The Use of Plug-In Hybrid Electric Vehicles For Peak Shaving

by

BENJAMIN ANDREW MAPLES

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This thesis entitled:

The Use Of Plug In Hybrid Electric Vehicles For Peak Shaving

written by Benjamin Andrew Maples

has been approved for the Department of Mechanical Engineering

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Frank Kreith

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Sehee Lee

Date______________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

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Thesis directed by Professor Emeritus Frank Kreith

Abstract

This thesis entitled The Use of Plug-In Hybrid Electric Vehicles For Peak Shaving by Benjamin Maples, submitted to the department of Mechanical Engineering in partial fulfillment of the degree of Master of Science, performed under the supervision of Professor Frank Kreith, is a feasibility analysis of the capabilities of PHEV's for peak shaving. The analysis focuses on energy availability of the PHEV fleet as well as the potential financial benefit to the vehicle owner by analyzing different charging scenarios and circuitry. The energy availability is heavily dependent on the location and availability of charging stations. The potential consumer profit is most dependent on the charging circuitry. The major findings of the study shows that under certain scenarios, such as the charge everywhere baseline case, using PHEV's for peak shaving is possible and could provide vehicle owners with significant compensation for the energy stored in their vehicles batteries.

Acknowledgements

I am forever in dept to the many people who have helped me along the way to making this thesis possible.

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I would like to thank all of the teachers and professors who have taught and mentored me my entire life. A special thank you to Bruce Kawanami who taught Intro to Engineering in High School. You confirmed that engineering can sometimes be difficult but above all else it's fun. (And that even though contract states one thing, they can always change at the drop of a hat by the customer.)

A thank you to Keith Parks and Jim Himelic at Xcel Energy for their help catching me up to speed with all things related to the electricity grid. And a thank you to professors Sehee Lee and John Daily for serving on my thesis committee.

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CHAPTER I

INTRODUCTION

Background

Several major auto manufacturers are currently offering hybrid electric vehicles (HEV's) that add an electric motor and battery to the internal combustion engine in order to improve the vehicles fuel consumption. This addition allows the vehicle's internal combustion engine to shut down during stops and light acceleration as well as recapture otherwise wasted kinetic energy during deceleration through regenerative breaking. Though all of the energy used by the vehicle is derived from gasoline, the overall efficiency of the vehicle is dramatically increased relative to an internal combustion (IC) only vehicle.

Plug-In Hybrid Electric Vehicles (PHEV's) use the same technology but with two changes; a larger battery pack and the ability to charge the battery pack from electricity supplied by the electric grid. Electric Vehicles (EV's) increase the battery pack further and get rid of the internal combustion engine all together. Extended Range Electric Vehicles (EREVs) are a bridge between EVs and PHEVs by having a completely electric drive train like the EVs but with an onboard IC engine used as a generator to charge the vehicles battery packs to extend the vehicles range. PHEVs and EREVs use less gasoline than HEV's and are a more economical near term option over EV's because they avoid the EV's large battery cost, charge times, and range limitations without a network of battery swap or quick charge stations.

PHEV's can be classified by the range that they can travel in pure electric mode. For example, a PHEV that can travel 40 miles on electricity only before the onboard internal combustion engine has to start is generally referred to as a PHEV-40. When a PHEV has traveled the designated number of miles in electricity mode only, it then operates in the same fashion that a HEV operates, commonly referred to as a charge sustaining mode. PHEVs can reduce overall gasoline consumption by over 50% per vehicle when compared to a current average IC vehicle [1].

Currently, no major auto manufacturer has a PHEV on market, though some are very close, such as the Toyota Prius PHEV and the Chevrolet Volt. Many studies have indicated that there would be a major market for PHEV's depending on the vehicle cost and future cost of gasoline [2]. Current estimates of PHEV vehicle efficiencies range from 3.5 miles per kWh for compact cars to 2.4 miles per kWh for SUVs [12]. An average sized vehicle that can travel 30 miles on a gallon of gasoline would use the energy equivalent of approximately 10 kWh. If the vehicle was supplied with electricity at a rate of 7.5 cents/kWh, that vehicle could travel the same 30 miles for less than $1, considerable less than the current $2.50 per gallon of gasoline that would be spent for a current average IC vehicle [2].

Wide spread fleet penetration of PHEV's can potentially shift the use of electricity and the operation of power plants that supply electricity to the grid. With a large number of vehicles charging from the grid, power plants will be burdened with additional loads (at all hours of the day). Though previous studies of EV's have shown that a 20% market penetration could be handled by the current infrastructure if the vehicles were charged overnight, the grid may need major improvements in order to handle the increased load created by charging vehicles [1, 14].

While PHEV's will require the grid to produce more electricity than before, concepts have emerged that aim to reduce the peak capacity needed from the grid. These concepts require that vehicles with charged batteries transfer some of their stored energy back to the grid during times of high demand, a process known as peak shaving. The concept of using the stored energy in vehicles for peak shaving is most commonly known as "vehicle to grid" operation or V2G for short [10]. V2G operation would require improvements to power electronics and the ability for the grid to rapidly communicate with vehicles in order to regulate charging and discharging of the fleet. Several areas in the U.S. are beginning these upgrades to the electrical infrastructure, commonly referred to as upgrading to the "smart grid".

Peak shaving is the concept to use an alternative source of electricity to fill the highest load so that the utility does not have to build, maintain, and charge the customer for a power plant that sits idle for the majority of the year. It is referred to as peak shaving because when the utility views the demand it must provide, the peaks of the demand appear to be shaved off because it is being supplied by another source.

Over the course of the day the grid load fluctuates and when viewed graphically over time, looks like a wave with the peaks of the wave typically occurring around 4-5 in the afternoon, as seen in Figure 1.

