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Plug-In Hybrid Vehicles and the Vermont Grid: A Scoping Analysis

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Executive Summary

The concentration of greenhouse gases (GHG) in the earth's atmosphere is creating changes in the world's climate. Reducing GHG emissions has become a national and international priority. Combusting carbon in the transportation sector contributes more than 28 percent of total U.S. GHG emissions (EPA, 2006). Within the transportation sector, light duty vehicles comprise about 60 percent of the GHG emissions footprint.

GHG emissions from the transportation sector are the fastest growing source of GHG emissions in the United States (EPA, 2006). In Vermont, the transportation sector is the largest in-state contributor of GHG emissions. One strategy to reduce transportation's GHG emissions (primarily carbon dioxide, CO_2) is to switch to lower carbon fuels. Because of Vermont's low carbon electricity supply, switching some portion of the state's light duty vehicle fleet to electricity could reduce GHG emissions. *

This research report specifically examines the CO_2 and NO_x emissions of switching a significant number of Vermont vehicles from gasoline to electricity. In addition to the environmental and social impacts, the reliance on petroleum to fuel Vermont vehicles impacts the state's economy and the pocket-books of consumers. Drivers in Vermont spent more than $1.1 billion to fuel vehicles in 2007, an increase of about $500 million dollars from 2002.

Changing the fuel in Vermont vehicles can address both emissions and economic issues. Advances in electric drive systems and energy storage devices have made plug-in hybrid electric vehicles (PHEVs) a reality. Building on the success of hybrid electric vehicles, PHEVs allow the consumer to charge the vehicle's battery pack directly from the electric grid rather than from the vehicle's gas engine.

This research report looks at the ability of the Vermont electric grid to handle large numbers of PHEVs, and at the emissions impact and end-user economic costs. This report is based on an analysis by researchers at the University of Vermont and Green Mountain College with support from the Vermont Department of Public Service, Central Vermont Public Service, Green Mountain Power and Burlington Electric Department.

The assumptions used in the following findings are detailed in the report. The type of reference vehicles, the price of gasoline and the price of electricity all impact the findings. A second phase of this study with more detailed information on Vermont vehicles and actual vehicle performance has been proposed.

Major Findings

- Vermont has a low-carbon electricity supply mix, thus shifting some portion of energy used for transportation from gasoline to electricity will result in a reduction in greenhouse gas emissions. Furthermore, because of the present relative prices of gasoline and electricity, vehicles running on electricity will cost consumers less.

- Switching 50,000 existing vehicles from gasoline to plug-in hybrid electric vehicles would reduce carbon emissions by 31 percent, assuming that the average miles per

gallon of the gasoline vehicle is 27.7 and that the PHEV has an electric range of 20 miles. The carbon emission savings from less efficient gas vehicles and/or higher electric range PHEVs would be greater.

- Switching 50,000 existing vehicles from gasoline to PHEVs would result in a 30% decrease in NO_x emissions.

- The existing electric grid could charge 100,000 PHEVs under a delayed nighttime charging scenario without adding to system peaks or adding additional generation and transmission. Because there is less electricity used during the overnight hours, charging vehicles at night could also increase the overall efficiency of the electric system.

- Allowing 100,000 PHEVs to charge at peak times would cause a significant increase in peak demand for electricity in Vermont. This scenario assumes that Vermonters plug their vehicles into the grid when they arrive at work and arrive home from work.

- Vermont could reduce annual gallons of gasoline consumption between 11.4 and 12.9 million gallons by replacing 50,000 gasoline vehicles with PHEVs. The difference in the two estimates is detailed in the report and is based on the miles per gallons gasoline consumption assumptions of the reference vehicle.

- Electricity equivalent costs to power a vehicle are about one-third the gasoline equivalent costs. Driving in the electric mode would cost about 4.2 cents per mile. The gas equivalent cost of a similar vehicle is 12.2 cents (assuming a 25 mpg gasoline vehicle and gasoline at $3.00 a gallon).

- The gasoline gallon equivalent cost to drive a PHEV on the electric mode would be $1.05 a gallon. A vehicle driving on the electric mode could travel 25 miles for $1.05 while a gas-equivalent vehicle would cost $3.00 to travel the same distance (assuming a PHEV20, traveling 2.38 miles per kWh and kWh costs at $0.10/kWh).

- Preferential rates offered by electric utilities to provide incentive for off-peak charging could further reduce the electric costs and increase the efficiency (load factors) of the Vermont electric grid.

Acknowledgements

The authors thank Bruce Bentley and Dan Mackey at Central Vermont Public Service, Rebecca Towne and Dorothy Schnure at Green Mountain Power, T.J. Poor and David Lamont at the Vermont Department of Public Service UVM Graduate Student Keith Pelletier and Tom Buckley and Mary Sullivan at Burlington Electric Department for their financial support, encouragement and critical review.

* Vermont's current low carbon fuel electricity supply could change as contracts with the Vermont Yankee Nucler power plant and Hydro-Quebec are set to expire in the next 5-8 years.

I. Introduction

The transportation sector is the leading contributor of carbon dioxide emissions in Vermont. Furthermore, as illustrated in Figure 1, carbon dioxide emissions in the transportation sector increased to a greater degree during the ten years from 1993 and 2003 than in any other sector. Vermont must address its transport-related emissions of carbon dioxide to reduce the state's carbon footprint.

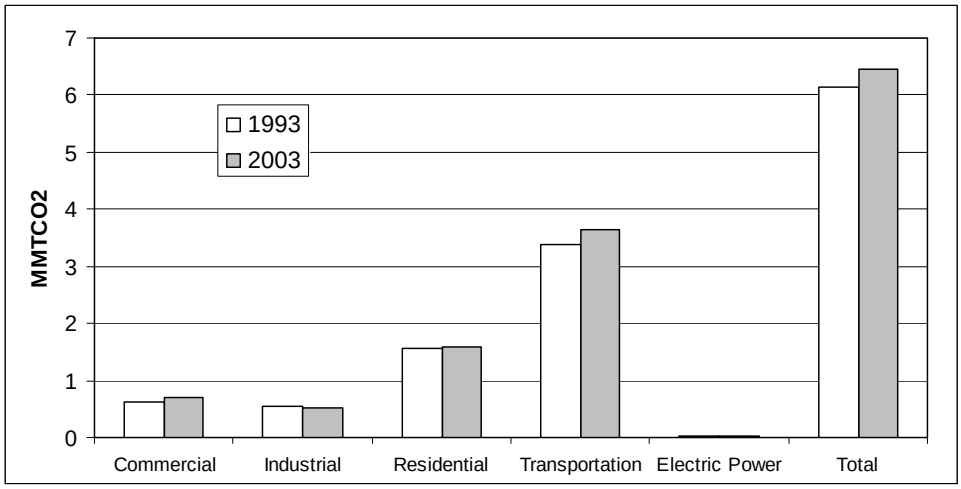

Figure 1: Vermont CO_2 Emissions by Sector: 1993 vs. 2003 (Million Metric Tons). Source: US DOE Energy Information Administration

Although total vehicle miles traveled (VMT) in Vermont have declined slightly in recent years, longer term trends indicate that Vermonters are driving more today then they did a decade ago. Figure 2 compares total VMT and per capita VMT from 1995 and 2005. Per capita vehicle miles traveled in Vermont increased by 17 percent between 1995 and 2005. Per capita VMT in Vermont in 2005 were 12,600, well above the national per capita VMT of just over 10,000. Total VMT in Vermont currently stands at just over the 7.5 billion mark (Watts, Glitman and Wang, 2007).

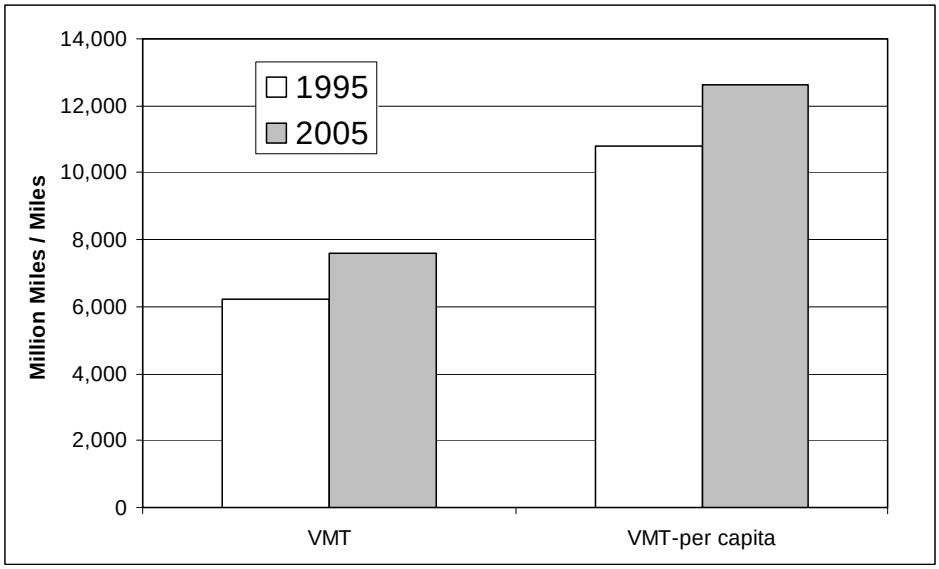

Figure 2: Total VMT and Per Capita VMT in Vermont: 1995 vs. 2005. Source: Vermont Agency of Transportation

Gasoline prices in New England have risen significantly over the past decade at the same time that the demand for automobile travel has increased. As a result, Vermonters are forced to allocate more of their income to transportation. In 2006, Vermonters consumed 344 million gallons of gasoline and 72 million gallons of diesel fuel at a total expenditure of $1.1 billion. Expenditures on transportation fuels in 2006 were up over $500 million from 2002 due to rising fuel prices (Watts, Glitman and Wang, 2007). Most of the money spent on fueling vehicles each year in Vermont leaves the state to outside interests—the so called "leaky bucket" phenomena.

Advances in electric drive systems and energy storage devices have made hybrid electric vehicles a reality. In 2006, 1.5 percent of all new vehicles sold were hybrids (www.hybridcars.com). Data from the Vermont Department of Motor Vehicles indicates that a total of 2,389 hybrid electric vehicles are registered in the state. A growing national movement is calling for the automobile manufacturers to develop the next generation hybrid electric vehicles that allow charging from the electric grid. These plug in hybrid electric vehicles (PHEVs) offer the potential for the light vehicle fleet to substitute electricity supplied from the grid for gasoline purchased at the pump. Prototype PHEVs have demonstrated the ability to achieve over 100 miles of travel per gallon of gasoline consumed (www.calcars.org). Furthermore, studies have found that the cost of electricity to drive the same distance as a gallon of gasoline is less than one dollar.

A PHEV differs from a conventional hybrid electric vehicle commercially available today in two important ways. First, additional battery storage and a three-pronged plug allow a PHEV to displace gasoline with electricity purchased from the local utility. Conventional hybrids use the battery pack in what is described as a charge sustaining mode, meaning the battery pack is subject to shallow cycles of discharging and charging from the vehicle engine and the regenerative breaking system. In contrast, a PHEV uses a charge depletion strategy, whereby it uses a much greater percentage of the battery pack for vehicle operations (Gonder and Markel, 2007). Once the battery pack is nearing depletion, the vehicle reverts back to a charge sustaining mode similar to its non plug-in counterpart.
PHEVs are often categorized by the potential all-electric range given different battery pack storage capacities. A PHEV20 offers sufficient energy storage to deliver 20 miles of travel in all-electric mode. Similarly a PHEV40 has a larger battery pack than a PHEV20, and thus has the potential to

travel 40 miles in all-electric mode. While all-electric range is a useful way to characterize PHEVs, these vehicles will likely operate in a blended mode using both the engine and an electric motor to propel the vehicle in an effort to optimize the overall efficiency and cost of the vehicle (Gonder and Markel, 2007).

PHEVs could offer Vermont the ability to keep a portion of its transportation dollars in state and at the same time reduce household transportation-related expenses and emissions of greenhouse gases and other pollutants. As Figure 1 above illustrates, Vermont has a low-carbon electricity supply mix, thus shifting some portion of energy used for transportation from gasoline to electricity should result in a reduction in greenhouse gas emissions. Furthermore, using the idle capacity of Vermont's electric power infrastructure can serve to increase its utilization, thus putting downward pressure on electricity rates. To date, however, there is no conclusive assessment of the PHEV opportunity in Vermont. The University of Vermont's Transportation Center, in conjunction with the state's leading electric utility companies, has launched the first ever study to understand the grid impacts of an emerging fleet of PHEVs in Vermont. Specifically, the study's main objectives are:

- How Many PHEVs could the Vermont electric power system charge without the need to build additional generation, transmission, and/or distribution facilities assuming three plausible consumer charging patterns?
- How much gasoline could be displaced annually from three different PHEV penetration scenarios—low, medium, and high-in Vermont?
- What are the net regional emissions impacts from the introduction of PHEVs in Vermont, including greenhouse gas emissions and other key pollutants?
- From an end-user perspective, how do consumers evaluate the economics of PHEVs? This will include calculations of the MPG equivalent cost of displacing gasoline with electricity.

While no PHEVs are currently being sold today, there are a number prototypes currently being tested. The Electric Power Research Institute and DaimlerChrysler have several PHEV Sprinter vans being evaluated in different locations in the US and Europe. Three start-up companies have developed retrofit kits that convert existing hybrid electric vehicles to PHEVs. One of these companies, based in Toronto, Canada called Hymotion, recently converted two Toyota Prius vehicles for Vermont's largest utility, Central Vermont Public Service. Researchers at Green Mountain College in Poultney, Vermont are gathering performance data on these vehicles under the direction of Steven Letendre. An additional Hymotion converted Toyota Prius is in a research project at the University of Vermont's Transportation Center. Together these three vehicles are part of a second phase of Vermont-based PHEV research.

