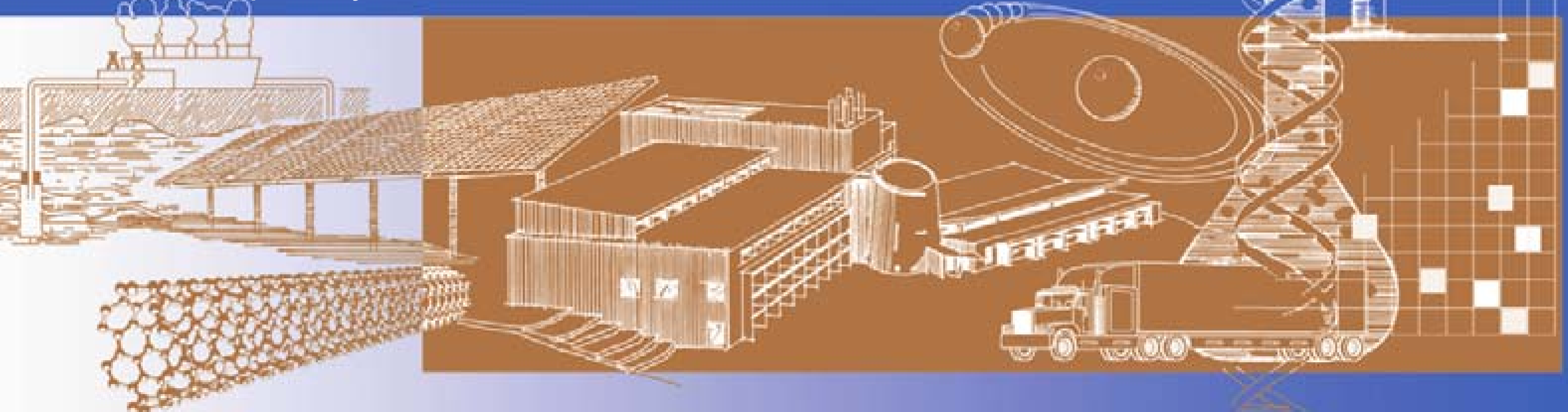
National Renewable Energy Laboratory
Innovation for Our Energy Future
A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

Costs and Emissions Associated with Plug-In Hybrid Electric Vehicle Charging in the Xcel Energy Colorado Service Territory

Technical Report
NREL/TP-640-41410
May 2007

K. Parks, P. Denholm, and T. Markel

NREL is operated by Midwest Research Institute • Battelle   Contract No. DE-AC36-99-GO10337



Costs and Emissions Associated with Plug-In Hybrid Electric Vehicle Charging in the Xcel Energy Colorado Service Territory

Technical Report
NREL/TP-640-41410
May 2007

K. Parks, P. Denholm, and T. Markel

Prepared under Task No. WR61.2001

National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
303-275-3000 • www.nrel.gov

Operated for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
by Midwest Research Institute • Battelle

Contract No. DE-AC36-99-GO10337

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

Table of Contents

1. Introduction

The combination of high oil costs, concerns about oil security and availability, and air quality issues related to vehicle emissions are driving interest in "plug-in" hybrid electric vehicles (PHEVs). PHEVs are similar to conventional hybrid electric vehicles, but feature a larger battery and plug-in charger that allows electricity from the grid to replace a portion of the petroleum-fueled drive energy. PHEVs may derive a substantial fraction of their miles from grid-derived electricity, but without the range restrictions of pure battery electric vehicles.

As of early 2007, production of PHEVs is essentially limited to demonstration vehicles and prototypes. However, the technology has received considerable attention from the media, national security interests, environmental organizations, and the electric power industry.[1,2] In 2006, the Bush administration announced the U.S. Advanced Energy Initiative, which includes the goal of developing a PHEV capable of traveling up to 40 miles on a single electric charge.[3] For many U.S. drivers, a PHEV-40 could reduce average gasoline consumption by 50% or more.[4]