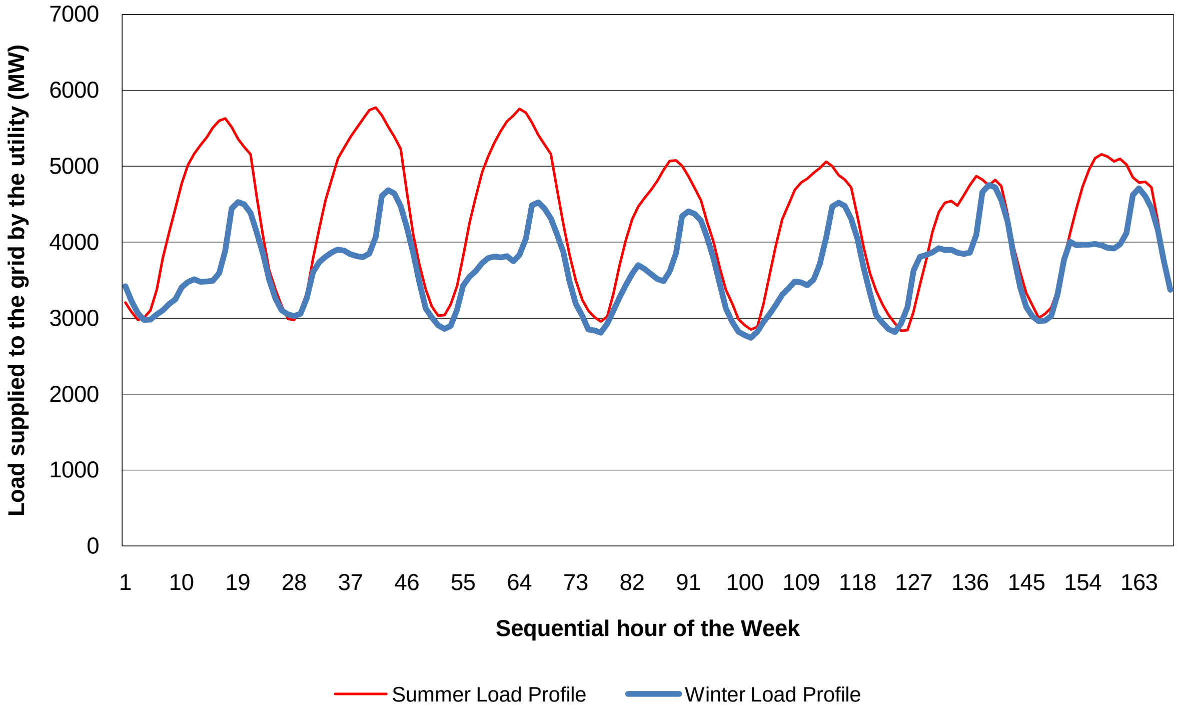

Figure 1: Typical summer and winter weekly load profiles.

In order for the utility to provide this extra load to the consumer, another power plant must be turned on to generate the electricity. Due to the nature of how different power plants operate, only some types of power plants can be turned on and off quickly enough to fulfill this demand. These power plants are typically more expensive to operate and typically sit idle for a large portion of the year. Because the consumer requires power no matter how high the demand gets, the utility must have extra power plants ready for the extremely high demand days, typically hot summer days when people crank up the AC. The consumer must pay the utility to build and maintain those extra power plants even if they are not providing power to the customer for more than a few percent of the time. Figure 2 illustrates how the highest load demand only occurs for a very small fraction of the year.

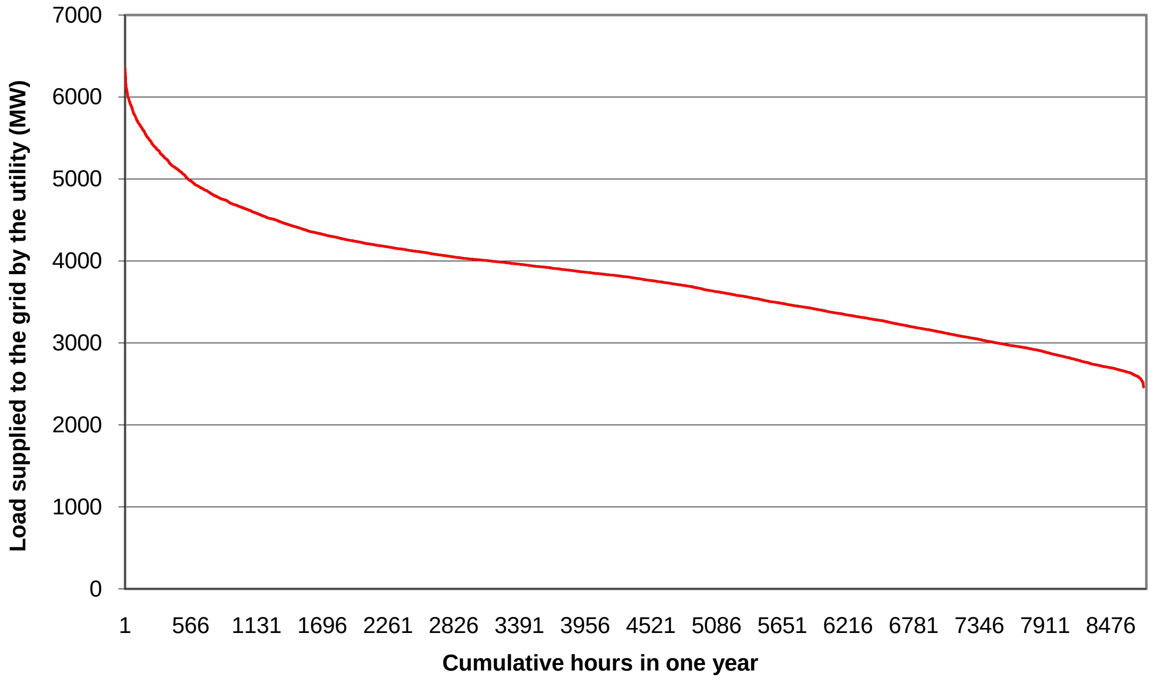

Figure 2: Yearly load duration curve.

Currently there are only about 54 million garages for the 247 million registered vehicles in the United States [7]. This number becomes more staggering when taking into account the vehicles that are parked in driveways due to garages being used for storage, work space or other uses. In order for V2G to become a reality much work will be needed on how to charge the vehicles that are parked on the street or in parking lots [7]. Fortunately, companies such as Coulomb

Technologies and General Electric have started that effort by offering products and services that provide a smart-charging infrastructure for plug-in vehicles [15].

Previous Findings

The V2G operation of PHEV's can pose a source of revenue for vehicle owners by supplying the grid with high value electric system services such as spinning reserve, distributed frequency regulation, and peak shaving [6]. These services, if demonstrated publicly and adopted by the utility providers, can expedite the public's adoption of PHEV's by providing financial benefits to PHEV owners.

The top 20% of U.S. installed electric capacity operates less than 5% of the time and supplies less than 1% of the systems demand. Consumers must therefore pay an increased rate in order for the utilities to recover the costs associated with purchase and upkeep on these frequently idle plants. It is also typical for utilities to have an extra spinning reserve of 5-10% over expected peak demand in preparation for the event of a plant failure during peak demand. It has been shown that charging vehicles over night when the system demand is low can extend plant life by reducing the amount of cycling the plants endure. This in turn can reduce the cost of operation of the plants and subsequently reduce the cost of electricity to the consumer [1].

Previous work has examined the potential of PHEV's to supply the grid with distributed frequency regulation and peaking capacity for a single scenario [6].

Future work however, needs to focus on using today's technology to assess the variability of the fallowing parameters that influence the viability of V2G services.

- Charging and Discharging circuit capabilities
- PHEV battery capacity
- Charging locations and timing (Home, Work, Store, etc.)