It now appears that the major automobile manufacturers are planning to offer PHEV products within the next several years. General Motors Corporation has announced plans to offer two PHEV options, one being a version of its Saturn Vue SUV and the other a new model referred to as the Volt. Very recently, Toyota announced that it would be testing several PHEVs based on the Prius platform in Japan and the US. It appears likely that Toyota will soon manufacture and sell a commercial PHEV product. Ford Motor Company and the electric utility company Southern California Edison also recently announced plans to test PHEV versions of the Ford Escape. In addition, there are several pure electric vehicle developers that have plans to offer products in the next 12 months. These include Tesla Motors with its two-seater all electric sports car and Phoenix Motors Cars, which is producing and marketing an all electric four-door truck for fleet applications.

Given these developments, it is important to understand the potential of the Vermont grid to accommodate a growing number of grid-connected cars over the coming decades. Furthermore, it is important to understand this potential particularly as Vermont is faced with important decisions about its power supply as contracts with Hydro Quebec and Vermont Yankee are set to expire. In addition, it is useful to understand the implications from a potential shift from tailpipe emissions to power plant emissions associated with a transition to PHEVs and other electric drive vehicles. And finally, energy security is a vital issue for the nation and Vermont. Understanding the petroleum displacement benefits of a transition to electric drive, along with the economic benefits, is helpful to policymakers as they devise policies to address climate change and strengthen local economies.

II. Literature Review

The oldest PHEV development program is housed at the University of California Davis, where Professor Andrew Frank has worked with students for two decades designing and building prototype PHEVs (www.team-fate.net). Since 1999, much of the technical work on defining and characterizing PHEV technology has occurred under the auspices of the Hybrid Electric Vehicle Working Group (WG) convened by the Electric Power Research Institute (EPRI), an electric industry-supported research organization. EPRI brought together representatives from the electric utility and automotive industries, the US Department of Energy and its laboratories, other regulatory agencies, and university research centers to study a wide range of technical issues related to PHEV development. A WG report published by EPRI (2001) titled Comparing The Benefits And Impacts Of Hybrid Electric Vehicle Options concluded:

> This report indicates that HEVs, including grid-connected (plug-in) models, can probably be designed for a wide variety of vehicle platforms meeting performance characteristics customers are familiar with. Plug-in hybrids provide significantly improved fuel economy over conventional vehicles, reductions in greenhouse and smog precursor emissions, and petroleum use. However, HEVs, especially plug-in HEVs with an all-electric capability, cost more than conventional vehicles. HEVs are expensive due to complex motors and chargers and the energy storage required. Battery life and costs are challenges that need to be addressed. Potential battery replacements can significantly increase the vehicle's life-cycle cost.
>
> The Customer Survey indicated that people preferred plugging in a vehicle instead of going to the gas station. The study also indicated a large market potential for all HEVs—if cost equivalence with conventional vehicles can be achieved and significant even when priced 25% more than a conventional vehicle counterpart. (EPRI, 2001, p. vi)

A. PHEV Technical Specifications

The PHEV technical specifications that emerged from two of the WG reports have served as a basis for most research on PHEV grid impacts. EPRI (2001) study cited above provides specifications for a mid-sized sedan PHEV and EPRI (2002) titled Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sport Utility Vehicles provides technical specifications for a compact sedan, and mid-sized and full-sized SUVs. Table 1 lists the technical specifications on PHEV technology described in the reports.

Table 1: Technical Specifications for PHEV20 in Compact Sedan, Mid-Size Sedan, Mid-Size SUV, and Full-Size SUV Vehicle Platforms

	PHEV20 compact sedan	**PHEV20 mid-size sedan**	**PHEV20 mid-size SUV**	**PHEV20 full-size SUV**
Motor Rated Power, kW	37	51	84	98
Nominal Battery Pack Size, kWh	5.1	5.9	7.9	9.3
Battery Rated Capacity, usable kWh[+]	4.1	4.7	6.3	7.4
Gasoline mpg (PHEV/conventional vehicle)	52.7/37.7	43.5/28.9	34.7/22.2	29.5/18.2
Electric Only Economy (mpeg)*	134	117	90.5	77
All Electric Efficiency (miles/kWh)	4.0	3.49	2.7	2.3
Mileage Weighted Probability Fuel Economy (mpeg)[@]	71.7	58	46.6	39.8
Vehicle Mass, kg	1,292	1,664	2,402	2,824
Charging time (hours, 120 V 15 amp, 1 kWh/hr.)^	4	4.7	6.3	7.4
Charging time (hours, 120 V 20 amp, 1.3kWh/hr.)^	3	3.5	4.7	5.6
Charging time (hours, 240 V 40 amp, 5.7 kWh/hr.)^	0.7	0.8	1.1	1.3

[+]The battery rated size is assumed to be 80% of the nominal pack size.

*The report expresses the all electric range as miles per energy equivalent gasoline gallon (mpeg). This calculation assumes 33.44 kWh per gallon of gasoline.

[@]The mileage weighted probability (MWP) fuel economy provides an estimate of a blended electric/gasoline operation efficiency. The MWP gives an estimation of what portion of PHEV's daily annual mileage will be in all electric mode based on national driving statistics. The values presented in the table assume nightly charging of the vehicle.

^The charging rate per hour assumes an 80% required safety factor for continuous charging and assumes an 82% efficiency for 120 V chargers and 87% for 240 V chargers and 85% battery efficiency.

The vehicle parameters evolved through sophisticated vehicle design modeling using a tool known as ADVISOR (ADvanced VehIcle SimulatOR), which was developed by researchers at the National Renewable Energy Laboratory, one of the US Department of Energy's research laboratories. It is important to note that the vehicle fuel economy, a critical parameter for understanding PHEVs, is dependent on a number of key factors including the drive cycle and the frequency of charging. Table 1 above reports three different fuel economy measures.

The first measure of fuel economy in Table 1 is the gasoline miles per gallon, which indicates the lower bound mileage number based on the vehicle operating in charging sustaining mode similar to conventional hybrid vehicles sold today. The second fuel economy measure is based on operation of the vehicle in electric-only mode and is expressed as miles per energy equivalent gasoline gallon (mpeg). The energy content of a gallon of gasoline is expressed in terms of electrical energy at 33.44 kWh per gallon to derive this value. The mpeg serves as the upper bound efficiency potential of the vehicle. The "Mileage Weighted Probability Fuel Economy" presented in Table 1 is an attempt to present a likely "real world" fuel economy estimate based on a statistical approximation of the number of miles driven each year in all-electric mode and with the vehicle being recharged nightly.

The two EPRI WG studies also present vehicle parameters for PHEV60s—plug-in hybrid vehicles with a 60 mile all-electric range. These vehicles achieve better fuel economies for each of the three measures presented in Table 1, although this is not a simple multiple due to the higher vehicle mass resulting from a larger battery pack.

Finally, it should be noted that the technical parameters of PHEVs developed by the EPRI WG may not necessarily conform to those of PHEVs that ultimately reach the market. While it is very likely that major vehicle manufacturers are doing their own vehicle design work, this information is not readily available to the public. As a result, the WG PHEV technical specifications serve as the best approximation in terms of what to expect regarding PHEV characteristics and performance. As a result, these values have served as key inputs to research on PHEV grid impacts.

B. PHEV Grid Impact Studies

Four prominent studies analyzed the grid impacts from an emerging fleet of PHEVs. While there are some similarities across the studies, each one takes a different approach in terms of the electric system, PHEV configurations, and charging scenarios analyzed. In the end, however, each study finds that the existing electric power infrastructure is capable of charging a large fleet of PHEVs without the need to build additional generating, transmission, or distribution infrastructure. Table 2 lists the studies reviewed here, along with some key features of each.

Table 2: PHEV Grid Impact Studies

Title	Authors' Affiliation	Geographic Focus	Vehicle Configuration	Charging Scenario(s)	Emissions Assessment
Impacts Assessment of Plug-In Hybrid Vehicles on Electric Utilities and Regional U.S. Power Grids	Pacific Northwest National Laboratory	Entire U.S., based on 12 modified North American Electric Reliability Council regions	PHEV33, this vehicle configuration is used to estimate the electricity consumption that would satisfy the average daily commute as determined by travel survey data.	The study assumes all excess capacity is used. Produces estimates based on 24-hour charging and 12-hour charging scenarios.	Yes
An Evaluation of Utility System Impacts and Benefits of Optimally Dispatched Plug-In Hybrid Electric Vehicles	National Renewable Energy Laboratory	Six different geographic regions, using hourly load data from electric utility control areas.	This study simulated the energy requirements of a PHEV fleet that meets on average 40% of its daily miles traveled with electricity. This translates into a PHEV with an all-electric range between 20 and 40 miles	Charging is based on an optimized 24-hour cycle assuming direct utility control of when the vehicles are charged.	No
Costs and Emissions Associated with Plug-In Hybrid Electric Vehicle Charging in the Xcel Energy Colorado Service Territory	National Renewable Laboratory	This study was focused specifically on Xcel Energy's Colorado service territory.	A mid-size PHEV20 vehicle with 37 mpg gasoline and 2.78 miles/kWh and 7.2 kWh of battery storage capacity.	Four charging scenarios were evaluated: uncontrolled charging; delayed charging; off-peak charging; and continuous charging.	Yes
Effects of Plug-In Hybrid Electric Vehicles in California Energy Markets	Energy and Resources Group at the University of California Berkeley	This study used load data from the California Independent System Operator and thus was focused exclusively on CA.	A compact PHEV20 vehicle with 50 mpg gasoline, 130 mpeg, and 5 kWh of usable stored energy. Also conducted sensitivity analysis using a full-size SUV.	Three charging scenarios were modeled: optimal charging, evening charging, and twice a day charging.	No

The study conducted by researchers at the Pacific Northwest National Laboratory (PNL) adopted what might be described as a top down approach. In each of the 12 North American Electric Reliability Council regions, 24-hour load profiles were developed for a typical summer day and a typical winter day. This simplification from an 8,760 load profile is justified by the fact that these two periods are likely to have the least reserve capacity relative to the other times of the year (Kintner-Meyer, Schneider, and Pratt, 2007). The two load profiles were used to estimate the unused generating capacity in each region. The study calculates the number of PHEVs that could be charged with this excess generating capacity. It should be noted that the study did not include peaking plants as available for PHEV charging, given that these units are designed for short run-times and thus would likely be uneconomic to have running for extended periods.

Nationwide, the PNL study estimates that 73 percent of energy for the light-duty vehicle (LDV) fleet could be supported by the existing US electric power infrastructure, assuming a daily drive of 33 miles on average. This is considered the "technical" potential given the current installed generating capacity installed nationwide, which represents 217 million vehicles. In this scenario, the power sector would be running at near full capacity most hours of the day. The authors recognize that this would put strain on the system, which was engineered to meet widely fluctuating demands for power. As a result, the authors assess a second scenario whereby PHEVs can only charge for 12 hours each day, between the hours of 6:00 pm and 6:00 am. In this case, 43 percent of the energy of the nation's LDV fleet could be supplied by the existing electric power infrastructure.

The study identified significant difference between regions regarding the electric power systems' ability to charge an emerging fleet of PHEVs. For example, the technical potential of the region referred to as CNV (California and Southern Nevada) is only 23 percent of the energy requirements of

the LDV fleet in that region. In the US section of the Northeast Power Coordination Council (New York and the six New England States) region, the study estimates that 80 percent of the energy requirements of the light vehicle fleet could be met by the regional electric grid, or approximately 20 million vehicles.

The remaining PHEV grid-impact studies can be referred to as bottom up or scenario analyses. Different PHEV penetration scenarios are assessed to better understand the demands that charging PHEVs would place on regional grids. The Denholm and Short (2006) study used a PHEV load tool to incrementally add load to six different electric power systems assuming an optimal, utility-controlled charging regime to estimate the number of PHEVs that could be charged without adding to the region's system peak load. They found that vehicle penetration rates as high as 50 percent of the regional light vehicle fleets could be met given the existing generation capacity in each of the six study areas, assuming that 40 percent of the daily vehicle miles come from electricity. This level of PHEV penetration would increase the annual energy demand by 6 to 12 percent depending on the region. They also identified additional ancillary benefits in the form of increased loading of base load power plants and reduced cycling of intermediate generating resources; both of these factors could potentially lower overall operating costs.

The remaining two studies were much more geographically focused. Parks, Denholm, and Markel (2007) used a sophisticated production cost model known as PROSYM to model Xcel Energy Colorado's power system to investigate the implications of an emerging fleet of PHEVs in their service territory. Xcel Energy provides electricity to 3.3 million customers in eight states. In Colorado, Xcel serves 1.3 million customers and delivers 26,500 GWh of energy annually.

The Xcel study, as referenced in Table 2, used a PHEV20 vehicle configuration to model the utility system impacts of 500,000 vehicles, roughly 30 percent of the 1.7 million vehicles in the Xcel service territory. Three charging scenarios were analyzed to understand the power system impacts of a range of possible consumer charging preferences. Parks, Denholm, and Markel (2007) define the study's charging scenarios as follows:

- **Case 1: Uncontrolled Charging**: The uncontrolled charging case considers a simple PHEV scenario where vehicle owners charge their vehicles exclusively at home in an uncontrolled manner.
- **Case 2: Delayed Charging**: The delayed charging case is similar to Case 1, in that all charging occurs at home. However, it attempts to better optimize the utilization of low-cost off-peak energy by delaying initiation of household charging until 10 p.m.
- **Case 3: Off-Peak Charging**: The off-peak charging scenario also assumes that all charging occurs at home in the overnight hours. However, it attempts to provide the most optimal, low-cost charging electricity by assuming that vehicle charging can be controlled directly or indirectly by the local utility.
- **Case 4: Continuous Charging**: The continuous charging scenario is similar to Case 1, in that it assumes that charging occurs in an uncontrolled fashion (at 1.4 kW) whenever the vehicle is plugged in. However, it also assumes that public charging stations are available wherever the vehicle is parked.