The economic incentive for drivers to use electricity as fuel is the comparatively low cost of fuel. The electric equivalent of the "drive energy" in a gallon of gasoline delivering 25-30 miles in a typical midsized car is about 9-10 kWh, assuming a vehicle efficiency of 2.9 mile/kWh.[5] The cost of this electricity using the U.S. average residential rate for 2005 (9.4 cents/kWh)[6] is under $1, and could be even less when using off-peak power at preferential rates. This cost is directly comparable to the end-user cost of gasoline, which nationally averaged $2.60 for regular-unleaded in the 12-month period ending August 2006.[7] Given these potential cost advantages, a study by the Electric Power Research Institute (EPRI) found a significant potential market for PHEVs, depending on vehicle cost and the future cost of petroleum.[8] Furthermore, several researchers have noted that by adding "vehicle-to-grid" (V2G) capability, where the vehicle can discharge as well as charge, PHEV owners may also receive substantial revenue by using the stored energy in

---

[1] "Plugging into the Future," *The Economist*, June 8, 2006. Via http://www.economist.com/displaystory.cfm?story_id=7001862
[2] Plug-In Partners, via http://www.pluginpartners.com/
[3] National Economic Council (2006) "Advanced Energy Initiative." Via http://www.whitehouse.gov/stateoftheunion/2006/energy/
[4] Electric Power Research Institute (2001). "Comparing the Benefits and Impact of Hybrid Electric Vehicle Options," EPRI, Palo Alto, Calif., 10003496892.
[5] Electric Power Research Institute (2001).
[6] U.S. Department of Energy (2006). *Annual Energy Outlook September 2006 With Data for June 2006*, DOE/EIA-26(2006/09), Energy Information Administration, Washington, D.C. Via http://www.eia.doe.gov/cneaf/electricity/epm/epm_sum.html
[7] Energy Information Agency "Retail Gasoline Historical Prices" http://www.eia.doe.gov/oil_gas/petroleum/data_publications/wrgp/mogas_history.html
[8] Electric Power Research Institute, 2002. "Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sport Utility Vehicles," EPRI, Palo Alto, Calif., 1006891

their vehicles to provide high-value electric system services such as regulation, spinning reserve, and peaking capacity.[9,10]

The use of PHEVs would represent a significant potential shift in the use of electricity and the operation of electric power systems. Electrification of the transportation sector could increase generation capacity and transmission and distribution (T&D) requirements, especially if vehicles are charged during periods of high demand. Other concerns include emissions impacts including regulated emissions (NO_X and SO_2) and currently unregulated greenhouse gas emissions. Utilities are interested in the net costs associated with this potential new load, including possible benefits of improved system utilization enabled by controlled PHEV charging.

This study is designed to evaluate several of these PHEV-charging impacts on utility system operations within the Xcel Energy Colorado service territory. We performed a series of simulations in which the expected electricity demand of a fleet of PHEVs was added to projected utility loads under a variety of charging scenarios. The simulations provide some basic insight into the potential grid impacts of PHEVs, focusing on the following issues:

- How do various PHEV-charging scenarios affect the total system load?
- What are the emissions associated with PHEV charging, and what are the combined emissions from both generator and vehicle? How do these emissions compare to a conventional vehicle?
- What are the marginal costs associated with PHEV charging?
- What are the quantifiable system benefits associated with controlled PHEV charging?

2. Study Methods and Assumptions

2.1 Utility System

The study area for this analysis is the Xcel Energy Colorado service territory. This utility serves about 55% of the state's population including Denver and most of the surrounding suburbs.

This analysis used data from a variety of public sources, along with proprietary system data from Xcel Energy Colorado (we considered generation capacity available in 2007). While it will likely be some time until PHEVs are deployed on a large scale, using current data allows for a "baseline" analysis with a high level of certainty, as opposed to a "future" analysis where the generation mix is less certain.

---

[9] Kempton, W. and S. E. Letendre (1997). "Electric Vehicles as a New Power Source for Electric Utilities." *Transportation Research D* 3: 157-175.
[10] Kempton, W. and J. Tomic (2005). "Vehicle-to-grid power fundamentals: Calculating capacity and net revenue." *Journal of Power Sources* 144(1): 268-279.

Table 1 provides a summary of the Xcel Energy service territory compared to the entire state.

