | 20.0 |
| PHEV20 | 8.2 | 13.9 | 47.4 | 7.4 | 11.8 | 29.5 | 6.9 | 10.7 | 23.5 |
| PHEV30 | 8.9 | 15.6 | 64.6 | 7.9 | 12.7 | 33.5 | 7.3 | 11.3 | 25.3 |
| PHEV40 | 9.5 | 17.2 | 90.9 | 8.3 | 13.5 | 37.5 | 7.6 | 11.9 | 26.9 |
| PHEV50 | 9.9 | 18.1 | 111.9 | 8.5 | 14.0 | 39.8 | 7.8 | 12.1 | 27.7 |
| PHEV60 | 10.0 | 18.7 | 137.2 | 8.6 | 14.2 | 41.4 | 7.8 | 12.2 | 28.1 |

## Assuming 70 miles of travel per day

| | on-peak and high cost | on-peak and medium cost | on-peak and low cost | typical and high cost | typical and medium cost | typical and low cost | off-peak and high cost | off-peak and medium cost | off-peak and low cost |
|---|---|---|---|---|---|---|---|---|---|
| HEV | 1.7 | 2.6 | 5.2 | 1.7 | 2.6 | 5.2 | 1.7 | 2.6 | 5.2 |
| PHEV10 | 2.9 | 4.7 | 12.5 | 2.7 | 4.3 | 9.8 | 2.6 | 4.0 | 8.6 |
| PHEV20 | 3.5 | 6.0 | 20.3 | 3.2 | 5.1 | 12.6 | 3.0 | 4.6 | 10.1 |
| PHEV30 | 3.8 | 6.7 | 27.7 | 3.4 | 5.5 | 14.4 | 3.1 | 4.9 | 10.8 |
| PHEV40 | 4.1 | 7.4 | 39.0 | 3.5 | 5.8 | 16.1 | 3.3 | 5.1 | 11.5 |
| PHEV50 | 4.2 | 7.8 | 48.0 | 3.6 | 6.0 | 17.1 | 3.3 | 5.2 | 11.9 |
| PHEV60 | 4.3 | 8.0 | 58.8 | 3.7 | 6.1 | 17.7 | 3.3 | 5.2 | 12.1 |

Policy decision: PHEV owners who participate in time-of-use programs will receive an incentive per kWh
Years required to repay the purchase premium of HEV/PHEV over CV

Assuming 10 miles of travel per day

|  | on-peak and high cost | on-peak and medium cost | on-peak and low cost | typical and high cost | typical and medium cost | typical and low cost | off-peak and high cost | off-peak and medium cost | off-peak and low cost |
|---|---|---|---|---|---|---|---|---|---|
| HEV | 12.1 | 18.2 | 36.3 | 12.1 | 18.2 | 36.3 | 12.1 | 18.2 | 36.3 |
| PHEV10 | 19.8 | 31.4 | 75.8 | 18.6 | 28.5 | 61.2 | 17.9 | 26.9 | 54.1 |
| PHEV20 | 23.1 | 37.9 | 105.8 | 21.0 | 32.6 | 72.8 | 19.8 | 29.8 | 60.1 |
| PHEV30 | 24.8 | 41.5 | 127.1 | 22.2 | 34.6 | 79.0 | 20.7 | 31.2 | 62.9 |
| PHEV40 | 26.3 | 44.8 | 151.1 | 23.1 | 36.3 | 84.5 | 21.4 | 32.2 | 65.1 |
| PHEV50 | 27.1 | 46.6 | 165.8 | 23.7 | 37.2 | 87.5 | 21.8 | 32.8 | 66.4 |
| PHEV60 | 27.5 | 47.6 | 178.2 | 23.8 | 37.5 | 89.0 | 21.8 | 32.9 | 66.5 |