Purpose

This study is a feasibility analysis of the peak shaving potential of V2G. More specifically, this analysis intends to address the following uncertainties with regard to V2G peak shaving:

1. How many vehicles/MW will be needed in order to supply the grid with a given percentage of peak shaving power, assuming the batteries will not be discharged below a specified charge state?
2. How much is the stored energy in the PHEV's worth? Assuming specific costs associated with building and operating a natural gas fired turbine with a lifetime of 20 years. How often will the vehicles be drawn from in order to supply the load of the highest load hours?

Both of the above questions will be investigated for different charging scenarios. (Charge at home only, charge anywhere the car is not moving, etc) and for different circuitry scenarios (Voltages, currents, etc.)

By answering these questions, the idea of using PHEVs or other plug in capable vehicles as a means of peak shaving through V2G can be confirmed as possible or put to rest as a good idea that wouldn't work out in the real world. If the study shows that using PHEVs and V2G could be used for peak shaving then it is important to notify those working in the industry so that they can get to work implementing the necessary infrastructure such as charging stations and the vehicles themselves.

Scope

The scope of this study focused on several scenarios in order to answer the questions presented in the Purpose section of the report. As discussed later in the Limitations section, only one data set for vehicles and grid load is used. Reasonable effort was made to include a wide range of values for the various parameters, however an investigation into more variables or combinations of variables would have unduly prolonged this preliminary study and where therefore not considered.

Limitations

The only publicly available vehicle usage data is based on a NREL analysis of 227 unique consumer vehicles in the St Louis Metro Area only. The 227 detailed vehicle operating scenarios were collected in support of the St Louis Regional Transportation Study conducted in 2002 [4]. The study included more than 5000 randomly selected participants and of those, the owners of 227 vehicles voluntarily participated in the GPS portion of the study. That is, the 227 vehicles were self-selected from a random representative sample of St Louis vehicle owning residents.

A limitation of the data and the analysis is that it represents weekday travel only. Due to the lack of detailed electricity load data, St Louis Metro Area load data was unavailable and PSCOs' service territory was used instead. The load does not match the vehicle operation area, however the two data sets were the best available and it is assumed that the difference in locations does not significantly affect the outcome of the analysis.

Due to the large amounts of computing power needed for the calculations, the analysis was performed on an hourly averaged basis. Because this is only a feasibility analysis, the hour granularity is sufficient.

Numbers used for the financial calculations as well as the vehicle parameters were taken from literature [3, 8, 9, 10, 12, 16, 17] and there is a potential for the conclusions to change based on a number of variables. The Results and Conclusion sections of this report addresses these potential changes in more depth.

In this analysis it was assumed that the charge rate was constant throughout the charge time. In reality, the battery charging is tapered down when the battery is approaching maximum capacity in order to avoid overheating. Although the taper would increase the charge time, it was assumed insignificant with respect to the overall goal of this feasibility analysis.

CHAPTER II

PROCEDURES

Previously Completed Work

This thesis builds upon previous work completed at the National Renewable Energy Laboratory (NREL) performed by Keith Parks, Paul Denholm, and Tony Markel [11]. This work took the St. Louis Regional Metropolitan Transportation study and PSCOs' service territory load data and compiled the two data sets to analyze the increase in load that a fleet of PHEV's would put on the system.

The analysis was performed for two different charging scenarios. The two charging scenarios were an opportunity charge scenario and a base or home charge only scenario. The opportunity charging scenario is a scenario that assumed that there is no restriction on time of day or location that the vehicle can be charging. This scenario assumes that every time the vehicle is parked it is connected to the grid and has the ability to draw power from the grid. The charge at home only scenario assumes that there is no charging infrastructure anywhere except at the vehicles home. Therefore, under this scenario, the only time that the vehicle can charge is when the vehicle is parked overnight.

NREL's analysis was accomplished by importing the data from the 227 vehicles that responded in the St. Louis Regional Metropolitan Transportation study into an Excel spreadsheet. The data that was used from the transportation study included information regarding each vehicles mid-week travel data regarding times of day when the vehicle was parked (from here on out referred to as a stop or stops) and distances traveled between stops. The Excel spreadsheet was then populated with PHEV vehicle information regarding battery size, battery charge/discharge efficiency, battery state of charge limitations, and vehicle travel efficiency (Wh/mi). Charging circuitry capabilities, including efficiencies, were also included for the analysis.

Once the spreadsheet was populated with the data, analysis was divided into two major sections. The two major sections analyzed were; at what times of the day the vehicles were connected to the grid and the power draw by the vehicles when they were charging.

The analysis on when the vehicles were connected to the grid was rather strait forward. The travel information from the transportation study listed exact times of when each vehicle was stopped. This data was then translated into a table on an hourly basis to show percentages of the fleet that were connected, or at least had the capabilities to be connected, to the grid assuming there was charging infrastructure at the location of the stop.

The second major calculation was determining the power draw by the fleet as it recharged its batteries. The power draw for each vehicle was dictated by the charging infrastructure and whether or not it was plugged in; however the total power draw from the fleet was determined by how many of the vehicles were drawing from the grid at any given time. Calculating individual vehicle power draw needs was performed by taking the distance traveled by the vehicle between each stop, combined with the vehicle efficiency information to determine the state of charge of the battery and subsequently how much energy was needed to return the battery to full charge. For example, if the vehicle traveled 10 miles with a vehicle efficiency of 300 Wh/mi, then the vehicle would need 3kWh of energy to return the battery to a full charge. This information was then cross analyzed with the connectivity data described earlier to check whether the vehicle will be connected to the grid long enough to completely charge the battery. To perform this check the spreadsheet used the charging infrastructure data to determine how much power can be transferred to the battery. Then the sheet determines if, at that charging rate, the battery can be fully charged before it disconnects from the grid. If there was not enough time to charge the battery fully, it calculates the state of charge of the battery at the time of disconnect in order to accurately determine the state of charge once the vehicle comes to its next stop. The power draw calculations for this section were averaged on an hourly basis. Below are two examples of how this calculation is performed.

- If the vehicle needs 3kWh of energy and is connected to the grid through a 1.5kW circuit for one hour, then the battery would draw 1.5kW for that hour and then the vehicle's battery would start its next drive with a battery that is 1.5kWh less than a full charge, which would be reflected on the state of charge for the next charging opportunity.

- If the vehicle needs 3kWh of energy and is connected to the grid through a 1.5kW circuit for three hours, then the battery would draw 1.5kW for the first two hours, then the vehicle's battery would be fully charged and would not draw any power from the grid for the final hour, and would start its next drive with a full battery.

The calculations were compiled, for each charging scenario and every vehicle in the fleet, to obtain a load profile comparison. The added demand from the PHEVs charging was levelized to the Denver area vehicle fleet size, added to the Denver area load profile and graphed for a visual comparison on a yearly, weakly, daily, and hourly basis.

Extrapolation of Previous Work

Previous work [11] provided a solid foundation for the work performed by this thesis and was used to its greatest potential. This section provides information on the procedures that were used to extrapolate the previous work in order to come to the conclusions of this thesis.