Table 1: Characteristics of the Xcel Energy Service Territory

	Xcel Energy	Colorado
Electricity Customers (2005)[11]	1,296,200	2,349,921
Estimated Population (2000)[12]	2,347,000	4,301,000
Annual Electricity Demand (GWh – year)[13]	26,481	48,353
Estimated Number of Vehicles (2000)[12]	1,730,000	3,135,000

Figure 1 illustrates the Xcel Energy service territory within Colorado, as well as the major power plants in Colorado operated by Xcel Energy.

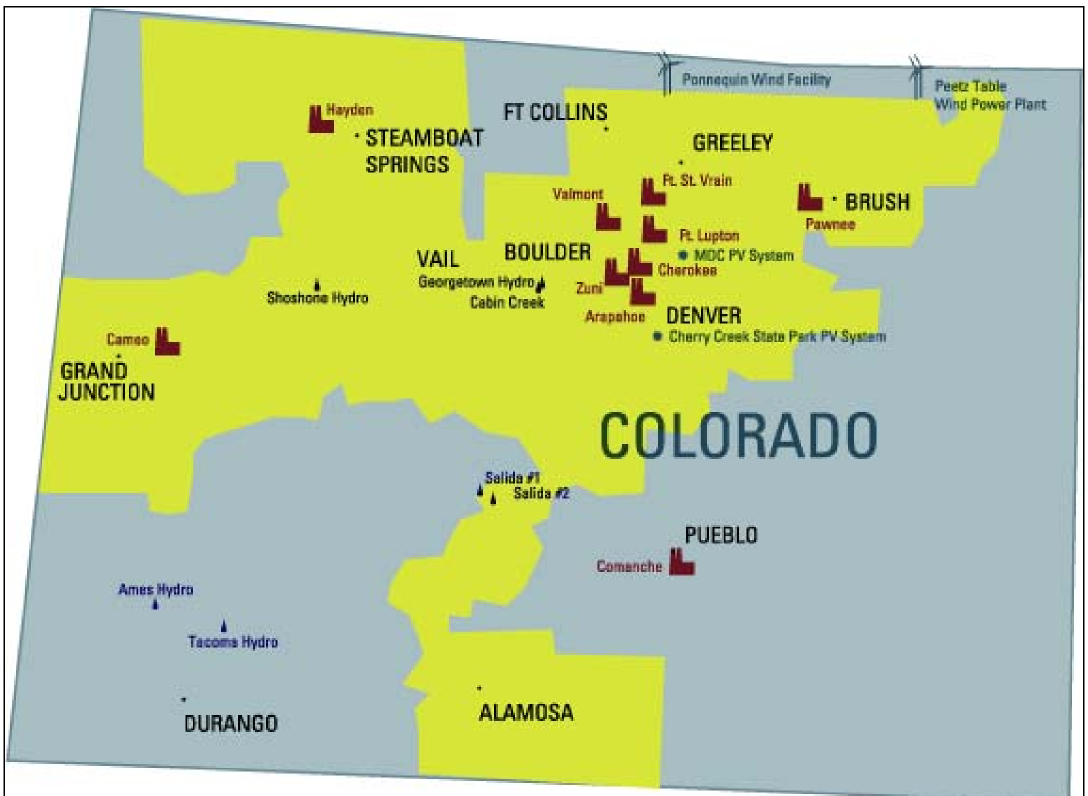


Figure 1: Xcel Energy Colorado Service Territory and Major Generation Facilities[14]

---

[11] Energy Information Agency (2005), "Form EIA-861 Database" Via http://www.eia.doe.gov/cneaf/electricity/page/eia861.html

[12] U.S. Census Bureau. "Annual Estimates of the Population for the United States, Regions, States, and for Puerto Rico: April 1, 2000, to July 1, 2006" (NST-EST2006-01)

[13] Energy Information Agency (2005), "Form EIA-861 Database"

[14] Xcel Energy "Power Generating Facilities – Colorado." Via http://www.xcelenergy.com/XLWEB/CDA/0,3080,1-1-1_1875_4797_4010-3475-2_261_448-0,00.html

Xcel Energy's electricity supply is dominated by fossil fuels, with small amounts of hydro and some wind. **Figures 2 and 3** provide estimates of the current capacity mix and average energy supply for the entire state.