(Parks, Denholm, and Merkal, 2007, pp. 7 – 10)

Not surprisingly, the uncontrolled and continuous charging added considerable load that is coincident with periods of high power demands in both the summer and winter months. However, the impacts

were quite modest, with the uncontrolled charging scenario adding 2.5 percent to the system peak demand and the continuous charging scenario adding 4.6 percent. In terms of energy, charging 500,000 PHEVs from Xcel Colorado would add 3 percent to the total energy required annually, again assuming a PHEV20 that derives 39 percent of its drive energy from electricity. Furthermore, the authors of this study conclude that if modest steps were taken to encourage optimal charging, a massive penetration of PHEVs could be accommodated without adding to Xcel Colorado's system peak. The greatest system-wide benefits could be achieved through direct utility control of PHEV charging.

The Lemoine, Kammen, and Farrell (2007) study from the University of California Berkeley focused its PHEV assessment on the State of California. In addition to assessing system load impacts, this study evaluated the economic trade-offs between charging from the grid versus using gasoline to fuel a vehicle. Like the previous study discussed above, the authors select a PHEV20 as a base case to assess the economics of PHEV charging and system load impacts. Sensitivity analysis was conducted assuming a full-size SUV configuration with a gasoline economy rating of 30 mpg and 8.7 kWh of usable electricity to meet the 20 mile all-electric range target.

Using 1999 wholesale power prices, the authors estimated the number of vehicles that could charge economically from the California grid (e.g., electricity would serve as a less expensive fuel as compared to gasoline). Residual PHEV electricity supply curves were constructed along with PHEV electricity demand curves based on various gasoline prices. The analysis found that 6 million vehicles could charge economically off-peak and 3 million on-peak if gasoline prices are assumed to be $3 per gallon. This "economic" potential represents a significant portion of the 17 million vehicles located in the study region.

The grid impact assessment was based on three different PHEV penetration scenarios and three different vehicle charging assumptions. The system load impacts were calculated for 1, 5, and 10 million PHEVs charging from the California grid, assuming an effective charging rate of 1 kWh per hour. The three charging scenarios analyzed were defined as follows:

> **1) Optimal Charging**. This corresponds to the best case assumptions used in prior analyses. It is optimal from the grid operator's perspective. The vehicles are charged in a pattern that smoothes demand as much as possible by charging during periods of lowest demand, and vehicles need not charge for 5 continuous hours. This scenario bounds the possible beneficial load-leveling effects of PHEVs.
> **2) Evening Charging**. The times at which the PHEVs begin charging are evenly distributed between 6, 7, and 8 PM. Each PHEV charges for 5 continuous hours. This represents drivers returning home from work and plugging in their vehicles. This and the next scenario are meant to provide worst-case baselines for possible behavior in the absence of price incentives or technical means of shaping charging patterns.
> **3) Twice Per Day Charging**. This is a high demand scenario: each PHEV is assumed to be plugged in to charge fully at the end of each commute leg. Thus, each vehicle fully charges twice each day, once upon arriving at work in the morning and once upon arriving home in the evening. Charging start times are evenly distributed between 8 and 9 AM and again between 6, 7, and 8 PM. Each PHEV charges for 5 continuous hours in the morning and again in the evening.
> (Lemoine, Kammen, and Farrell, 2007, p. 4)

Under all three charging regimes the system level impacts of 1 million PHEVs do not cause any major problems. However, the 5 and 10 million PHEV scenarios would clearly increase peak demand under the evening charging and twice per day charging scenarios. The authors note that even 1 million vehicles charging during peak price hours could increase the price of electricity for everyone, and thus public pressure to strongly encourage off peak charging could emerge. The study concludes that it is unlikely that a large fleet of PHEVs will emerge in the next decade given that the fuel savings over the life of the vehicle is likely not sufficient to justify the initial price premium of a PHEV over a conventional internal combustion engine or currently available non-plug in hybrid vehicles (Lemoine, Kammen, and Farrell, 2007).

All four of the PHEV grid impact studies reviewed here demonstrate that the electric power infrastructure currently in place throughout the nation's regional grids could charge a large fleet of PHEVs. Even large penetrations of PHEVs represent a small increase in the total electrical energy consumed nationwide. Direct utility control of charging is the optimal approach to avoid having PHEV charging contribute to system peak demand, and thus offers the best chance to efficiently and economically integrate PHEVs into the nation's vehicle fleet. Price incentives to consumers could increase the likelihood of off-peak charging.

C. PHEV Net Emissions Implications

PHEVs allow greater use of electricity as transportation fuel, thereby displacing gasoline. From an emissions perspective, this entails substituting tailpipe emissions from vehicles for emissions discharged from the stacks of large, central-station power plants. For human health, ecosystem protection, and existing air quality regulations, it is important to understand the net emissions impacts associated with greater use of electricity for fueling the nation's light vehicle fleet.

The EPRI WG studies calculated the net greenhouse gas emissions and smog precursor emissions on a per vehicle basis to allow for comparisons. Two of the grid impact studies also assessed the net emission impacts from an emerging fleet of PHEVs. Researchers at the National Renewable Energy Laboratory produced an analysis of the potential carbon emissions reduction by 2030 from PHEVs. This study was part of a larger project initiated by the American Solar Energy Society (ASES) to assess potential carbon emissions reductions in all sectors by 2030. In early 2007, ASES published a comprehensive report based on the project's findings.

In addition, one very recent study which focused exclusively on the emissions implications from the introduction of PHEV technology was conducted jointly by the Natural Resources Defense Council (NRDC) and EPRI. Two reports were produced and recently published from this joint study, which claim to be the most comprehensive environmental assessment of electric transportation to date. Volume 1 of the NRDC and EPRI study estimated the net greenhouse gas emissions and Volume 2 presents results based on extensive modeling of air quality impacts from the introduction of PHEVs.

The two original EPRI WG studies presented a "well to wheels" emissions analysis of the entire fuel cycle. This includes emissions associated with extraction, processing, and distribution of gasoline and the stack emissions from power plants used to charge PHEVs (these are referred to as upstream emissions or fuel-cycle emissions), in addition to the tailpipe emissions. Sophisticated emissions models were used to estimate fuel-cycle emissions and the ADVISOR model was used to estimate tailpipe emissions.

The specific pollutants assessed included CO_2 and smog precursors (NO_x and HC). Emissions per mile of travel were calculated for a comparable conventional vehicle, hybrid electric vehicle (HEV), PHEV20, and PHEV60. It was assumed that the conventional vehicle and the HEV meet the Super Ultra Low Emission Vehicle (SULEV) standards and that the plug-ins are charged at night with efficient combined cycle power plants using natural gas as a fuel source. Table 3 presents the results of the EPRI WG (2001) report based on an emissions analysis for a mid-size sedan; the values are reported as the percent reduction as compared to a conventional vehicle. The EPRI WG (2002) study found similar results for compact, mid-size SUV, and full-size SUV vehicle configurations with regards to emissions reduction potential of PHEVs over conventional vehicles.

Table 3: Emissions Reduction Potential for Mid-Size Sedan HEVs and PHEVs: Percent Below a Conventional Vehicle (SULEV)

	HEV	**PHEV20**	**PHEV60**
CO_2	28%	44%	57%
Smog Precursors	15%	35%	52%

The PHEV grid impact study conducted by researchers at the Pacific Northwest National Laboratory (PNL) included an assessment of net emissions from the large-scale penetration of PHEVs nationwide, also using a well to wheels approach. The PNL study used the Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model to estimate the net emissions impacts associated with the introduction of PHEVs. The emissions analysis was performed for the 12 modified North American Electric Reliability Council's regions to reflect the varying electric generation mix for charging PHEV batteries. The emissions study was based on the estimated technical potential, whereby 73 percent of energy from the light vehicle fleet would come from electricity. The net emissions findings from this study include the following:

- For the nation as a whole, the total greenhouse gases are expected to be reduced by 27% from the projected penetration of PHEVs.
- Total volatile organic compounds (VOCs) and carbon monoxide (CO) emissions would improve radically by 93% and 98%, respectively, as a result of eliminating the use of the internal combustion engine.
- The total nitrogen oxides (NO_X) emissions are reduced (31%), primarily because of the avoidance of the internal combustion process in the vehicle as well as eliminating the refining process to produce gasoline.
- The total particulate emissions (PM10) are likely to increase nationally by 18%, caused primarily by increased dispatch of coal-fired plants.
- The total SO_X emissions are increased at the national level by about 125%, also caused by coal-fired power plants.

(Kintner-Meyer, Schneider, and Pratt, 2007, p. 12)

The PHEV study of Xcel Colorado's service territory also included a net emissions assessment for three key pollutants: SO_2, NO_x, and CO_2. This study did not include the entire fuel cycle; considering refinery operations but not the emissions associated with fuel extraction and transport. Given that the production cost model used in the study contains parameters for each power plant in Xcel's service territory, the researchers were able to estimate the net emissions impacts for each of the four charging scenarios evaluated.

Under all charging scenarios, PHEVs produced fewer CO_2 emissions than both a conventional internal combustion engine vehicle and a non-plug in HEV. Relative to HEVs, NO_x emissions were similar or slightly less under each charging scenario, but significantly below those produced by a conventional vehicle. While the study did not differentiate between urban and non-urban NO_x emissions, the authors speculate that although minor emissions reductions are achieved, there is a significant shift in the source from tailpipe to stack emissions, which could offer significant smog reduction benefits in the greater Denver metropolitan area. Finally, comparative SO_2 emissions were not consistent over the four different charging regimes modeled. For the daytime and delayed charging scenarios, total PHEV-related SO_2 emissions are expected to be less than those from conventional and hybrid vehicles. In contrast, the off-peak charging case SO_2 emissions are expected to be greater. This result is due to the fact that coal-fired power plants tend to be the marginal units during off-peak hours.

National Renewable Energy Laboratory researchers Peter Lilienthal and Howard Brown (2007) produced estimates of the potential carbon emission reductions from PHEVs by 2030. As mentioned above, this analysis was part of a larger study commissioned by the American Solar Energy Society. The Lilienthal and Brown (2007) analysis did not look at the total carbon emissions reduction potential based on projected PHEV penetration scenarios, but instead estimated the percentage of per mile driven carbon emissions reductions from substituting electricity for gasoline. They found that, on a nationwide average, carbon dioxide emission would be reduced by 42 percent for each mile driven with electricity. The results varied widely across states with some states seeing no potential reductions in carbon from a transition from gasoline to electricity for drive energy such as North Dakota, which relies mostly on low-Btu lignite coal (Lilienthal and Brown, 2007). In some regions, however, the potential reductions were very high, including Vermont with a carbon emission reduction potential of over 80 percent.

Volume 1 of the EPRI/NRDC environmental assessment of PHEVs investigates the nationwide greenhouse gas (GHG) emissions for the 2010 – 2050 timeframe under three different PHEV market penetration scenarios. In the high penetration scenario, PHEVs achieve 80 percent new vehicle market share. In addition, three scenarios for GHG intensities of the power sector were considered. The low carbon intensity scenario has total GHG emissions from the power sector decline by 85 percent between 2010 and 2050. Sophisticated energy sector models of both the electric power and transport sectors were used during the 18-month study to evaluate each combination of these scenarios for a total of nine different possible outcomes, which led to the following conclusions:

- Annual and cumulative GHG emissions are reduced significantly across each of the nine scenario combinations.
- Annual GHG emissions reductions were significant in every scenario combination of the study, reaching a maximum reduction of 612 million metric tons in 2050 (High PHEV fleet penetration, Low electric sector CO_2 intensity case).
- Cumulative GHG emissions reductions from 2010 to 2050 can range from 3.4 to 10.3 billion metric tons.
- Each region of the country will yield reductions in GHG emissions.

(EPRI and NRDC, 2007: 1, p. 2)

The second volume describes the US air quality analysis that was conducted based on the assumptions contained in the US DOE Energy Information Administration's Annual Energy Outlook 2006 for the year 2030. The study modeled the transportation and electric power sectors in the year 2030 to investigate the impact of PHEVs on criteria emissions and subsequent effects on air quality and

deposition. The study was based on PHEVs reaching 50 percent of new car sales and representing 40 percent of the total on-road vehicles in 2030. It is assumed that 20 percent of the total vehicle miles traveled in the US in 2030 use electricity. Again, very sophisticated energy sector modeling was conducted to predict the air quality implications from a shift from gasoline to electricity for transportation. The key findings from the EPRI/NRDC air quality assessment are as follows:

- In most regions of the United States, PHEVs result in small but significant improvements in ambient air quality and reduction in deposition of various pollutants such as acids, nutrients and mercury.
- On a population weighted basis, the improvements in ambient air quality are small but numerically significant for most of the country.
- The emissions of gaseous criteria pollutants (NO_x and SO_2) are constrained nationally by regulatory caps. As a result, changes in total emissions of these pollutants due to PHEVs reflect slight differences in allowance banking during the study's time horizon.
- Considering the electric and transportation sector together, total emissions of VOC, NOx and SO_2 from the electric sector and transportation sector decrease due to PHEVs. Ozone levels decreased for most regions, but increased in some local areas. When assuming a minimum detection limit of 0.25 parts per billion, modeling estimates that 61% of the population would see decreased ozone levels and 1% of the population would see increased ozone levels.
- Mercury emissions increase by 2.4% with increased generation needs to meet PHEV charging loads. The study assumes that mercury is constrained by a cap-and-trade program, with the option for using banked allowances, proposed by EPA during the execution of the study. The electric sector modeling indicates that utilities take advantage of the banking provision to realize early reductions in mercury that result in greater mercury emissions at the end of the study timeframe (2030).
- Primary emissions of particulate matter (PM) increase by 10% with the use of PHEVs due primarily to the large growth in coal generation assumed in the study.
- In most regions, particulate matter concentrations decrease due to significant reductions in VOC and NOx emissions from the transportation sector leading to less secondary PM.