The previous work was used primarily to estimate how much energy is available, through V2G, for the use of peak shaving at any given time. Both the analysis on when the vehicles were connected to the grid and the analysis on power draw was used.

This analysis was performed for both of the charging scenarios used in the Xcel analysis. These two scenarios were chosen because they represent 'book ends' to all the possible scenarios. Meaning that if the analysis showed that the charge at home only scenario would work, then all of the other possible scenarios would also be viable for peak shaving because the vehicles would only have more energy at any given time for other scenarios. Conversely, if the opportunity charging showed that it would not work, then none of the other possible scenarios would work because the vehicle batteries would have even less charge available for peak shaving.

The first step for this analysis was to determine the state of the vehicles battery at any given time when connected to the grid. This was accomplished by taking the state of charge for the vehicle directly before it started its charge and adding to that the energy that it received from the grid, which was determined from the power draw data compiled by NREL [11]. With the same data set one can determine the number of vehicles that are actively charging by determining whether or not they are drawing power from the grid or not.

A note to the reader:

> Below the term 'total possible fleet's energy' is used to represent the theoretical maximum possible energy that a fleet could have. This theoretical maximum would occur if all of the vehicles in the fleet were 100% charged and connected to the grid.

By averaging the fleet battery state of charge, of charging vehicles, and multiplying that state of charge percentage by the percentage of vehicle that are actively charging the percentage of the total possible fleets energy that is in the charging vehicles can be determined. This percentage alone is rather useless until it is combined with other numbers later in the analysis to come up with the overarching numbers that have value.

Next, the percentage of the fleet that is connected to the grid with a full battery was calculated. This percentage was calculated by subtracting the percentage of charging vehicles from the percentage of vehicles that are connected to the grid. Again, this percentage alone may not provide much useful information, but it is combined with other numbers later in the analysis to come up with the overarching numbers that have value.

The above percentages were then combined to yield a daily profile of what percentage of the fleet's total possible energy would be available for V2G operation. The percentage of vehicles that are connected and have a full battery was added to the percentage of the total fleet's possible energy that is in charging vehicles, yielding a daily profile of the total percentage of the total possible fleet's energy that would be available for V2G peak shaving.

New Work

New analysis was performed to answer the questions regarding the number of vehicles needed and how much the stored energy is worth. This section provides information on the procedures and equations used in order to arrive at the conclusions of this thesis.

The potential annual profit to the vehicle owner was the baseline gauge for determining if peak shaving through V2G is financially sound. Both avoided costs from not building and operating a new natural gas fired turbine and the number of vehicles performing V2G operations is need.

The avoided cost of purchasing and operating a natural gas fired turbine represents the maximum potential amount of money which the electricity provider could pay to the vehicle owners for the energy used during peak shaving. Calculations for the cost of building and operating a natural gas fired turbine is based on the overnight cost of the plant, loan interest, loan period, fuel cost, heat rate, plant capacity factor, and operation and maintenance (O&M) costs. The total avoided cost is calculated in two sections; the variable costs and the fixed costs.

The variable costs are based on the plant capacity factor, plant size, natural gas costs, heat rate, and variable O&M. Because the variable costs are dependent on the annual energy production (AEP) of the plant, the first calculation is the plants AEP. The AEP is calculated by multiplying the capacity factor by the hours in a year and then multiplying by the plant size. The fuel cost is calculated by multiplying the heat rate by the cost of natural gas yielding a total fuel cost in $/kWh. This is then added to the variable O&M cost, yielding a total variable cost. This total variable cost is multiplied by the AEP to get a yearly variable cost.

The fixed costs are based on the overnight cost of the plant per MW, plant size, loan interest rate, loan period, and fixed O&M. The overnight plant cost per MW is multiplied by plant size to get a total plant cost. The built in Excel function PMT takes the plant cost, loan interest rate, and loan period numbers and produces a monthly payment for the loan. This payment is then converted to a yearly payment by multiplying by 12 months. The fixed O&M is multiplied by the plant size to get a total fixed O&M cost. The total fixed O&M is added to the yearly loan payment to get a yearly fixed cost.

The fixed cost is added to the variable cost resulting in a yearly cost that would be avoided by not building and operating a new natural gas fired turbine generation facility. It is assumed that all of the avoided cost can be used as payment incentive to the vehicle owners for the energy put back into the grid while they are being used for peak shaving.

The number of vehicles performing V2G operation determines how the avoided costs are distributed. In this analysis, the avoided cost is distributed equally between all of the vehicles used for peak shaving.

The number of vehicles needed to offset the construction of a new natural gas fired turbine is determined by the plant size, line voltage, line current, and discharge efficiency. By multiplying the line voltage, line current and discharge efficiency together, a total discharge rate per vehicle is determined. By dividing the plant size by the discharge rate per vehicle, the number of vehicles needed to offset the plant is determined.

The final step of the potential annual financial benefit to the vehicle owner is determined by subtracting the off-peak energy cost from the total avoided cost of a new natural gas fired turbine and then dividing by the number of vehicles needed to fill the plants void.

A Monte Carlo simulation for the potential annual consumer profit was calculated using the MCSim Excel add-in. 5000 repetitions were calculated using random combinations of input values in accordance to Monte Carlo simulation procedures. The input values were randomly and evenly selected for each input variable using the built in Excel function "RANDBETWEEN" with bounds between the best case scenario values and the worst case scenario values.

Numbers Used for Calculations

The numbers presented in Table 1 were used for the financial calculation analysis [3, 8, 9, 10, 12, 16, 17]. Upper and lower bounds were used for the sensitivity analysis. The set of average numbers were used for the baseline calculations. Worst case scenarios and best case scenarios utilize a mix of numbers from the low and high bounds depending on whether a low or high number is more or less favorable to V2G operation. For the potential financial benefit calculations both the baseline and best case scenarios use a line voltage of 240 volts and a current of 32 amps due to the unrealistic nature of V2G with a DC line at 480 volts and 400 amps. The 480 volt and 400 amp line was only used for the energy availability analysis due to the assumption that high voltage, high current DC quick charge stations could only be used for charging and not discharging.

Table 1: Numbers used for calculations including high and low bounds.

	Low	Average	High
Overnight Cost($/MW)	648,000	685,000	1,000,000
Plant Size(MW)	1	160	250
Loan Interest	0.05	0.078	0.1
Loan Period (yrs)	10	15	25
Fuel Cost ($/mmbtu)	3	3.95	6
Heat Rate (mmbtu/MWh)	6.8	10.788	11
VOM ($/MWh)	2.11	3.65	7.28
Fixed O&M ($/kW)	10.77	12.38	16.39
Vehicle Battery Capacity (kWh)	4.9	16.6	24
Minimum Charge state of Battery	0.1	0.3	0.5
Vehicle Consumption (Wh/mi)	280	300	420
Battery Efficiency	0.9	0.95	1
Charge/Discharge Efficiency	0.9	0.95	1
Off Peak Energy Cost (¢/kWh)	2.648	5	20
Line Voltage (V)	110	240	480
Line Current (A)	15	32	400

CHAPTER III

RESULTS

Energy Availability

For the opportunity charging scenario, energy availability peaks at 3:00am and dips to the lowest level at 4:00pm. The 3:00am peak reaches nearly 100% availability and drops to just under 80% availability at the lowest level at 4:00pm under the baseline scenario. Under the worst case scenario the lowest level declines to 75% at 4:00pm. The peak however remains at nearly 100% at 3:00am. Under the best case scenario the lowest level occurs at 4:00pm and reaches just under 85% while the peak remains unchanged as compared to the other two scenarios. Daily availability profiles for the baseline, worst, and best cases for the opportunity charging scenarios are presented in figures 3-5.