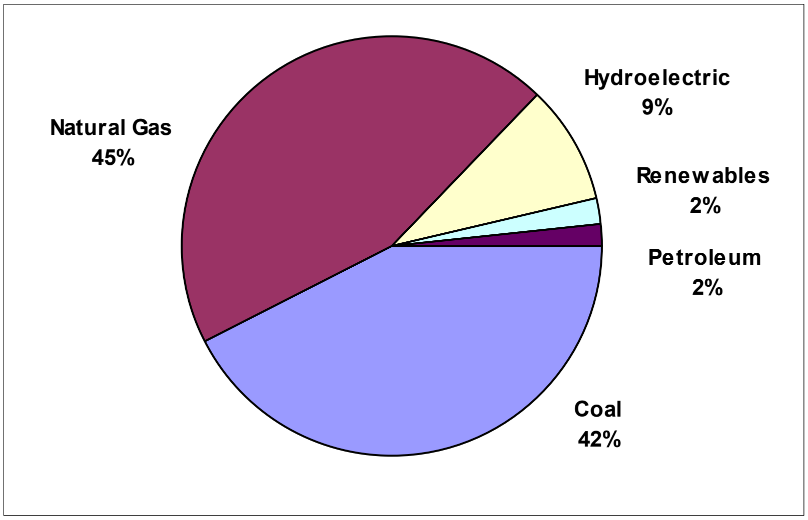


Figure 2: Distribution of Electric Generation Capacity within Colorado in 2005[15]

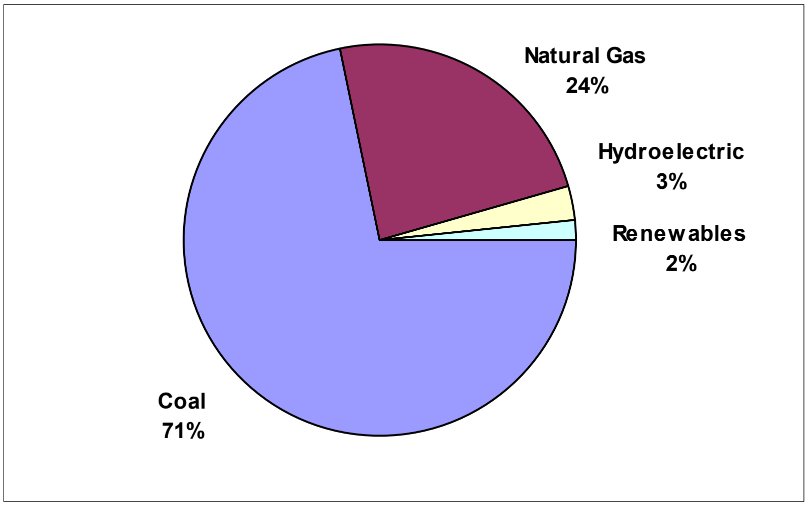


Figure 3: Distribution of Electric Generation Energy, by Source, within Colorado in 2005[16]

---

[15] U.S. Department of Energy (2005). Electric Power Annual 2006, DOE/EIA-0348(2005), Energy Information Administration, Washington, D.C. Via http://www.eia.doe.gov/cneaf/electricity/epa/epat2p2.html

[16] U.S. Department of Energy (2005). Electric Power Annual 2006, DOE/EIA-0348(2005), Energy Information Administration, Washington, D.C. Via http://www.eia.doe.gov/cneaf/electricity/epa/epat1p1.html

2.2 Modeling

To simulate charging of PHEVs in the Xcel Energy service territory, we used a model that simulates the dispatch and operation of an electric power system on an hourly basis for an entire year. This type of tool is commonly referred to as a "production cost," "unit commitment and dispatch," or "chronological dispatch" model.[17]

Production cost models use a forecast of hourly system loads, and optimally dispatch all generators available based on each generator's variable cost. When calculating variable cost, the model considers fuel, O&M, and startup costs. The model also considers constraints of emissions permits, individual power plant performance limits including ramping rates and minimum loading, and transmission system limits.

The particular tool used (PROSYM) was provided by Global Energy Decisions[18] and is one of about four tools used by the nation's utilities to simulate their systems. PROSYM includes an extensive database of most power plants in the United States, along with a reduced-form approximation of the transmission system.