(EPRI and NRDC, 2007: 2, p. 4)

To date, the studies of net emissions suggest a clear benefit in terms of reduced CO_2 emission as more and more PHEVs are introduced onto the nation's highways. This result is driven largely by the efficiency improvements along the electricity generation path as compared to the fuel-cycle chain for gasoline, from crude oil extraction, refining, transportation, to ultimate combustion in the vehicle's engine (Kintner-Meyer, Schneider, and Pratt, 2007). In contrast, the net emission impacts from other pollutants are uncertain. Nationwide, there seems to be general air quality benefits, however the results can vary significantly across regions as the electric supply mix changes from location to location. Future outcomes are also highly dependent on how the electric power supply mix changes over time. If the electric power supply mix becomes cleaner over time, this would serve to reinforce the air quality benefits of an emerging fleet of PHEVs.

D. PHEV Petroleum Displacement Potential and Equivalent Costs (Electricity vs. Gasoline)

This section of the literature review turns to two additional benefits that PHEVs may offer. In light of rising gasoline prices and the so-called "peak oil" phenomenon, PHEVs are of interest in terms of the

potential to displace oil as a fuel for transportation. The ability to substitute a domestic resource for foreign oil is very attractive to policymakers and in some circles is viewed as a critical foreign policy initiative. On the consumer side, PHEVs allow households to substitute a low-cost energy source (electricity) for a higher cost source (gasoline). Here we briefly review what the literature on PHEVs has found on these two fronts.

The EPRI (2001) study estimates that a single mid-sized sedan PHEV20 can save approximately 2,000 gallons of gasoline over its life (100,000 miles) compared to a comparable internal combustion engine vehicle. A simple calculation assuming a price $2.50 per gallon of gasoline results in total savings of $5,000. To calculate net savings, the cost of electricity must be subtracted from the avoided fuel expenditures on gasoline. Using the mileage base probability discussed earlier, a PHEV20 could meet, on a statistical basis, an average of 40 percent of total miles traveled. This would translate into 40,000 all-electric miles over the life of the vehicle for a total of 11,460 kWh consumed, assuming an all-electric efficiency of 3.49 miles/kWh. At $0.10/kWh this would translate into $1,150 worth of electricity purchased over 100,000 miles of travel. Thus, the net fuel cost savings over the 100,000 miles would be $3,850. Similarly, the Lemoine, Kammen, and Farrell, (2007) study of California estimated present value fuel savings over 14 years from a PHEV20 over a conventional vehicle to be $3,726 assuming $3.00/gallon and $0.10/kWh. They also find that the fuel savings of a PHEV20 relative to an HEV would be just $1,000. Thus, they conclude that if consumers have low discount rates over long periods they may find a PHEV economical compared to a conventional vehicle, but not to an HEV.

Kintner-Meyer, Schneider, and Pratt (2007) in their study estimate total potential petroleum displacement from providing 73 percent of the daily energy needs of the light-duty vehicle fleet with electricity through widespread deployment of PHEVs. In this scenario, 271 million PHEVs with 33 miles of all-electric ranges would reduce gasoline consumption, by crude oil equivalence, by 6.5 million barrels per day, which is equivalent to 52 percent of current US foreign petroleum imports. Furthermore, Markel et al. (2006) calculate that 1,000,000 PHEVs would save approximately 10 million barrels of oil annually. Certainly, the petroleum displacement potential that PHEVs could achieve is significant, and depends on the number of PHEVs on the nation's highways and the percentage of miles delivered from electricity, either in all-electric or blended modes.

A popular way to express the economics of PHEVs from a consumer's perspective is to estimate the cost to purchase an amount of electricity that delivers an equivalent number of drive miles as a gallon of gasoline, the so called cost of "electric fuel". One dollar or less is often quoted as the cost equivalent of the electrical energy that delivers the same miles of travel as one gallon of gasoline (www.pluginpartners.org). This calculation is quite simple. For example, Denholm and Short (2006) estimate the cost of electricity to drive the equivalent distant as a vehicle getting 30 mpg. Assuming 2.9 miles/kWh for a mid-size sedan, 10 kWh of electricity would be needed. At a cost of $0.08/kWh results in an electric fuel equivalent cost of $0.80/gallon gasoline equivalent.

The electric equivalent energy cost as compared to gasoline is sensitive to several key assumptions. The first is the reference vehicle. Given the calculations above, if we use an HEV as the reference vehicle at 50 mpg, the electric equivalent cost of gasoline would be $1.38. The second key variable is the efficiency assumption of the PHEV, if we assume a full-size SUV at 2.3 miles/kWh and using an HEV as the reference vehicle brings the electric equivalent cost of gasoline to $1.74. Finally, the price of electricity is also a key factor in these calculations. In a high-cost electricity region, at $0.15/kWh, assuming an HEV as the reference vehicle and the electric efficiency of a full-size SUV would result in the electric energy cost of $3.26 per gallon equivalent. However, given the fact that PHEVs would

charge at night, it is reasonable to assume that lower than average rates would apply. Under even conservative assumptions for each of these key variables, electricity is less expensive than gasoline as an energy source for light vehicles at today's fuel prices of approximately $3.00/gallon.

E. Vehicle to Grid (V2G) Opportunities

Typically, electric utilities view PHEVs and other electric vehicles connecting to the grid as new load. Over the past ten years, however, an emerging literature has developed that expands this view and considers the potential role that grid-connected cars could serve as distributed energy storage devices. A bi-directional charger could allow power to both flow into the battery pack and out of the pack to the electric grid serving any number of grid services (Kempton and Letendre, 1997). Depending on the size of the battery pack and power rating of the plug circuit, a V2G capable vehicle could potentially generate hundreds of dollars, or perhaps thousands of dollars, annually providing ancillary services to the electric utility sector (Letendre, Denholm, and Lilienthal, 2006). Interest in V2G technology has increased significantly in recent years. A Google web search using the term "vehicle to grid" yields 35,000 hits. A number of technology and commercial development efforts are currently underway to facilitate grid-interactive vehicles based on the V2G concept. Among other projects, the California utility Pacific Gas & Electric recently demonstrated a V2G capable PHEV and is working with the philanthropic organization Google.org to advance this concept.

This phase of the PHEV Vermont study does not address V2G. In future phases, however, the University of Vermont's Transportation Center and Green Mountain College plan to develop projects that explore V2G opportunities in Vermont.

III. Methodology for Vermont PHEV Study

Vermont is a small state with strong environmental values. In Vermont, there are approximately 615,000 vehicles—state vehicles, municipal vehicles, trucks, and autos—registered for a population of around 620,000 (Watts, Glitman and Wang, 2007). Similarly, the electric power sector that serves the state's approximately 340,000 electric customers is small compared to the nation and the region delivering just over 6 GWh of energy each year.

The electric power sector in the state is fragmented with 4 investor-owned utilities, 15 municipal electric departments, and 2 member-owned rural electric cooperatives. The four largest utilities—Central Vermont Public Service (IOU), Green Mountain Power (IOU), Vermont Electric Coop, and the Burlington Electric Department (municipal)—serve 87 percent of the state's electricity customers. Vermont's power supply comes primarily from Vermont Yankee, a nuclear power facility located in Vernon, VT and a purchase power contract with Hydro Quebec. The contracts for both of these power sources are set to expire within a decade, thus much uncertainty exists about Vermont's future power supply. Figure 3 presents the total GWh consumed in 2003 from each of the various sources meeting the state's electricity requirements.

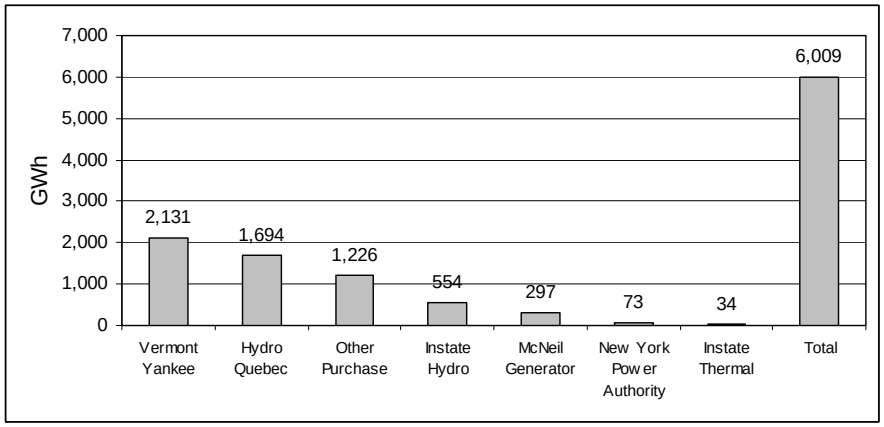

Figure 3: Vermont's 2003 Energy Supply Mix (GWh). Source: Vermont Department of Public Service

The Vermont bulk transmission system is operated by VELCO, which is a regulated utility owned and controlled in various percentages by 14 of the state's electric utilities. Central Vermont Public Service and Green Mountain Power own 86 percent of VELCO. VELCO was originally formed in 1956 to develop an integrated transmission system in the state, and today conducts a variety of planning and reliability functions, and serves as the representative of the state's electric utilities to the Independent System Operator (ISO) of New England, the organization that controls the New England grid to assure reliable and efficient operation of the regional power system. ISO New England also manages the region's wholesale power markets. Vermont is considered one of eight zones that comprise the New England grid.

Vermont was the first state to organize an efficiency utility, charged with the sole purpose of assisting Vermont energy consumers to manage and reduce their electricity consumption. Efficiency Vermont (EVT), operated by the non-profit Vermont Energy Investment Corporation, has gained national recognition for its programs and has served as a model for other states across the country. A small per kWh charge is added onto electric rates to provide a pool of funds for EVT to pursue numerous

efficiency programs to help Vermont households and businesses become more efficient in their use of electricity.

A. Assessing PHEV Load Impacts in Vermont

This study adopts a bottom-up approach to assessing the load impacts from an emerging fleet of PHEVs, similar to three of the grid impact studies reviewed earlier. A composite plug-in hybrid vehicle profile was developed based on the types of new vehicles purchased in Vermont that has an all-electric range of 20 miles—a so-called PHEV20. According to a report by RL Polk, commissioned by the University of Vermont Transportation Center, over 25 percent of new cars purchased in 2006 were smaller vehicles, over 40 percent were medium-sized, and over 30 percent were larger vehicles (Watts, Glitman and Wang, 2007). Based on a review of the literature, a PHEV20 was assumed in most studies and represents a likely architecture of first-generation PHEVs as it is expected that battery storage costs will be a key factor in designing an affordable PHEV.

Three different PHEV penetration scenarios are assessed. The low penetration scenario evaluates the grid impacts of a fleet of 50,000 PHEVs. Based on statistics from the Vermont Department of Motor vehicles, there were approximately 650,000 light vehicles registered in the state of Vermont in 2005. The low PHEV penetration scenario represents 7.6 percent of the total light vehicle fleet. The second scenario analyzed assumes a fleet of 100,000 PHEVs or approximately 15 percent of light vehicles registered in Vermont. The high penetration scenario at 200,000 vehicles, while not likely within a reasonable planning timeframe, serves to establish an upper bound impact on the Vermont grid from an emerging fleet of PHEVs. This represents just over 30 percent of the total light vehicle fleet and serves to highlight possible impacts from a smaller number of all electric vehicles or PHEVs with higher all-electric ranges than a PHEV20, both of which would create higher per vehicle consumption of electricity.

Hourly load data for the entire state of Vermont was acquired. The data represents Vermont demand at the transmission level, and thus the PHEV load must be adjusted to account for line losses through the distribution network. For this study line losses were assumed to be 6 percent. The peak summer and winter season days were identified and used to assess PHEV load impacts. In addition, average load profiles for each of the four seasons were constructed and were also used to assess PHEV load impacts for an "average" load day in each season. The seasons are defined as follows:

- Winter—December, January, and February.
- Spring—March, April, and May
- Summer—June, July, and August
- Fall—September, October, and November

This study analyzes four different charging scenarios that are a slight modification of the three charging scenarios used by Lemoine, Kammen, and Farrell (2007) in their study of the impacts of PHEVs in California's energy market. These modified scenarios are described below and represent four possible situations in terms of consumer and electric utility charging preferences here in Vermont. It is informative to understand the system-wide load impacts from these four different charging scenarios. In doing so, the study indicates how critical incentives or direct utility control may be able to promote charging that does not add to system peak demands.

> **1) Uncontrolled Evening Charging:** In this scenario it is assumed that the vehicle owner comes home from work and begins charging the vehicle. Charging start times are evenly

distributed between 6:00 pm, 7:00 pm, and 8:00 pm. Each PHEV charges for 6 continuous hours.