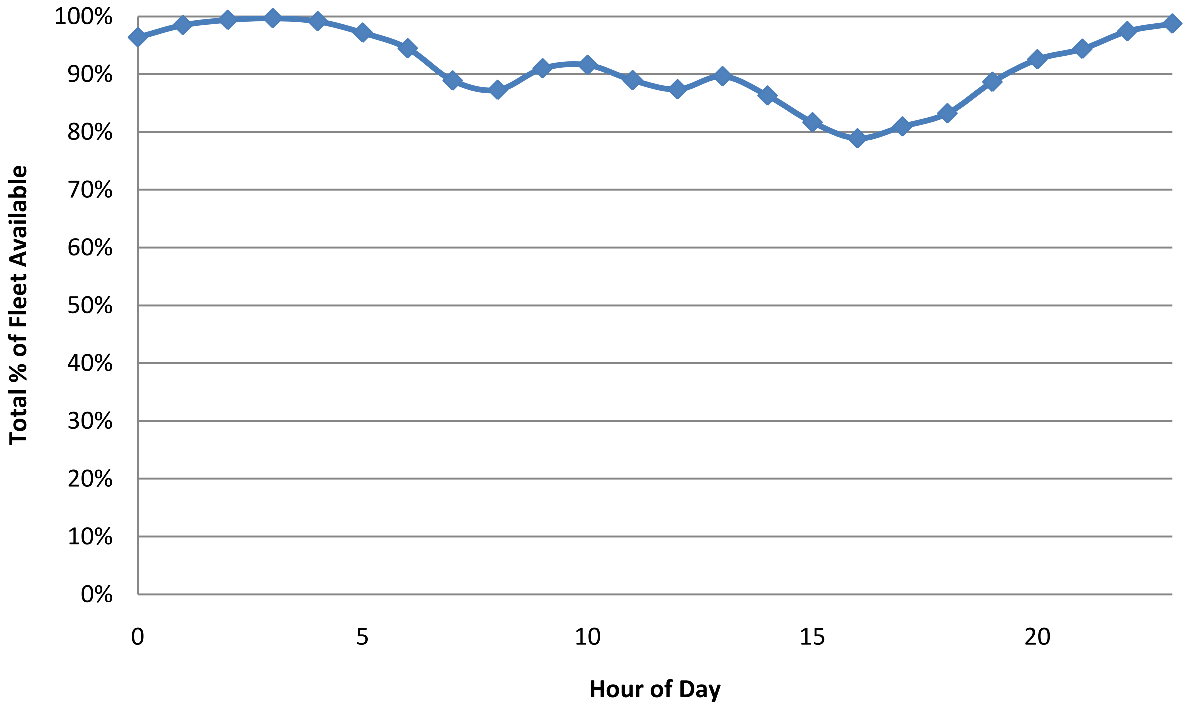

Figure 3: Energy availability for the baseline opportunity charging scenario

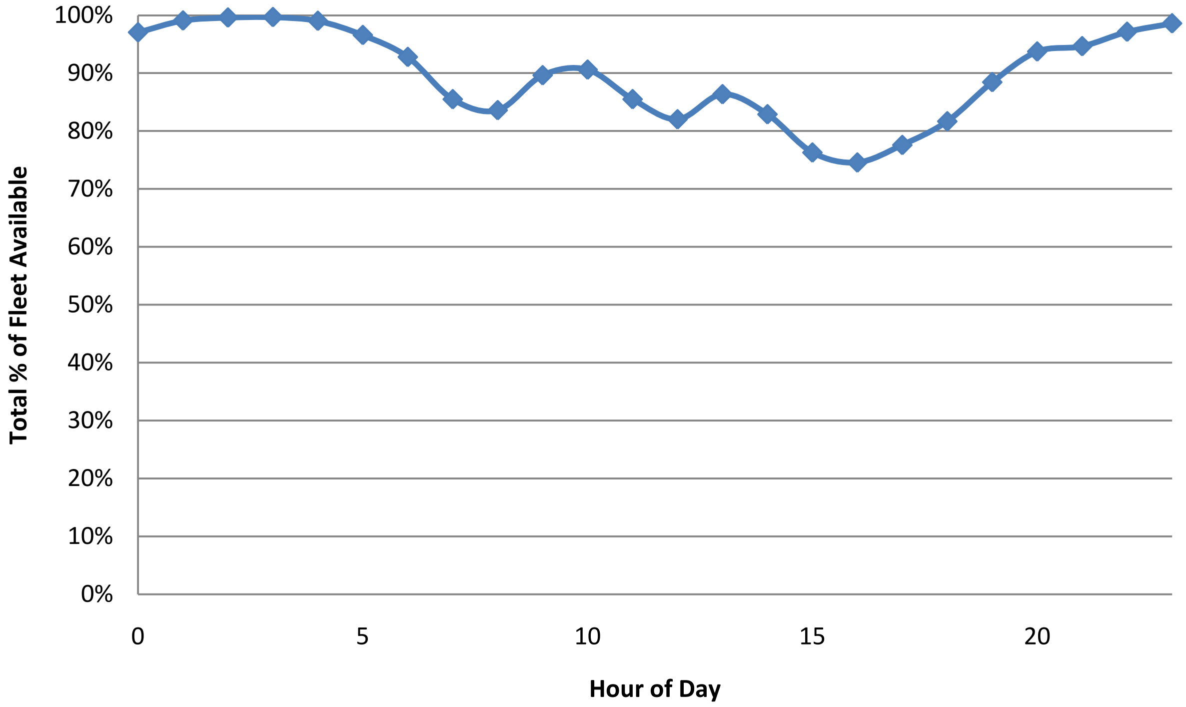

Figure 4: Energy availability for the worst case opportunity charging scenario

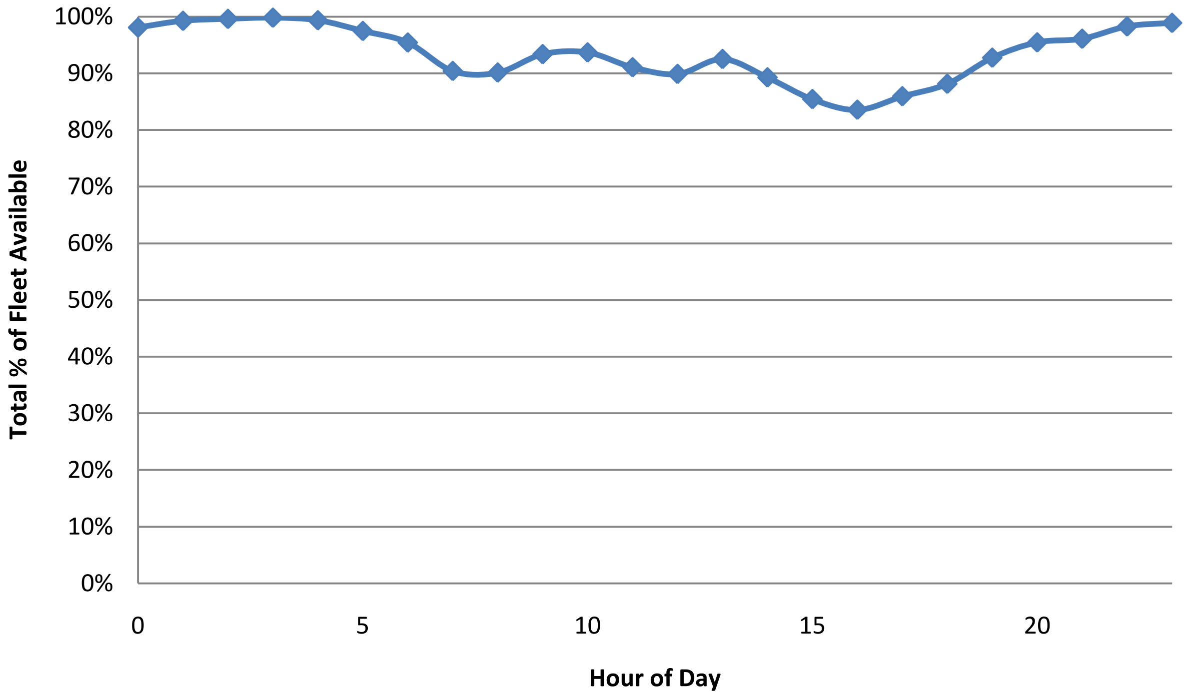

Figure 5: Energy availability for the best case opportunity charging scenario

For the charge at home only scenario, energy availability peaks at 4:00am and drops to the lowest level at 2:00pm. The 4:00am peak reaches just over 90% availability and drops to just over 15% availability at the lowest level at 2:00pm for the baseline scenario. Under the worst case scenario the lowest level declines to just over 15% at 2:00pm; however, the peak jumps to 93% at 4:00am. Under the best case scenario the lowest level occurs at 2:00pm and reaches just over 17% while the peak remains at 91% at 4:00am as it is in the baseline case. Daily availability profiles for the baseline, worst, and best cases for the charge at home only scenarios are presented in figures 6-8.