A base case model "run" involves dispatching the utilities' power plant fleet to a forecast load, including projected wholesale purchases and sales. Once a base case is established, the modeled electric power system may then be redispatched to any number of scenarios desired. In this study, the additional load from PHEVs was added to the base load, and then the incremental generation associated with PHEV charging was identified, along with its associated cost and emissions.

While PROSYM can produce a large number of outputs, we focused on the following parameters for this study:

- Net System Load
- Generation Mix
- Fuel Cost
- Variable O&M Cost
- Additional Generator Startups and Startup Costs
- CO_2 Emissions
- SO_2 Emissions
- NO_X Emissions

[17] J.H. Eto. 1990. "An Overview of Analysis Tools For Integrated Resource Planning" *Energy* 15 (11) 969-977.
[18] Global Energy Decisions. Via http://www.globalenergy.com/products-enerprise-overview.asp

2.3 Vehicle Assumptions

There is considerable uncertainty regarding the most economical size and configuration of marketable PHEVs.[19] A PHEV represents a tradeoff between various components including the battery size (both energy and power), electric motor size, and internal combustion (IC) engine size. The vehicle's electric range[20] is variable (PHEV-20, PHEV-40, etc.) and so is the instantaneous fraction of drive energy derived from the battery. While the PHEV-20 nomenclature implies that the vehicle drives for the first 20 miles on electricity and then switches to gasoline, this clean switch from one mode of operation to the other is only one of several possible operating strategies. Another is "blended" operation where the electric motor supplies low-speed operation, supplemented by the combustion engine at high speed. With this mode of operation, the maximum power draw on the batteries and electric drivetrain is reduced, which reduces the cost of the hybrid vehicle system. The fraction of miles displaced by electricity for a specific PHEV size is also uncertain, given the significant variation in driving habits and PHEV operational modes. **Figure 4** provides one estimate of the potential miles displaced by electricity for a variety of PHEV ranges, assuming a single charge per day.[21]

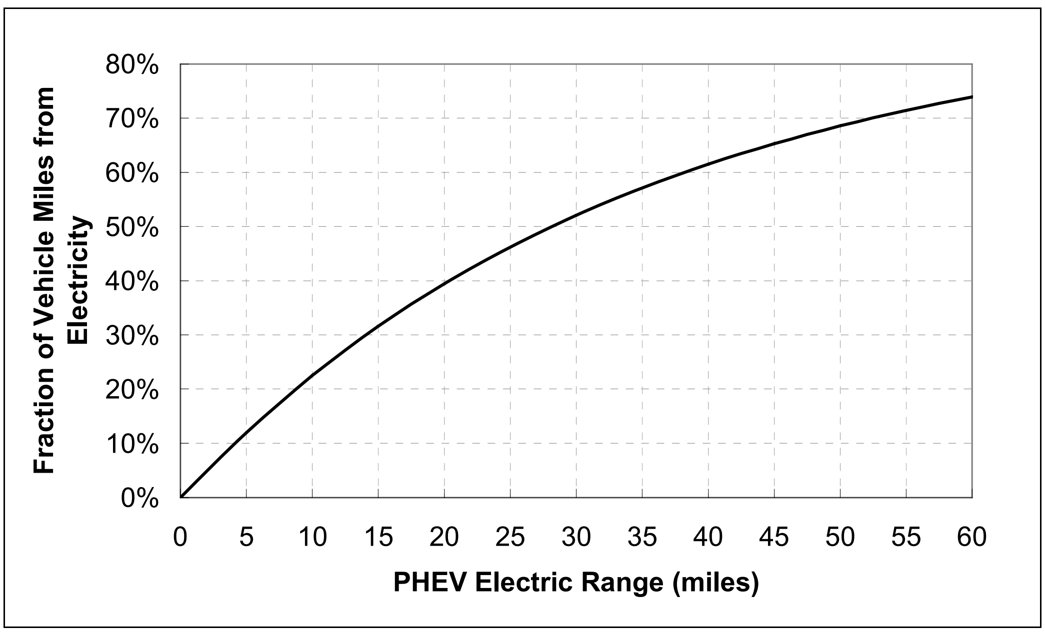


Figure 4: Fraction of PHEV Miles Derived from Electricity

We chose a midsize PHEV-20 for our base case vehicle. The vehicle design characteristics and performance were generated using the ADvanced VehIcle SimulatOR

[19] Markel, T.; O'Keefe, M.; Simpson, A.; Gonder, J.; Brooker A. (2005) "Plug-in HEVs: A Near-term Option to Reduce Petroleum Consumption FY05 Milestone Report," National Renewable Energy Laboratory, Golden, Colorado, August 2005.