2) Uncontrolled Evening Charging / Twice Per Day Charging.
This scenario represents the worse case, whereby uncontrolled charging in the evening is paired with daytime charging. Each PHEV is assumed to be plugged in to charge fully at the end of each commute leg. Thus, each vehicle fully charges twice each day, once upon arriving at work in the morning and once upon arriving home in the evening. The start times for the uncontrolled evening charging are described above. The daytime charging start times are evenly distributed between 8:00 am and 9:00 am.

3) Delayed Nighttime Charging: This scenario assumes that either off-peak rates for PHEV charging or direct load control are used to delay PHEV charging times until 12:00 am. It is assumed that the entire PHEV fleet begins charging at the same time and ends at the same time, which is 6:00 am in this scenario.

4) Optimal Nighttime Charging. This represents the best case scenario from the grid operator's perspective. The vehicles are charged in a pattern that smoothes demand as much as possible by charging during periods of lowest demand, and vehicles need not charge continuously during the late evening and early morning hours. This scenario bounds the possible beneficial load-leveling effects of PHEVs.

The load impacts are displayed graphically with 24 different line charts produced using MS Excel. The line charts depict 24-hour load curves. Four charts were produced for both the peak summer and winter days based on 2005 Vermont load data. Each chart depicts the three different PHEV penetration scenarios described above. These 8 charts are presented in the results section of this report. Appendix A contains the remaining 16 line charts using the average seasonal load curves. Again, each of the four dispatch scenarios are evaluated for each of the seasonal load curves, and each chart depicts the three PHEV penetration scenarios.

Table 4: PHEV Grid Impact Study Scenarios: Results Section of Report

Figure 4	peak summer load profile; charging scenario #1, 3 PHEV penetration rates
Figure 5	peak winter load profile; charging scenario #1, 3 PHEV penetration rates
Figure 6	peak summer load profile; charging scenario #2, 3 PHEV penetration rates
Figure 7	peak winter load profile; charging scenario #2, 3 PHEV penetration rates
Figure 8	peak summer load profile; charging scenario #3, 3 PHEV penetration rates
Figure 9	peak winter load profile; charging scenario #3, 3 PHEV penetration rates
Figure 10	peak summer load profile; charging scenario #4, 3 PHEV penetration rates
Figure 11	peak winter load profile; charging scenario #4, 3 PHEV penetration rates

In all of two cases the calculations represent a marginal increase in emissions. In the near future, increases in marginal electricity use will be met with fossil fuels in the New England power pool. This

paper and analysis does not address electricity carbon caps required under the Regional Greenhouse Gas Inventory.

Table 5: PHEV Grid Impact Study Scenarios: Appendix A

Chart #1	average summer load profile; charging scenario #1, 3 PHEV penetration rates
Chart #2	average winter load profile; charging scenario #1, 3 PHEV penetration rates
Chart #3	average spring load profile; charging scenario #1, 3 PHEV penetration rates
Chart #4	average fall load profile; charging scenario #1, 3 PHEV penetration rates
Chart #5	average summer load profile; charging scenario #2, 3 PHEV penetration rates
Chart #6	average winter load profile; charging scenario #2, 3 PHEV penetration rates
Chart #7	average spring load profile; charging scenario #2, 3 PHEV penetration rates
Chart #8	average fall load profile; charging scenario #2, 3 PHEV penetration rates
Chart #9	average summer load profile; charging scenario #3, 3 PHEV penetration rates
Chart #10	average winter load profile; charging scenario #3, 3 PHEV penetration rates
Chart #11	average spring load profile; charging scenario #3, 3 PHEV penetration rates
Chart #12	average fall load profile; charging scenario #3, 3 PHEV penetration rates
Chart #13	average summer load profile; charging scenario #4, 3 PHEV penetration rates
Chart #14	average winter load profile; charging scenario #4, 3 PHEV penetration rates
Chart #15	average spring load profile; charging scenario #4, 3 PHEV penetration rates
Chart #16	average fall load profile; charging scenario #5, 3 PHEV penetration rates

B. Assessing PHEV Emissions Impacts in Vermont

One of the driving forces for the implementation of PHEVs is the potential for substantial reduction in emissions from transportation. In this report, the emissions (specifically CO_2 and NO_x) performance of a PHEV20 is compared to that of an internal combustion engine automobile with a fuel economy of 27.7 mpg (ICE27.7). For this study, a penetration level of 50K PHEV20s is used and it is assumed that the PHEV will travel in electric mode for 40% of the VMT. While in charge-sustaining mode, it is assumed that a PHEV20 will achieve a fuel economy of 40.4 mpg.

The total emissions of a PHEV are attributed to the emissions produced while in charge-depleting mode (emissions which are produced through the generation of electricity) and the emissions produced by the internal combustion engine while in charge-sustaining mode. The emissions associated with the generation of electricity were calculated as:

Power plant emissions x # vehicles x # miles/year

and the emissions associated with the operation of the internal combustion engine were calculated as:

Tail pipe emissions x # vehicles x # miles/year

Both calculations yield an emission value of pounds/year. The results shown in section IV-B indicate that a migration from 50k ICE27.7s to PHEV20s will in fact lead to a reduction in CO_2 and NO_x emissions.

C. Petroleum Displacement Potential and End-User PHEV Economics

Estimates of annual reductions in gasoline consumption were produced for each of the three PHEV penetration scenarios described above. Gasoline displacement is a function of the number of PHEVs operating in Vermont and the percentage of total drive miles from electricity. In addition, the reference vehicle for comparison purposes is also important when estimating future petroleum displacement opportunities. For this study, we assume two different reference vehicles. First, we assume that the PHEVs that enter the market are replacing conventional internal combustion engines vehicles that achieve 25 mpg. This provides an upper bound estimate of the petroleum displacement potential of PHEVs here in Vermont. Next, the study considers the petroleum displacement potential assuming that PHEVs displace comparable standard hybrid electric vehicles, without the ability to charge from the electric grid. It is assumed that these vehicles have an efficiency of 45 mpg.

Ultimately, the economics from an end-user perspective will drive the market for PHEVs in Vermont. This study performs a simplified assessment of the lifecycle fuel costs savings of a PHEV relative to conventional vehicles. For simplicity, maintenance costs are assumed to be equivalent between the comparison vehicles. Thus, the analysis focuses on the fuel costs to operate a PHEV over its life, which is then compared to fuel use of both a conventional and standard non-plug in hybrid electric vehicle. These calculations are performed for a mid-sized sedan PHEV20. The present value fuel savings of a PHEV are compared to likely cost premiums associated with PHEVs due to the larger battery pack.

In addition, electric rates for each of Vermont's major utilities are used to calculate an electricity equivalent cost of a gallon of gasoline. The equations presented in the literature review section above are adapted for this purpose. Again, these calculations are performed for a mid-sized sedan PHEV20 using two different reference vehicles, a conventional internal combustion vehicle and a non-plug in hybrid electric vehicle.

IV. Vermont PHEV Study Results

This section contains the results of the Vermont PHEV study. First, the PHEV load impact results are presented followed by the emissions impact assessment. Next, the end-user economic assessment results are presented.

A. PHEV Load Impact Results

For this study, a PHEV with a twenty mile all electric range—a so-called PHEV20—is assumed. The technical specifications for a mid-sized PHEV sedan are adopted, assuming that this vehicle configuration would equate to the average of an emerging PHEV fleet in Vermont—some may be bigger, and some may be smaller. Table 6 provides the technical parameters of the composite PHEV20 for use in this study. These specifications were adapted from the Electric Power Research Institute's (EPRI) 2001 report. The battery size was increased over the specifications in the EPRI study to provide a PHEV with a true 20 mile all electric range potential.

Table 6: PHEV 20 Technical Specifications for Vermont Study

Nominal Battery Pack Size	7.5 kWh
Usable Energy in Battery Pack	6 kWh
Round Trip Battery Efficiency	85%
Charger Efficiency	82%
Charge Rate	1.4 kW / hour
Time for Full Charge	6 hours
Purchased Electricity per Charge	8.4 kWh
Electric Efficiency	3.49 miles / kWh
All Electric Range	20 miles

As described in the previous section, three PHEV penetration scenarios are studied: low (50,000 PHEVs), medium (100,000 PHEVs), and high (200,000 PHEVs). Table 7 lists the MW demand and total energy for each scenario, including a twice per day charging scenario. This assumes that the vehicles use the full 20 mile all electric range each day, or consumes 6 kWh of energy. The twice per day charging assumes that the full 20 mile all electric range is used on each leg of the commute. Table 7 also provides comparisons of PHEV energy requirements and contribution to peak demand with the total energy consumed in Vermont in 2005 and the peak summer and winter demand. Line losses of 6 percent were added to the PHEV load to estimate the transmission-level increase in demand and energy associated with PHEV charging.

Table 7: Demand and Energy Assessment for Three PHEV Penetration Scenarios

	50,000 PHEVs	**100,000 PHEVs**	**200,000 PHEVs**
Demand	74 MW	148 MW	297 MW
% Summer Peak (1,038 MW)	7.15 %	14.30 %	28.59 %
% Winter Peak (1,054 MW)	7.01%	14.03 %	28.05 %
Daily Energy (1 charge per day)	445 MWh	890 MWh	1,781 MWh
Annual Energy (1 charge 365 days)	162,498 MWh	324,996 MWh	649,992 MWh
% 2005 MWh (6,325,960)	2.57 %	5.14 %	10.27 %
Daily Energy (2 charges per day)	890 MWh	1,781 MWh	3,562 MWh
Annual Energy (2 charges per day)	324,996 MWh	649,992 MWh	1,299,984 MWh
% 2005 MWh (6,325,960)	5.14 %	10.27 %	20.55 %

PHEV charging has the potential to cause a significant increase in peak demand for electricity in Vermont. The high PHEV penetration scenario, at 30 percent of Vermont's light vehicle fleet, represents over one-forth of the peak demand for both the summer and winter seasons. Thus, it is critical to understand when this new load would appear on the network to assess the true peak impacts of PHEV charging. This issue is analyzed below.

A dataset containing hourly loads for Vermont was obtained from the Vermont Department of Public Service. This data represents electricity demand in Vermont at the transmission level for 2005. The PHEV load simulated is increased by 6 percent to account for line losses in the distribution system. The summer and winter peak days were identified. The peak summer load of 1,038 MW occurred on August 19th at 2:00 pm. The peak winter load of 1,054 MW was reached on January 21st at 6:00 pm. The PHEV load impact assessments based on these two load curves are presented in this section of the report. The hourly load from the three different PHEV penetration scenarios were simulated and added to the actual demand in each hour to produce a modified load profile. This was performed for each of the four different charging scenarios: uncontrolled, uncontrolled twice per day, delayed nighttime charging, and optimal nighttime charging.

Average load profiles were also created for each of the four seasons: winter, spring, summer, and fall. An average for each hour was created using values for all days during the three-month period in each season. The same PHEV charging analysis conducted for the peak summer and winter days were performed for each of the seasonal load curves. Appendix A contains the results of the seasonal load analyses.

Uncontrolled Evening Charging

Figures 4 and 5 depict the load impacts from uncontrolled evening charging on the summer and winter peak day load profiles for each of the 3 PHEV penetration scenarios. Based on (Lemoine, Kammen, and Farrell, 2007) it is assumed that charging start times are evenly distributed between 6:00 pm, 7:00 pm, and 8:00 pm. It is assumed that the battery has been completely depleted from the roundtrip commute to work and thus charges for a full six hours.

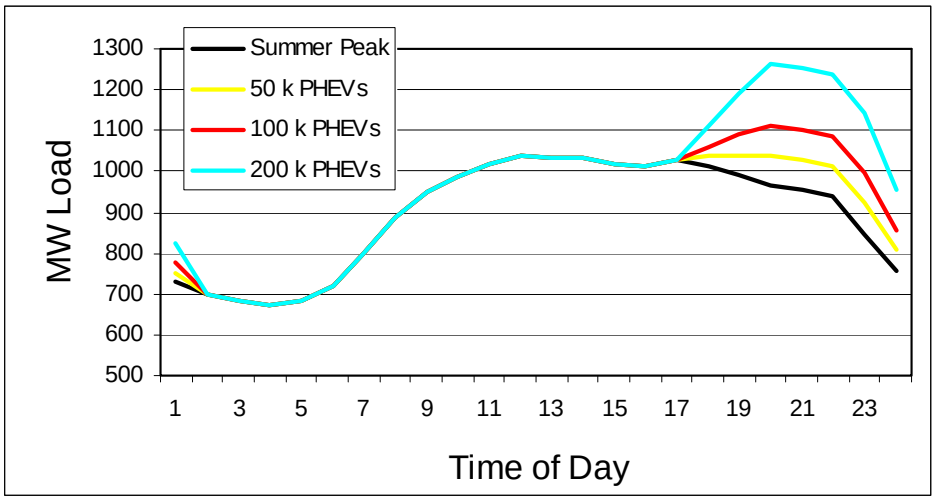

Figure 4: Summer Peak PHEV Load Impacts: Uncontrolled Evening Charging

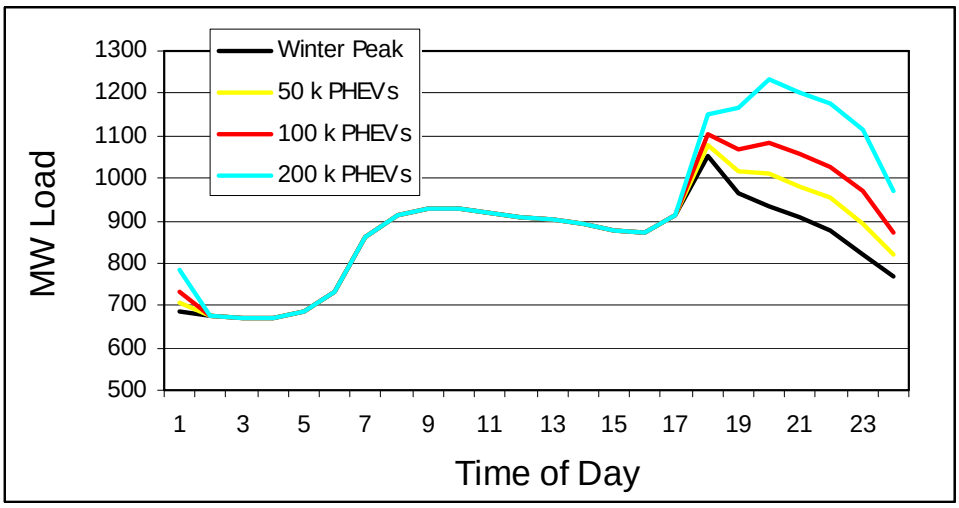

Figure 5: Winter Peak PHEV Load Impacts: Uncontrolled Evening Charging

The uncontrolled charging scenario in most cases would add to the system peak. The low penetration scenario's impact on the summer peak load is minimal; it simply extends the peak period into the evening hour, but on an absolute basis does not increase the peak demand for the day. However, both the medium and high PHEV penetration scenarios would increase the peak demand on the peak summer day. In the uncontrolled charging scenario, one-third of the PHEV fleet begins charging at 6:00 pm, exactly the time when the peak demand occurred on the peak winter day in 2005. As a result, all of the PHEV penetration scenarios analyzed here would add to the system peak. In the winter months, the early evening peak is driven by residential energy use. People come home from work turn up the heat and begin to use other electricity consuming appliances. Given that PHEVs represent a significant household load, charging when returning home from work would further reinforce the early evening peak demand for electrical energy during the cold weather months.