Assuming 30 miles of travel per day

|  | on-peak and high cost | on-peak and medium cost | on-peak and low cost | typical and high cost | typical and medium cost | typical and low cost | off-peak and high cost | off-peak and medium cost | off-peak and low cost |
|---|---|---|---|---|---|---|---|---|---|
| HEV | 4.0 | 6.1 | 12.1 | 4.0 | 6.1 | 12.1 | 4.0 | 6.1 | 12.1 |
| PHEV10 | 6.6 | 10.5 | 25.3 | 6.2 | 9.5 | 20.4 | 6.0 | 9.0 | 18.0 |
| PHEV20 | 7.7 | 12.6 | 35.3 | 7.0 | 10.9 | 24.3 | 6.6 | 9.9 | 20.0 |
| PHEV30 | 8.3 | 13.8 | 42.4 | 7.4 | 11.5 | 26.3 | 6.9 | 10.4 | 21.0 |
| PHEV40 | 8.8 | 14.9 | 50.4 | 7.7 | 12.1 | 28.2 | 7.1 | 10.7 | 21.7 |
| PHEV50 | 9.0 | 15.5 | 55.3 | 7.9 | 12.4 | 29.2 | 7.3 | 10.9 | 22.1 |
| PHEV60 | 9.2 | 15.9 | 59.4 | 7.9 | 12.5 | 29.7 | 7.3 | 11.0 | 22.2 |

Assuming 70 miles of travel per day

|  | on-peak and high cost | on-peak and medium cost | on-peak and low cost | typical and high cost | typical and medium cost | typical and low cost | off-peak and high cost | off-peak and medium cost | off-peak and low cost |
|---|---|---|---|---|---|---|---|---|---|
| HEV | 1.7 | 2.6 | 5.2 | 1.7 | 2.6 | 5.2 | 1.7 | 2.6 | 5.2 |
| PHEV10 | 2.8 | 4.5 | 10.8 | 2.7 | 4.1 | 8.7 | 2.6 | 3.8 | 7.7 |
| PHEV20 | 3.3 | 5.4 | 15.1 | 3.0 | 4.7 | 10.4 | 2.8 | 4.3 | 8.6 |
| PHEV30 | 3.5 | 5.9 | 18.2 | 3.2 | 4.9 | 11.3 | 3.0 | 4.5 | 9.0 |
| PHEV40 | 3.8 | 6.4 | 21.6 | 3.3 | 5.2 | 12.1 | 3.1 | 4.6 | 9.3 |
| PHEV50 | 3.9 | 6.7 | 23.7 | 3.4 | 5.3 | 12.5 | 3.1 | 4.7 | 9.5 |
| PHEV60 | 3.9 | 6.8 | 25.5 | 3.4 | 5.4 | 12.7 | 3.1 | 4.7 | 9.5 |

Policy decision: HEV/PHEV owners who purchase vehicles receive a one-time, up-front rebate
Years required to repay the purchase premium of HEV/PHEV over CV

Assuming 10 miles of travel per day

| | on-peak and high cost | on-peak and medium cost | on-peak and low cost | typical and high cost | typical and medium cost | typical and low cost | off-peak and high cost | off-peak and medium cost | off-peak and low cost |
|---|---|---|---|---|---|---|---|---|---|
| HEV | 2.7 | 4.1 | 8.2 | 2.7 | 4.1 | 8.2 | 2.7 | 4.1 | 8.2 |
| PHEV10 | 7.5 | 12.1 | 32.1 | 7.0 | 11.0 | 25.1 | 6.8 | 10.3 | 21.9 |
| PHEV20 | 12.9 | 22.0 | 74.8 | 11.6 | 18.6 | 46.5 | 10.9 | 16.9 | 37.0 |
| PHEV30 | 16.1 | 28.3 | 117.4 | 14.3 | 23.2 | 60.9 | 13.3 | 20.6 | 45.9 |
| PHEV40 | 18.5 | 33.6 | 177.5 | 16.1 | 26.4 | 73.2 | 14.8 | 23.1 | 52.4 |
| PHEV50 | 20.1 | 36.9 | 228.0 | 17.3 | 28.5 | 81.1 | 15.8 | 24.7 | 56.5 |
| PHEV60 | 21.0 | 39.2 | 287.7 | 18.0 | 29.8 | 86.8 | 16.4 | 25.6 | 59.0 |