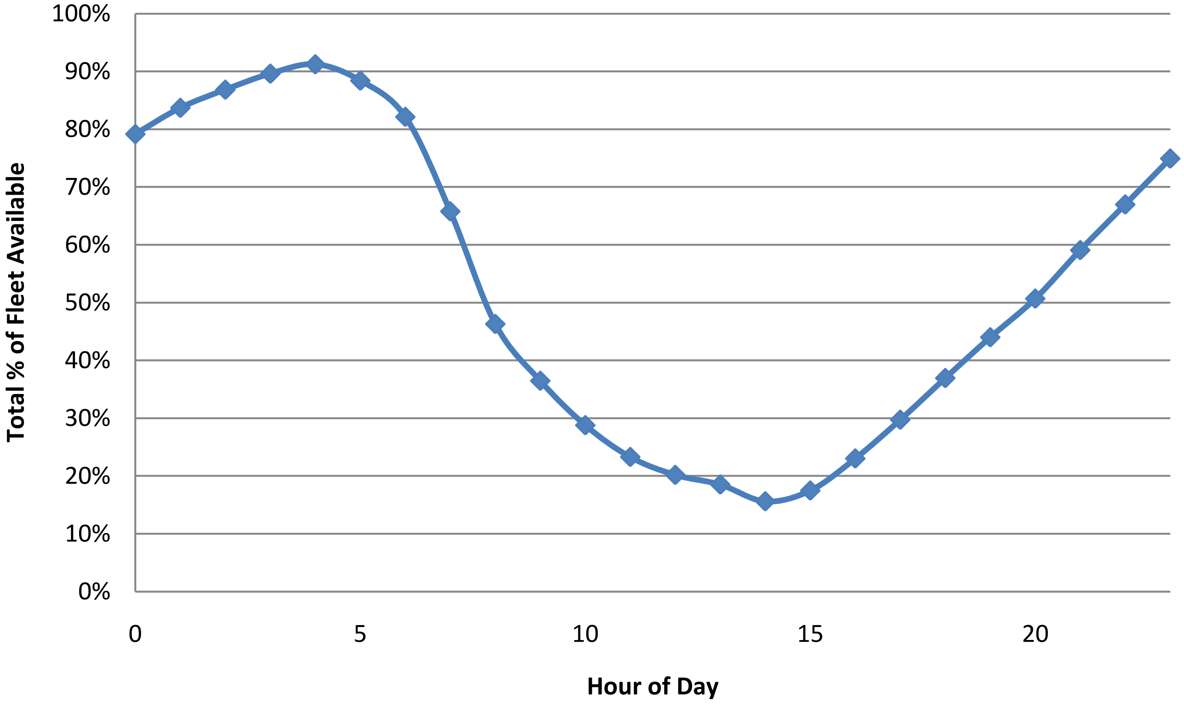

Figure 6: Energy availability for the baseline charge at home only scenario

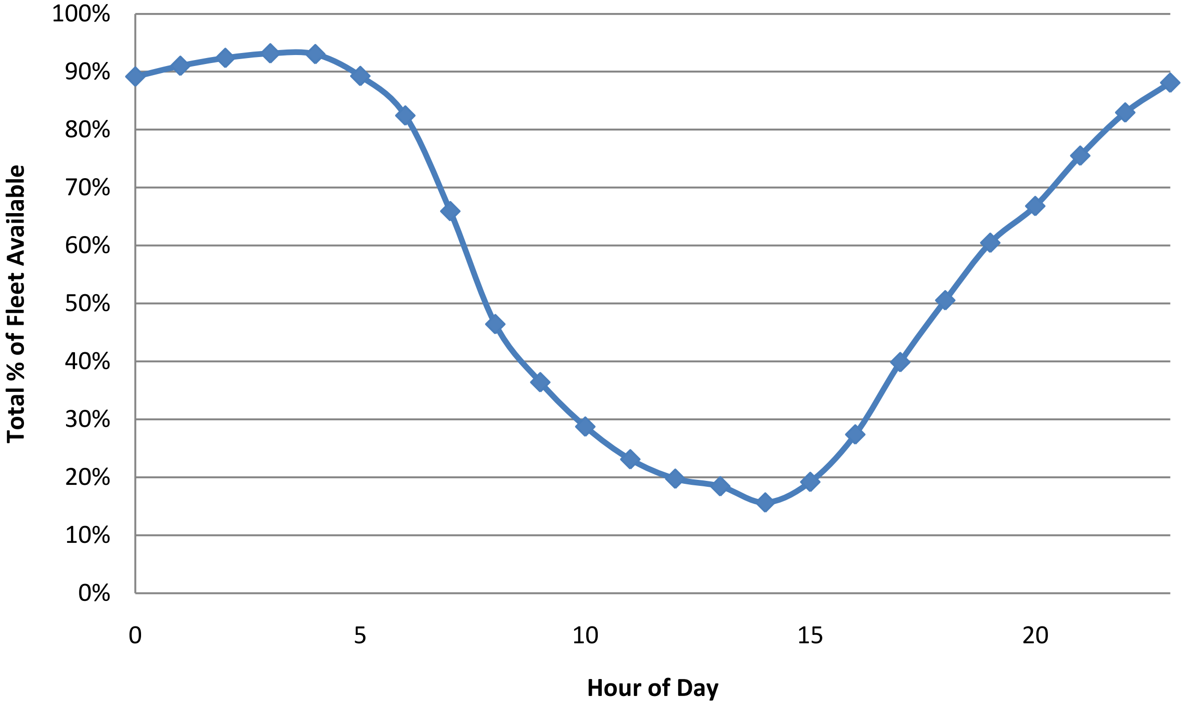

Figure 7: Energy availability for the worst case charge at home only scenario

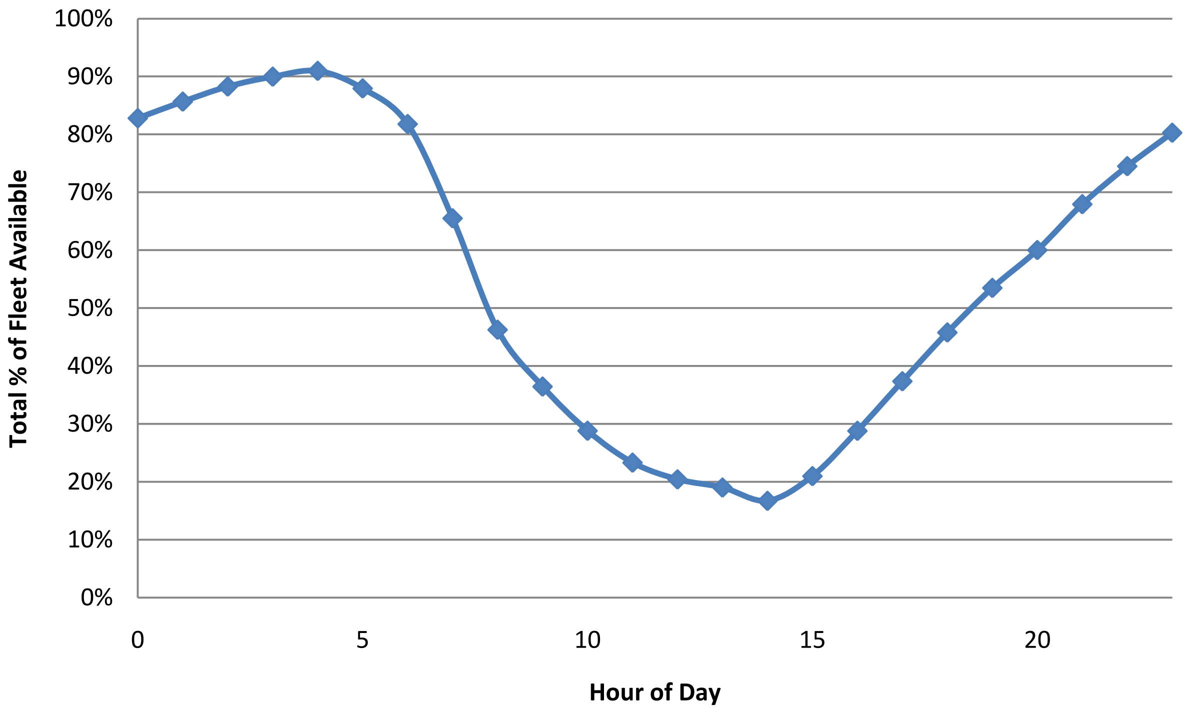

Figure 8: Energy availability for the best case charge at home only scenario

Potential Financial Benefits

Three different cases were run for the potential financial benefit calculations; a baseline, worst case, and best case. For each scenario the potential annual consumer profit is presented for four different capacity factors. Under the baseline scenario annual consumer profit ranged from \$630 to \$660 depending on the capacity factor. The worst case scenario yielded a maximum of \$80 profit for a capacity factor of 0.1% and a potential loss of \$60 if operating at a 5% capacity factor. The best case scenario showed the highest potential annual profit ranging between $1350 and $1500 with the highest profit coming from the higher capacity factor; 5%. The baseline and worst case scenarios had a full battery discharge time of 1.5 hours and the best case scenario having a full battery discharge time of 2 hours and 50 minutes. For the baseline, worst case, and best case scenarios a total of 137, 673, and 130 vehicles respectively would be needed per MW of peak shaving capabilities. Annual consumer profit calculations and avoided plant costs for each of the scenarios are presented in Tables 2-4.