Uncontrolled Evening Charging / Twice Per Day

This charging scenario represents the worst case scenario. Based on Figures 4 and 5 above, it is clear that uncontrolled evening charging would lead to an increase in system peak demand, except for PHEV

penetration rates of 50,000 or less during the summer season. Here the impacts of twice per day charging are assessed. The second charge start times are evenly distributed between 8:00 am and 9:00 am. It is assumed that the battery has been completely depleted from the commute to work and thus charges for a full six hours during the day before the return trip home. This represents the worst case scenario in terms of load impacts. Figures 6 and 7 depict the load impacts from the above scenario using the summer and winter peak day load profiles respectively.

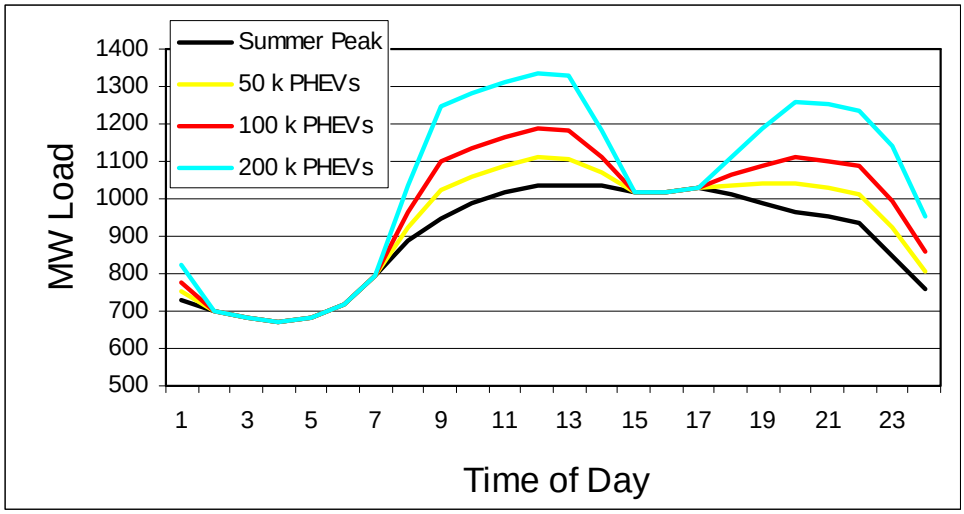

Figure 6: Summer Peak PHEV Load Impacts: Twice per Day Charging

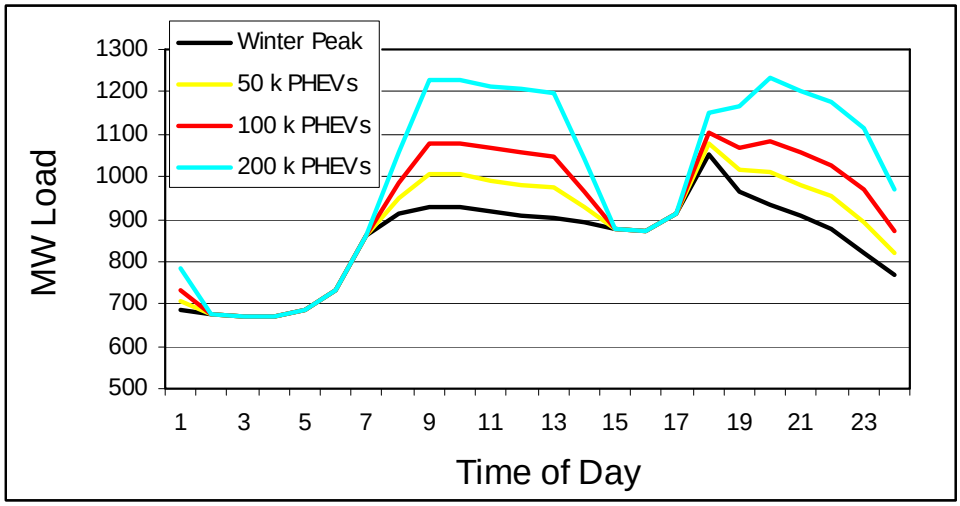

Figure 7: Winter Peak PHEV Load Impacts: Twice per Day Charging

The addition of a second charge increased demand during the daytime hours, in this case from 8:00 am through 2:00 pm. Based on the load impacts for the peak summer day, the daytime charging would increase the daily peak demand for electricity. Based on the load curve for a peak summer day in Vermont, the demand rises slowly through the afternoon and reaches a peak at around 2:00 pm. The onset of PHEV charging would create a peak earlier in the afternoon, given that the charging is completed at the end of the two o'clock hour.

Based on the load impact analysis for the peak winter day, the second charge event appears to be less problematic for the low and medium PHEV penetration scenarios. Given the sharp increase in demand in the early evening hours, the second charge event associated with the high PHEV penetration scenario is the only scenario that would lead to a new daytime peak that supersedes the early evening peak. However, as discussed above, the uncontrolled evening charging would likely create a new peak driven by PHEV charging.

Delayed Nighttime Charging

This charging scenario assumes that either through financial incentives such as off-peak rates or direct utility control that the PHEVs do not begin charging until the late evening hours. It is assumed that all vehicles begin charging at 12:00 am midnight and are fully charged by 6:00 am, ready for the morning commute. Figures 8 and 9 depict the load impacts from the three PHEV penetrations scenarios being assessed for the summer and winter peak days respectively.

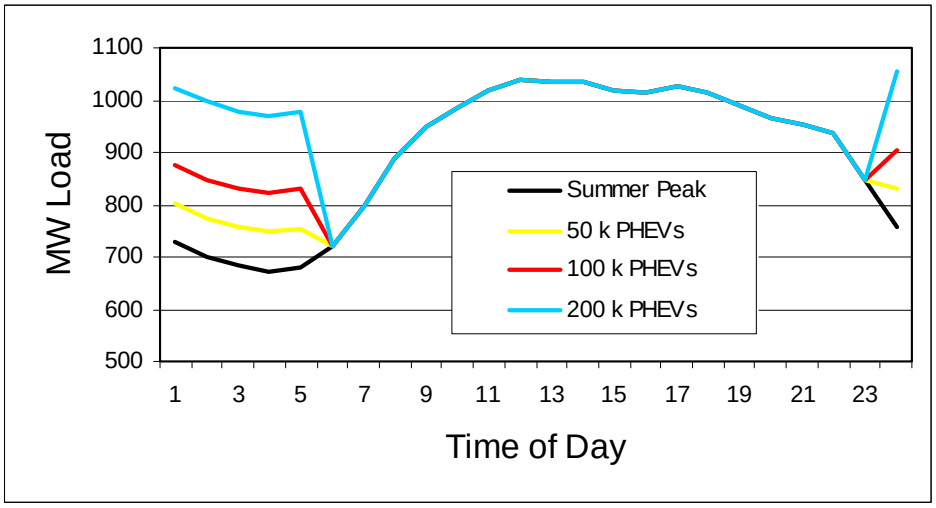

Figure 8: Summer Peak PHEV Load Impacts: Delayed Nighttime Charging

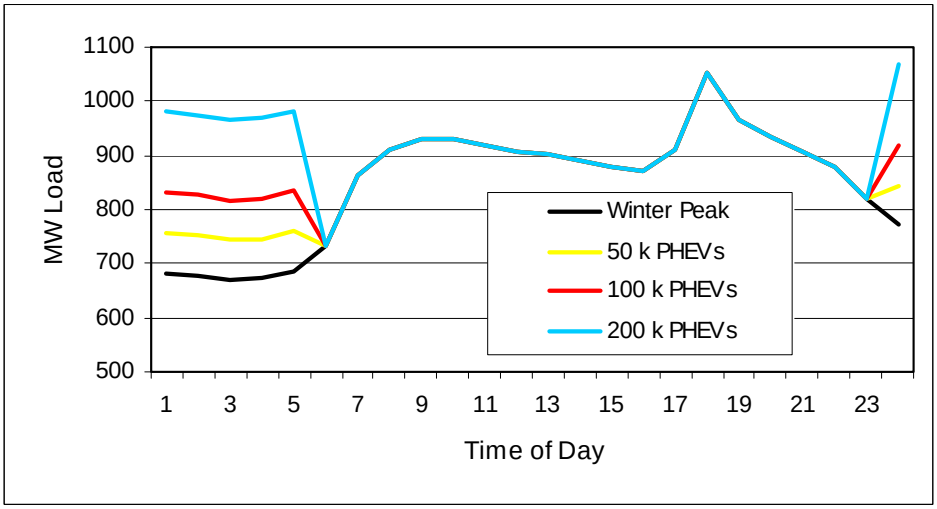

Figure 9: Winter Peak PHEV Load Impacts: Delayed Nighttime Charging

Figures 8 and 9 illustrate that a large number of PHEVs could charge from the Vermont grid without adding to system peak demand under a delayed nighttime charging scenario. In this case, all vehicles begin charging at 12:00 am midnight and conclude at 6:00 am. Penetration rates of more than 100,000 vehicles, or approximately 15 percent of the Vermont light vehicle fleet, could be accommodated without the need to build additional generation and transmission. While it is likely that the distribution system could accommodate the increase loading from PHEVs, additional issues of reliability are yet understood. The high penetration scenario studied here—200,000 PHEVs or one-third of the light vehicle fleet—would require additional power system infrastructure under the delayed nighttime charging approach.

Optimal Nighttime Charging

This scenario attempts to smooth the load of PHEVs during the off-peak period. This assumes direct utility control of charging to minimize costs and smooth the aggregate PHEV load curve. In this scenario not all PHEVs begin and end charging at the same time. In fact, it may be possible to begin charging a vehicle and then stop for some period and then resume charging. This scenario does, however, assure that each vehicle is fully charged for the morning commute. The technique used here represents a crude "eye ball" optimization approach. Figures 10 and 11 illustrate the load impacts from various PHEV penetration scenarios on the summer and winter peak load days assuming a nighttime optimal charging scenario.