Assuming 30 miles of travel per day

| | on-peak and high cost | on-peak and medium cost | on-peak and low cost | typical and high cost | typical and medium cost | typical and low cost | off-peak and high cost | off-peak and medium cost | off-peak and low cost |
|---|---|---|---|---|---|---|---|---|---|
| HEV | 0.9 | 1.4 | 2.7 | 0.9 | 1.4 | 2.7 | 0.9 | 1.4 | 2.7 |
| PHEV10 | 2.5 | 4.0 | 10.7 | 2.3 | 3.7 | 8.4 | 2.3 | 3.4 | 7.3 |
| PHEV20 | 4.3 | 7.3 | 24.9 | 3.9 | 6.2 | 15.5 | 3.6 | 5.6 | 12.3 |
| PHEV30 | 5.4 | 9.4 | 39.1 | 4.8 | 7.7 | 20.3 | 4.4 | 6.9 | 15.3 |
| PHEV40 | 6.2 | 11.2 | 59.2 | 5.4 | 8.8 | 24.4 | 4.9 | 7.7 | 17.5 |
| PHEV50 | 6.7 | 12.3 | 76.0 | 5.8 | 9.5 | 27.0 | 5.3 | 8.2 | 18.8 |
| PHEV60 | 7.0 | 13.1 | 95.9 | 6.0 | 9.9 | 28.9 | 5.5 | 8.5 | 19.7 |

Assuming 70 miles of travel per day

| | on-peak and high cost | on-peak and medium cost | on-peak and low cost | typical and high cost | typical and medium cost | typical and low cost | off-peak and high cost | off-peak and medium cost | off-peak and low cost |
|---|---|---|---|---|---|---|---|---|---|
| HEV | 0.4 | 0.6 | 1.2 | 0.4 | 0.6 | 1.2 | 0.4 | 0.6 | 1.2 |
| PHEV10 | 1.1 | 1.7 | 4.6 | 1.0 | 1.6 | 3.6 | 1.0 | 1.5 | 3.1 |
| PHEV20 | 1.8 | 3.1 | 10.7 | 1.7 | 2.7 | 6.6 | 1.6 | 2.4 | 5.3 |
| PHEV30 | 2.3 | 4.0 | 16.8 | 2.0 | 3.3 | 8.7 | 1.9 | 2.9 | 6.6 |
| PHEV40 | 2.6 | 4.8 | 25.4 | 2.3 | 3.8 | 10.5 | 2.1 | 3.3 | 7.5 |
| PHEV50 | 2.9 | 5.3 | 32.6 | 2.5 | 4.1 | 11.6 | 2.3 | 3.5 | 8.1 |
| PHEV60 | 3.0 | 5.6 | 41.1 | 2.6 | 4.3 | 12.4 | 2.3 | 3.7 | 8.4 |

# Appendix I: Aggregate Regional Battery Capacity Results

| | PHEV20 in 2018 with Non-Aggressive Penetration | Fleet Capacity (TWh) | PHEV20 in 2018 with Aggressive Penetration | Fleet Capacity (TWh) | PHEV20 in 2026 with Non-Aggressive Penetration | Fleet Capacity (TWh) | PHEV20 in 2026 with Aggressive Penetration | Fleet Capacity (TWh) |
|---|---|---|---|---|---|---|---|---|
| Dane County | 9459 | 0.02 | 13479 | 0.03 | 34136 | 0.07 | 48644 | 0.10 |
| Wisconsin | 83670 | 0.17 | 119230 | 0.24 | 301963 | 0.61 | 430298 | 0.87 |
| United States | 4105263 | 8.31 | 5850000 | 11.84 | 14815789 | 29.99 | 21112500 | 42.74 |

| | PHEV40 in 2018 with Non-Aggressive Penetration | Fleet Capacity (TWh) | PHEV40 in 2018 with Aggressive Penetration | Fleet Capacity (TWh) | PHEV40 in 2026 with Non-Aggressive Penetration | Fleet Capacity (TWh) | PHEV40 in 2026 with Aggressive Penetration | Fleet Capacity (TWh) |
|---|---|---|---|---|---|---|---|---|
| Dane County | 9459 | 0.04 | 13479 | 0.06 | 34136 | 0.14 | 48644 | 0.20 |
| Wisconsin | 83670 | 0.34 | 119230 | 0.49 | 301963 | 1.24 | 430298 | 1.76 |
| United States | 4105263 | 16.80 | 5850000 | 23.94 | 14815789 | 60.62 | 21112500 | 86.38 |