Table 2: Potential annual consumer profit for the baseline scenario

Capacity Factor	0.1%	0.5%	1%	5%
Variable Cost ($/MWh)	46	46	46	46
Fixed Cost ($/MWh)	10,273	2,055	1,027	205
Total Cost ($/MWh)	10,319	2,101	1,074	252
Max Rebate to Consumer (¢/kWh)	1,026	205	102	20
Annual Consumer Profit ($)	656	654	651	627

Table 3: Potential annual consumer profit for the worst case scenario

Capacity Factor	0.1%	0.5%	1%	5%
Variable Cost ($/MWh)	23	23	23	23
Fixed Cost ($/MWh)	6,419	1,284	642	128
Total Cost ($/MWh)	6,441	1,306	664	151
Max Rebate to Consumer (¢/kWh)	619	106	42	(10)
Annual Consumer Profit ($)	81	69	54	(62)

Table 4: Potential annual consumer profit for the best case scenario

Capacity Factor	0.1%	0.5%	1%	5%
Variable Cost ($/MWh)	73	73	73	73
Fixed Cost ($/MWh)	19,974	3,995	1,997	399
Total Cost ($/MWh)	20,047	4,068	2,071	473
Max Rebate to Consumer (¢/kWh)	2,002	404	204	45
Annual Consumer Profit ($)	1,347	1,360	1,375	1,501

The Monte Carlo simulation reveals that the average potential annual consumer profit for V2G peak shaving is roughly $330 with a standard deviation of $112. A histogram of the potential annual consumer profit from the Monte Carlo simulation is presented in Figure 9.