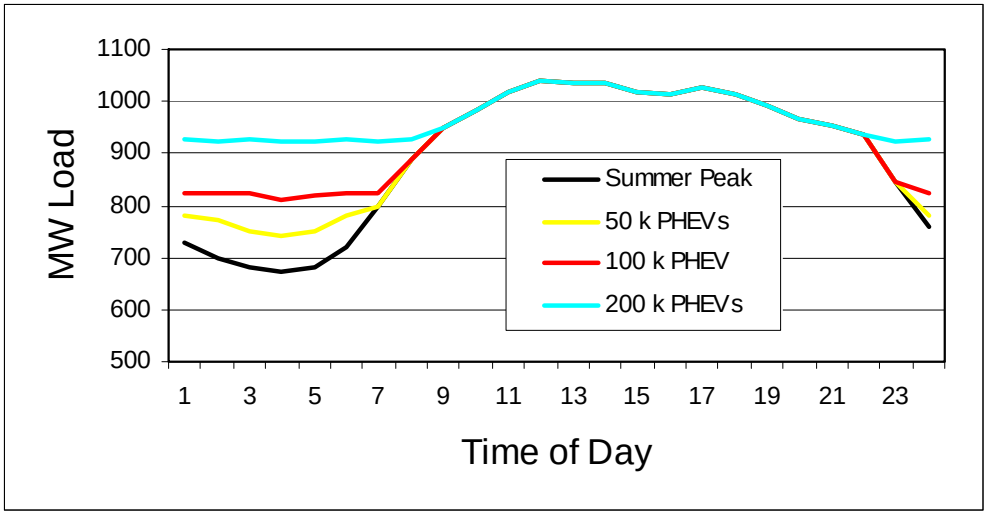

Figure 10: Summer Peak PHEV Load Impacts: Optimal Nighttime Charging

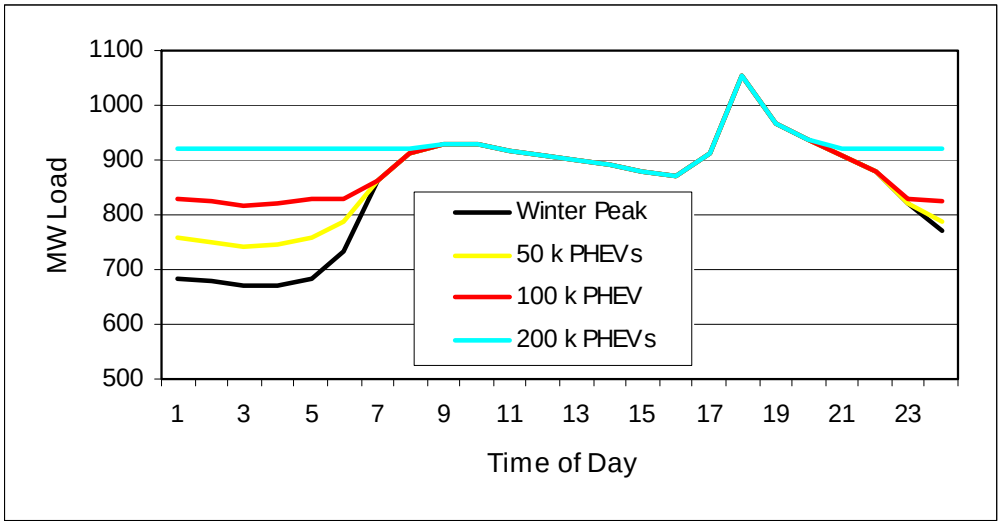

Figure 11: Winter Peak PHEV Load Impacts: Optimal Nighttime Charging

A large fleet of PHEVs could be accommodated in Vermont without the need to build additional generation, transmission, or distribution infrastructure. However, this would require either financial incentives for off-peak charging or direct utility control of PHEV charging. Simple delayed charging beginning at 12:00 am and ending with a full charge for the morning commute could accommodate over 100,000 PHEVs, or 15 percent of the Vermont light vehicle fleet, without adding to the system peak. PHEV fleets over 100,000 would require some form of direct utility control to smooth the additional PHEV load during the off-peak hours to avoid adding to the system-wide peak demand for power in Vermont. Figures 10 and 11 illustrate that an optimal charging strategy would allow 200,000 PHEVs to fully charge daily from the Vermont grid without adding to system level peak demand. Similar charts to those presented above were produced for average load curves for each of the four seasons. These can be found in Appendix A at the end of this report.

B. PHEV Net Emissions Impacts in Vermont Results

In this investigation, the emissions impact of a conventional internal combustion engine automobile (ICE) was compared to that of a plug-in hybrid vehicle (PHEV). For the purpose of this study, a penetration level of 50K vehicles is used. It is assumed that the VMT per VT capita is 12,379 miles.[3] In addition, it is assumed that the PHEV has a range of 20 miles and will be in electric-only mode for 40% of the yearly VMT (4,952 miles per VT capita). The remaining 60% of VMT (7427 miles per capita) are assumed to be in charge-sustaining HEV mode.[4] The PHEVs will be charged once daily, resulting in an energy requirement of 445 MWh.

While in electric-only mode, the "emissions" produced by a PHEV are solely those produced from the generation of the electricity used to charge the batteries. From the ISO New England 2005 New England Marginal Emissions Analysis[5], the amount of CO_2 produced per MWh was 1,107 lbs. For gas mode analysis, a PHEV20 is assumed to perform as a hybrid electric vehicle (HEV). The weighted average (based on percentage of total sales) of all hybrid electric vehicles sold in the US through October 2007 was used to calculate an average fuel economy of 40.4 mpg, see Table 8.[6-9] It should be noted that the combined mileage was calculated as 55% city, 45% highway. Ford Escape and Mercury

Mariner sales were divided evenly between 4WD and FWD versions. The internal combustion engine automobile is assumed to have an average fuel economy of 27.7 mpg.[10]

Table 8: Calculation of fuel economy for HEVs sold in the US through October 2007. Combined mileage was calculated as 55% city, 45% highway. Ford Escape and Mercury Mariner sales were divided evenly between 4WD and FWD versions.

Vehilce	2007 Sales	% of Total	City	Highway	Combined	Weighted Combined Mileage
Toyota Prius	150272	0.55	48	45	46.60	25.56
Honda Civic Hybrid	26114	0.10	40	45	42.11	4.01
Nissan Altima Hybrid	6245	0.02	35	33	34.07	0.78
Ford Escape Hybrid FWD	5722	0.02	34	30	32.08	0.67
Mazda Tribute Hybrid FWD		0.00	34	30	32.08	0.00
Mercury Mariner Hybrid FWD	434	0.00	34	30	32.08	0.05
Toyota Camry Hybrid	44390	0.16	33	34	33.44	5.42
Ford Escape Hybrid 4WD	5722	0.02	29	27	28.06	0.59
Mazda Tribute Hybrid 4WD		0.00	29	27	28.06	0.00
Mercury Mariner Hybrid 4WD	434	0.00	29	27	28.06	0.04
Toyota Highlander Hybrid 4WD	13707	0.05	27	25	26.06	1.30
Lexus RX 400h 2WD	6792.5	0.02	27	24	25.56	0.63
Lexus RX 400h 4WD	6792.5	0.02	26	24	25.06	0.62
Honda Accord Hybrid	3051	0.01	24	32	27.04	0.30
Chevy Malibu Hybrid		0.00	24	32	27.04	0.00
Saturn Vue Hybrid	3969	0.01	23	29	25.36	0.37
Lexus GS 450h		0.00	22	25	23.26	0.00
Lexus LS 600hL	371	0.00	20	22	20.85	0.03
Totals/Average	274016				29.83	40.37

Assuming 19.4 lbs of CO_2 produced per gallon of fuel consumed and the above fuel economies, the amount of CO_2 produced for the ICE27.7 and PHEV20 is 0.70 lbs/mi and 0.48 lbs/mi, respectively. The plot shown in Figure 12 indicates that a migration from 50K ICE27.7 to 50K PHEV20 vehicles will result in a 31% decrease in annual CO_2 emissions. It was found that the electric mode contributes 41% of the PHEV20 CO_2 emissions, with the remaining 59% contributed by the consumption of fuel while in hybrid mode.

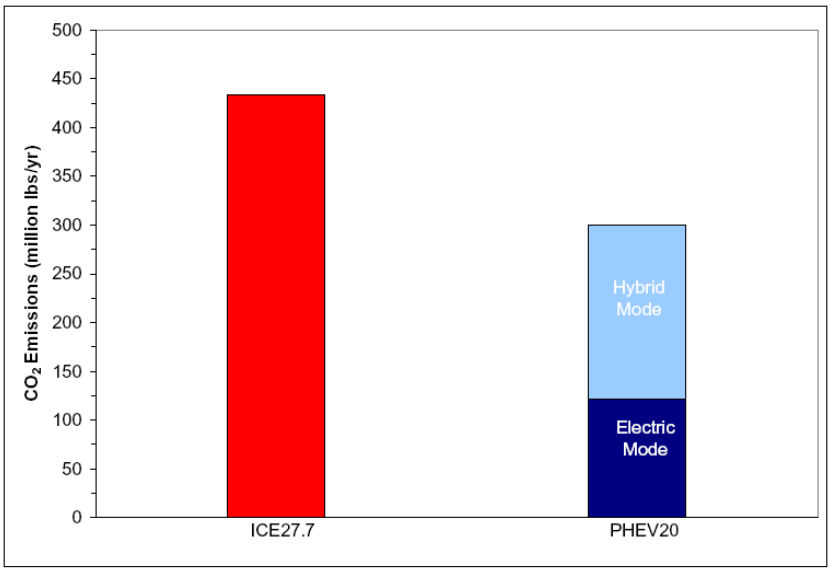

Figure 12: Annual CO_2 emissions from 50K ICE and 50K PHEV20 vehicles. It is assumed that each vehicle travels 12,379 mile annually.

In addition to CO_2, automobiles also emit nitrous oxides (NO_x), yet another "green house" gas. The ISO New England 2005 New England Marginal Emissions Analysis[5] reports that the level of NO_x emissions for electricity production was 0.54 lbs/MWh. Assuming a SULEVII standard for a PHEV20, the EPA mandated level of NO_x emissions is 0.00004 lbs/mi. For the case of an internal combustion engine automobile, the published data[10] for Ford's US fleet of cars (0.0002 lbs/mi) was used. Figure 13 indicates that a 30% decrease in NO_x emissions can be achieved through the replacement of 50K ICE27.7 vehicles with 50K PHEV20s. The electric mode contributes 78% of the PHEV20 NO_x emissions, with the remaining 22% contributed by the consumption of fuel while in hybrid mode.

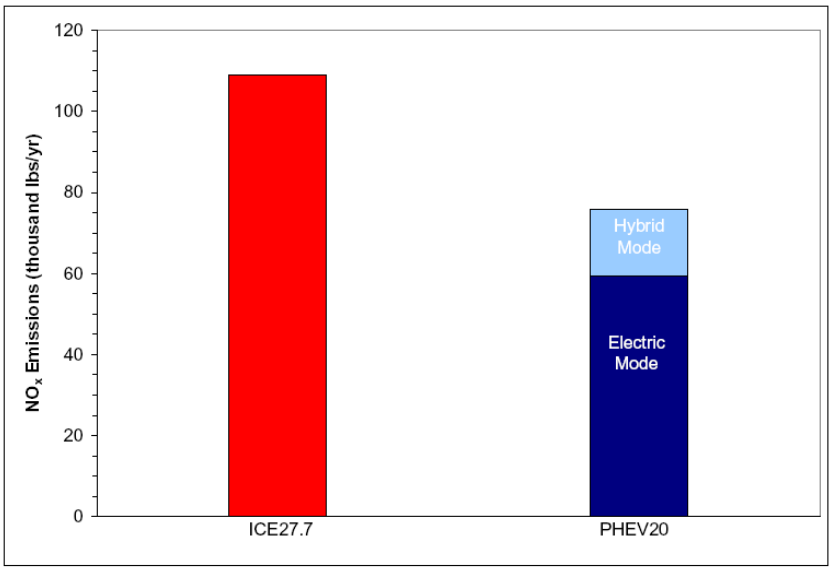

Figure 13: Annual NO_x emissions from 50K ICE and 50K PHEV20 vehicles. It is assumed that each vehicle travels 12,379 mile annually.

In addition to emissions reductions, PHEVs can also reduce the consumption of gasoline in Vermont. With the assumption that a PHEV20 will achieve a 40% increase in fuel economy as compared to a PHEV (due to 40% travel in electric mode, resulting in a fuel economy of 56.5 mpg), replacing 50K ICE27.7 vehicles with PHEV20s will reduce the amount of fuel consumed in VT from 22.34 million to 10.95 million gallons on an yearly basis, a savings of 11.39 million gallons annually!

In summary, replacing 50K ICE27.7 with PHEV20 vehicles will lead to a 31% decrease in CO_2 emissions and 30% decrease in NO_x emissions annually. With higher fuel economies, a fleet of 50K PHEV20s would save 11.39 million gallons of fuel in Vermont annually.

Future analysis will consider actual VT vehicle fleet data in order to obtain the true impact on VT emissions. This data can be compared/contrasted to the Ford data used in this study. Additionally, the actual driving behavior of individual Vermonters needs to be considered. This can include county and/or town variations in driving habits. Finally, other sources of electricity production can be studied to determine their contribution to the emissions impact of a fleet of PHEV20s.

C. PHEV Gasoline Displacement Potential and End-User Economics

One of the most important benefits associated with the use of electricity for light duty vehicles is the potential to displace a portion of the gasoline used for transportation. A PHEV provides greater fuel diversity. Furthermore, as an energy source for transportation, electricity is a less expensive and domestic alternative to gasoline. In this section of the report an analysis of the gasoline savings from the various PHEV penetration scenarios is presented along with an assessment of the end-user economics associated with PHEV ownership.

The total annual gallons of gasoline displaced from PHEVs are a function of the penetration rate, the percentage of total annual miles from electricity, and the fuel economy of the reference vehicle. The gasoline displacement potential was calculated for each of the three penetration scenarios described above.

Based on data from the US Department of Transportations Bureau of Transportation Statistics, the per capita vehicle miles traveled in Vermont in 2005 were 12,379, which is used as key input to calculate the gasoline displacement potential of an emerging fleet of PHEVs in Vermont. Based on the Electric Power Research Institute's 2001 report, using a mileage weighted probability (MWP) method, they predict that approximately 40 percent of total annual drive miles will be derived from electricity for a PHEV20. The MWP is a statistical probability that a vehicle is driven less than or equal to its all-electric range during a day.

The annual gasoline per PHEV can be calculated using the following equation:

Gallons of Gasoline = [Annual Miles Driven – (WMP * Annual Miles)] / Fuel Economy in HEV Mode (mpg)

Again, using the EPRI (2001) study, we assume that a mid-sized PHEV20 sedan would achieve 43.5 miles per gallon (mpg). Thus a single PHEV in Vermont would consume 171 gallons of fuel annually to travel 12,379 miles.

Two reference vehicles are used to calculate the annual gasoline displacement potential from a PHEV20. The first is a standard gasoline vehicle with an internal combustion engine (ICE) with a fuel economy rating of 28.9 mpg. In addition, we consider the fuel savings potential from a non-plug in hybrid electric vehicle (HEV) with a fuel economy rating of 41.9 mpg. The fuel economy rating for these two vehicles was obtained from the EPRI (2001) study. Figure 14 presents the annual gasoline consumption for each of the three vehicles: PHEV, ICE, and HEV. In addition, Table 9 presents the fuel displacement potential from PHEVs given these reference vehicles and the three penetration scenarios used for this study, along with the percent of fuel reductions based on total gasoline sales in Vermont in 2006.