| | PHEV60 in 2018 with Non-Aggressive Penetration | Fleet Capacity (TWh) | PHEV60 in 2018 with Aggressive Penetration | Fleet Capacity (TWh) | PHEV60 in 2026 with Non-Aggressive Penetration | Fleet Capacity (TWh) | PHEV60 in 2026 with Aggressive Penetration | Fleet Capacity (TWh) |
|---|---|---|---|---|---|---|---|---|
| Dane County | 9459 | 0.06 | 13479 | 0.08 | 34136 | 0.21 | 48644 | 0.31 |
| Wisconsin | 83670 | 0.53 | 119230 | 0.75 | 301963 | 1.90 | 430298 | 2.71 |
| United States | 4105263 | 25.81 | 5850000 | 36.79 | 14815789 | 93.16 | 21112500 | 132.76 |

# Appendix J: National Battery Capacity Results

| | PHEV20 in 2018 with Non-Aggressive Penetration | Fleet Capacity (TWh) | PHEV20 in 2018 with Aggressive Penetration | Fleet Capacity (TWh) | PHEV20 in 2026 with Non-Aggressive Penetration | Fleet Capacity (TWh) | PHEV20 in 2026 with Aggressive Penetration | Fleet Capacity (TWh) |
|---|---|---|---|---|---|---|---|---|
| Northeast | 673263 | 1.36 | 959400 | 1.94 | 2429789 | 4.92 | 3462450 | 7.01 |
| Midwest | 1030421 | 2.09 | 1468350 | 2.97 | 3718763 | 7.53 | 5299238 | 10.73 |
| South | 1498421 | 3.03 | 2135250 | 4.32 | 5407763 | 10.95 | 7706063 | 15.60 |
| West | 903158 | 1.83 | 1287000 | 2.61 | 3259474 | 6.60 | 4644750 | 9.40 |

| | PHEV40 in 2018 with Non-Aggressive Penetration | Fleet Capacity (TWh) | PHEV40 in 2018 with Aggressive Penetration | Fleet Capacity (TWh) | PHEV40 in 2026 with Non-Aggressive Penetration | Fleet Capacity (TWh) | PHEV40 in 2026 with Aggressive Penetration | Fleet Capacity (TWh) |
|---|---|---|---|---|---|---|---|---|
| Northeast | 673263 | 2.75 | 959400 | 3.93 | 2429789 | 9.94 | 3462450 | 14.17 |
| Midwest | 1030421 | 4.22 | 1468350 | 6.01 | 3718763 | 15.22 | 5299238 | 21.68 |
| South | 1498421 | 6.13 | 2135250 | 8.74 | 5407763 | 22.13 | 7706063 | 31.53 |
| West | 903158 | 3.70 | 1287000 | 5.27 | 3259474 | 13.34 | 4644750 | 19.00 |

| | PHEV60 in 2018 with Non-Aggressive Penetration | Fleet Capacity (TWh) | PHEV60 in 2018 with Aggressive Penetration | Fleet Capacity (TWh) | PHEV60 in 2026 with Non-Aggressive Penetration | Fleet Capacity (TWh) | PHEV60 in 2026 with Aggressive Penetration | Fleet Capacity (TWh) |
|---|---|---|---|---|---|---|---|---|
| Northeast | 673263 | 4.23 | 959400 | 6.03 | 2429789 | 15.28 | 3462450 | 21.77 |
| Midwest | 1030421 | 6.48 | 1468350 | 9.23 | 3718763 | 23.38 | 5299238 | 33.32 |
| South | 1498421 | 9.42 | 2135250 | 13.43 | 5407763 | 34.01 | 7706063 | 48.46 |
| West | 903158 | 5.68 | 1287000 | 8.09 | 3259474 | 20.50 | 4644750 | 29.21 |