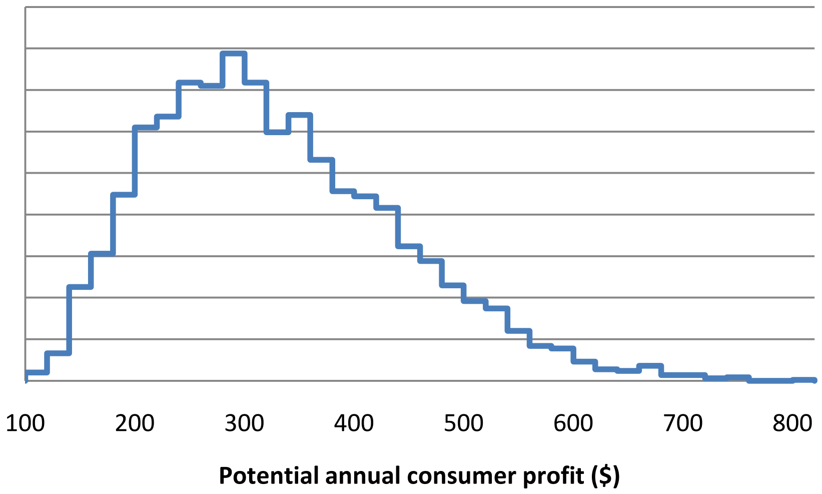

Figure 9: Histogram from Monte Carlo simulation of potential annual consumer profit

CHAPTER IV

CONCLUSIONS

Viability

The viability of using PHEV’s for the means of peak shaving is heavily dependent on the charging scenario and available infrastructure. Both the energy availability and the potential consumer profit are affected by the charging infrastructure. However, each is affected by a different charging infrastructure variable.

The energy availability is heavily dependent on the location and availability of charging stations and not very dependent on the circuit capabilities of the charging stations. For the opportunity charging scenario the potential for V2G peak shaving is very high because of the very high availability of the vehicle’s energy during times of peak demand. The potential for V2G peak shaving under the charge at home only scenario, however, does not show much potential because of the very low availability of the vehicles stored energy in the battery during times of peak demand.

Under either scenario, if V2G peak shaving were to be used, the energy availability curves would change. The change would occur at the time of day when peak shaving would start. At that point in time the energy availability curve would start to decline, at a steady rate if drawn at a steady rate, until the period of peak shaving ceased. The rate of decline would be dependent on both the amount of energy that is drawn as well as the fleet penetration of PHEV's capable of V2G. At the point in time when peak shaving ceases, a steady increase of availability would be seen until the curve reached its typical non-peak shaving state.

The potential consumer profit is most dependent on the charging circuitry, but also depends on the locations and availability of the charging stations because if the vehicle is not recharged or plugged in during peak shaving, then the circuitry doesn't matter. There is a direct one to one relationship between the charging circuitry capabilities and the potential annual consumer profit. Therefore, if the circuitry doubles the rate at which it can charge and discharge, then the potential consumer profit is doubled. The converse is also true. The overnight cost of the avoided natural gas fired turbine also played a significant role in the potential consumer profit, but due to the lower variability in the overnight cost, it did not affect the potential profit very much. Though the other variables affected the potential consumer profit, none of them showed an impact great enough to significantly change the potential consumer profit by more than 10%.

For the baseline scenario a total of 137 vehicles would be needed for each MW of peak shaving operation and could last 1.5 hrs if the batteries were fully charged before drawing from them. Under a 0.1% capacity factor and the demand load for the PSCO service area, peak shaving would only be necessary for approximately 8 hours per year, and never more than 3 hours continually. Initially this looks promising due to the high potential consumer profit, low number of vehicles need, and infrequency of power draw from the vehicle. There is one concern however, the load gap.

> Below the term 'load gap' is used to represent the difference between the absolute highest demand and the load at the capacity factor cut off. The load at the capacity factor cut off is the load at which the percentage of the time the load is above the cut off level is the same as the capacity factor percentage. Therefore if the capacity factor is 0.1%, and 0.1% of the time the load is above 6,750 MW and the absolute highest demand is 7,100 MW, then the load gap is 350 MW.

This is an issue because it increased the number of vehicles needed for peak shaving significantly. Under the same 0.1% capacity factor for the PSCO service area, the load gap would be roughly 350 MW, therefore increasing the number of vehicles needed by a factor of 350 as compared to the 137 vehicles needed per MW. This would result in nearly 2.8% of the 1.73 million vehicles in the PSCO service territory (48,000 vehicles) if the entire 350 MW load gap were to be covered by the V2G. The majority of this load gap occurs during only one day out of the year and most severely in years to come due to the ever increasing demand from year to year. If one were to assume that the American vehicle fleet is refreshed every ten years and from here on out one out of every ten cars sold were a V2G enabled PHEV, then the 2.8% fleet penetration could be covered in less than 3 years.

If the load gap were to be filled by many different types of peak shaving technologies, including V2G, then the number of vehicles needed is lessened. A number of other load reducing strategies could be implemented during these highest demand hours, such as curtailment of individual demand, to reduce the load gap and reduce the number of vehicles needed. If V2G were to become a reality, chances are that it would not have to cover the entire load gap analyzed here.

The major conclusion of the study shows that under certain situations, such as the opportunity charging baseline case, V2G operation for peak shaving is possible and could provide vehicle owners with significant compensation for the energy stored in their vehicles batteries. In order to avoid the construction of a natural gas fired turbine the utility provider needs to be assured that there is enough energy available from V2G operation and other sources to cover the load gap. For this assurance to be made by V2G alone (under the conditions used in this study) roughly 2.8% of the 1.73 million vehicles in the PSCO service territory would be needed to cover the entire peak load demand during the highest load hours. If the load gap were to be reduced or partially covered by another peak shaving source, the percentage of vehicles needed would be reduced and would make V2G a very attractive and viable source for peak shaving.

Future Work

Future work should target multiple, same region, data sets for both grid load and vehicle usage to increase the validity and precision of the study. An analysis of restricted charge timing should be added to the analysis to investigate the restriction of charging during peak load. Due to the upper bound of this analysis showing potential to work and the lower bound showing very little potential to work, analysis on a middle ground scenario, such as charge at home and work only, should be calculated. Calculations of the reduced energy availability during peak shaving should be incorporated to show how peak shaving affects the energy availability. Future work could also build upon this work by linking the potential financial benefit to the energy availability analysis for a more comprehensive and cohesive analysis. Furthermore, if access to a more powerful computer were available, a more detailed analysis could be performed down to the minute level. Additional analysis could focus on small isolated grids, such as islands not connected to the main grid, because V2G for peak shaving may be more practical in such areas.

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