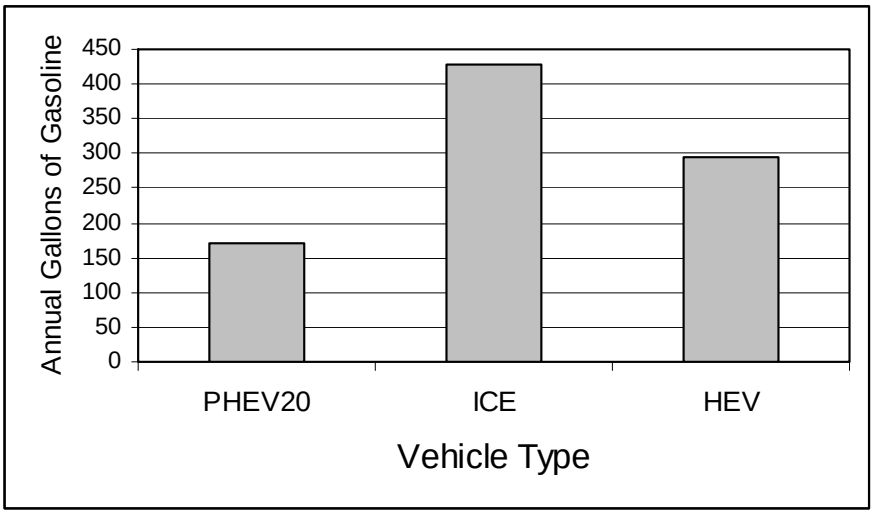

Figure 14: Annual Gasoline Consumption vs. Vehicle Type

Table 9: PHEV Gasoline Displacement Potential: PHEV vs. ICE & HEV

PHEV Penetration	PHEV vs. ICE (annual gallons)	% 2006 VT Gasoline Use	PHEV vs. HEV (annual gallons)	% 2006 VT Gasoline Use
50 k	12.9 million	3.74 %	6.2 million	1.81 %
100 k	25.8 million	7.49 %	12.5 million	3.62 %
200 k	51.5 million	14.98 %	24.9 million	7.25 %

PHEVs offer an avenue to displace gasoline in the transport sector. An important factor that would dictate the true displacement potential is what consumers would choose in the absence of a PHEV option. It seems reasonable to assume that a large number of consumers that are currently purchasing an HEV would possibly opt for the PHEV alternative. In this case, it would be prudent to consider the displacement potential using an HEV as the comparison vehicle. In the most aggressive scenario (200 k), PHEVs would displace 24.9 million gallons of fuel annually. This represents 7.25 percent of the total gasoline purchased in Vermont in 2006 at a market value of about $75 million dollars assuming $3.00 per gallon. Policy incentives and higher fuel costs might entice a larger number of the car-buying public to consider a PHEV purchase. Thus, the annual fuel displacement potential and the dollar savings could be much greater if more consumers were convinced to select a PHEV over both ICE and HEV options.

The underlying end-use economics dictates the macro benefits of PHEV technology. Given that PHEVs can charge from the grid, consumers would have the option to purchase electricity or gasoline to meet their transportation needs. Given the inherent limits of likely PHEV technology, the economic trade off between electricity and gasoline are bound by the size of the battery pack. However, being able to compare the fuel costs on an equal basis is informative.

Much of the excitement surrounding PHEV technology revolves around the fact that electricity as a fuel source costs less than gasoline purchased at the pump. It has been reported that the cost of electricity that delivers the same miles of travel as a gallon of gasoline can be as low as $0.75 (www.pluginpartners.org). Several key assumptions underlie this calculation. The first is the number of kWhs that must be purchased to deliver the same miles of travel as a gallon of gasoline, which is related to the efficiency of the PHEV, and the reference vehicle. For example, the PHEV20 used to assess the grid impacts in Vermont used above delivers 2.38 miles of travel for every kWh purchased

from the grid. If we assume a comparison vehicle that obtains 25 miles per gallon, a PHEV owner would require 10.5 kWh to travel the same distance (25 miles) as one gallon of gasoline. If we assume that electricity costs $0.10/kWh the electricity equivalent cost of a gallon of gasoline would be just $1.05, clearly less than the current price for a gallon of gasoline. The comparison vehicle is central to this calculation. For example, if we assume an HEV at 45 mpg as the reference vehicle the electricity equivalent cost of electricity would be $1.89. Table 10 contains similar calculations assuming two different comparison vehicles and different rates charged by Vermont's leading electric utilities. Based on the data in Table 10, electricity provided by each of Vermont's leading electric utilities is a less expensive fuel for transportation as compared to gasoline.

Table 10: Electricity Equivalent Cost per Gallon of Gasoline

	Comparison Vehicle	
Utility / Rate	**45 mpg**	**25 mpg**
Central Vermont / Rate 1 ($0.12/kWh)	$2.27	$1.26
Central Vermont / Rate 9 ($0.07/kWh)	$1.32	$0.74
Green Mtn. Power / Rate 01 ($0.13/kWh)	$2.46	$1.37
Green Mtn. Power / Rate 11 ($0.09/kWh)	$1.70	$0.95
Burlington Electric Dept. / Rate RS ($0.13)	$2.46	$1.37
Burlington Electric Dept. / Rate RT ($0.09)	$1.70	$0.95

A second way to compare the cost of electricity and gasoline as a fuel for vehicles is to calculate the cost per mile of travel for different fuels. In this case we simply divide the cost per kWh by the efficiency of the PHEV while operating in all electric mode. Similarly, we take the cost of a gallon of gasoline and divide by the fuel economy to get a cost per mile of travel. Figure 15 provides several comparisons assuming two different electric rates, two comparison vehicles, and two different fuel costs. Again, figure 15 illustrates that electricity is less expensive on a per mile basis than gasoline as an energy source for light vehicles.

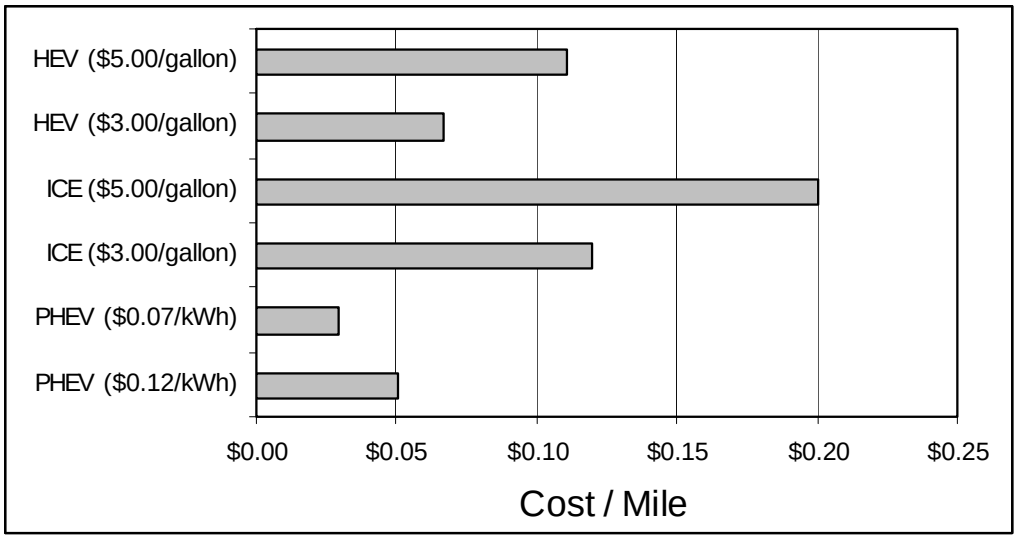

Figure 15: Comparison of Costs per Mile: PHEV, HEV, & ICE
(HEV) hybrid electric vehicle, 45 mpg
(ICE) internal combustion engine vehicle 25 mpg
(PHEV) plug-in hybrid vehicle 2.38 miles/kWh

While recognizing that electricity is a less expensive energy source for vehicles when compared to gasoline, this is just one part of understanding the end-user economics of PHEVs. For those vehicle models, such as the Toyota Camry, that come in both a conventional internal combustion engine (ICE) and hybrid option, there is a significant premium for the hybrid version. For example, the Camry hybrid has a $4,000 premium over a similar conventional model. The larger battery and more sophisticated controls result in a higher cost for the HEV model. When PHEVs become an option for consumers, it is reasonable to expect a significant price premium over comparable ICE versions, given the much larger battery pack.

While it is impossible to know just exactly what the price premium will be for a PHEV, it is useful to consider the lifecycle fuel savings to discuss what allowable premiums would have to be in order for PHEVs to be an economic choice for consumers. Figure 16 presents the present value fuel savings over 7 years for a PHEV20 over a conventional hybrid and a conventional gasoline vehicle. Again, two different gasoline prices were assumed: $3.00 and $5.00 per gallon. An electricity charging rate of $0.09 was assumed along with a 7 percent discount rate.

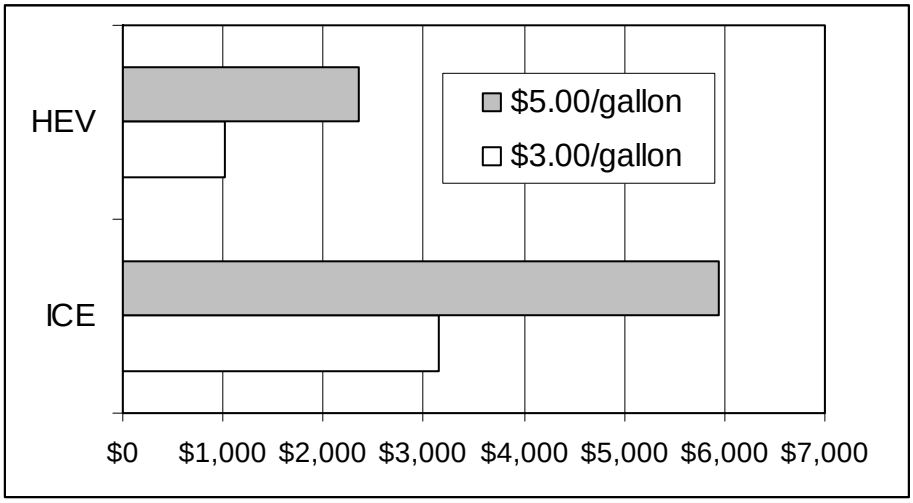

Figure 16: Lifecycle Fuel Costs Savings: Seven Year, Present Value

Based on Figure 16, comparing the present value fuel savings over 7 years of a PHEV relative to an HEV with fuel prices at $3.00 per gallon would yield a $1,000 savings. In contrast, when comparing a PHEV to a ICE the lifecycle fuel savings would be close to $6,000 assuming gasoline prices at $5.00 per gallon. These two scenarios represent the likely range of lifecycle fuel savings that would be realized by consumers selecting a PHEV option.

While it is impossible to know with certainty what the cost premiums will be for a PHEV over an HEV or a standard gasoline vehicle, two estimates place the cost premium of PHEVs in the range of $2,500 to $5,000 (EPRI, 2002 and Pesaran and Markel, 2007). Based on these estimates, the lifecycle fuel savings of a PHEV relative to an HEV would be insufficient to cover the expected price premium. However, the lifecycle fuel savings when comparing a PHEV to an ICE vehicle may very well cover the higher initial upfront cost of a PHEV. Further market analysis is needed to understand consumer decision making and the role that government incentives could play in promoting PHEV technology.

V. Conclusion

Reducing GHG emissions will take comprehensive strategies that address all sectors of the economy. Because transportation is close to one-third of the nation's GHG footprint and 44 percent of Vermont's, strategies targeted to reduce transportation-related GHG emissions are essential.

One strategy detailed in this report is to switch from gasoline to electricity to fuel some portion of the miles driven by light duty vehicles in Vermont. Because of Vermont's low carbon electricity supply, shifting some portion of energy used for transportation from gasoline to electricity will result in a reduction in greenhouse gas emissions. Furthermore, because of the present relative prices of gasoline and electricity, vehicles in Vermont traveling on electricity will cost consumers less.

The research summarized in this report found that changing the fuel in Vermont vehicles can address both emissions and economic issues. Switching 50,000 existing vehicles from gasoline to plug-in hybrid electric vehicles would reduce CO_2 emissions by 31 percent and NO_x by 30 percent.

Switching from gasoline to plug-in hybrid electric vehicles can also save Vermonters money. Because of increases in gasoline prices, drivers in Vermont spent $500 million more in 2007 than in 2002 to drive about the same amount of miles. Electricity costs for transportation are about one-third the cost of driving a gasoline vehicle.

This study has found that the existing electric grid could charge 100,000 PHEVs under a delayed nighttime charging scenario without adding to system peaks or adding additional generation and transmission. Because there is less electricity used during the overnight hours, charging vehicles at night could also increase the overall efficiency of the electric system. Furthermore, preferential rates provided by electric utilities as incentives for off-peak charging could further reduce the costs to consumers.

Further research is needed to more fully understand the actual driving patterns and performance of PHEVs in Vermont and compare them to suitable reference vehicles. This study has examined these issues at a macro level. In addition, further market analysis is needed to understand consumer decision making and the role that government incentives could play in promoting PHEV technology.

The University Transportation Center at the University of Vermont has several research projects underway and proposed to continue to explore these issues in more detail.