[20] The PHEV electric performance is designated by the nomenclature of "PHEV-XX", with the XX representing the vehicles battery storage capacity in miles, such as PHEV-20.

[21] Electric Power Research Institute (2001).

(ADVISOR) tool,[22] and are very close to those described in detail in a previous analysis.[23] The actual performance of the vehicle fleet for this study is based on actual driving-pattern data from 227 vehicles tracked with a global positioning system (GPS) in St. Louis in 2002.[24] The GPS data and vehicle simulations provide an estimate of total fleet miles traveled, electricity requirements, and gasoline consumption. An overall penetration of 500,000 vehicles was assumed, equal to roughly 30% of light-duty vehicles in the Xcel Energy service territory. **Table 2** summarizes the fleet-average vehicle assumptions used in this study.

Table 2: Assumed Vehicle Parameters

Vehicle Size	Conventional Vehicle (CV)	Hybrid Electric Vehicle (HEV)	Plug-In Hybrid (PHEV-20)[25]
Miles per Year	13,900	13,900	13,900
Gasoline Mode Efficiency	26 mpg	36 mpg	37 mpg
Electric Mode Consumption Rate	NA	NA	0.36 kWh/ mile
Battery Size (Usable Capacity)	0	2 kWh (charged from IC engine)	7.2 kWh

2.4 Vehicle Charging

We developed four vehicle-charging scenarios for evaluation. The four scenarios chosen are not necessarily the most likely, but instead represent boundary cases and perhaps some probable charging scenarios. In each of the four scenarios, we developed an aggregated hourly charging profile for a fleet of vehicles. This hourly load was then added to the base case load to evaluate the incremental system impacts. The four scenarios, described in additional detail as follows, are summarized in **Table 3**.

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. The PHEV begins charging as soon as it is plugged in, and stops when the battery is fully charged. This can be considered a reference or “do nothing” case, because it assumes a business-as-usual infrastructure requirement (no charging stations at work or other public locations). In addition, it requires no intelligent control of how or when charging occurs, or incentives (such as time-of-use rates) to influence individual consumer behavior. The case might

[22] T. Markel, A. Brooker, T. Hendricks, V. Johnson, K. Kelly, B. Kramer, M. O'Keefe, S. Sprik and K. Wipke, “ADVISOR: a systems analysis tool for advanced vehicle modeling,” *Journal of Power Sources*, Volume 110, Issue 2, August 22, 2002, Pages 255-266.
[23] Electric Power Research Institute (2001).
[24] Jeffrey Gonder, Tony Markel, Andrew Simpson, Matthew Thornton. “Using GPS Travel Data to Assess the Real World Driving Energy Use of Plug-in Hybrid Electric Vehicles (PHEVs).” (In Progress)
[25] For a PHEV, the “Electric Mode” describes operation when the vehicle is using stored electricity as its “primary” driving energy source. “Gasoline Mode” is operation after the battery has been depleted to the point where the vehicle is operating essentially as a conventional hybrid. The actual performance depends largely on the driving profile and the amount of “blended mode” operation.

also be considered a boundary (worst-case) scenario, given the high coincidence of normal electric system loads and likely consumer vehicle-charging patterns.

For this case, we assumed a constant charging rate of 1.4 kW, which is conservatively based on a common household 110/120 volt, 20A circuit, with a continuous rating of about 1.8-2.0 kW. Despite this low charging rate, the charge time for a completely discharged battery is still less than six hours.

Figure 5 illustrates the daily charging profile, which ramps up rapidly from 4-6 p.m. at the end of the normal workday. The actual time that vehicles arrive home is based on the St. Louis vehicle data set, and we assume that driving patterns are not significantly different in the study region. Data for this study was available only for a weekday, so this study assumes weekend travel patterns are identical to weekday patterns. In this scenario, most charging occurs in the mid- to late evening, with little charging occurring after midnight.

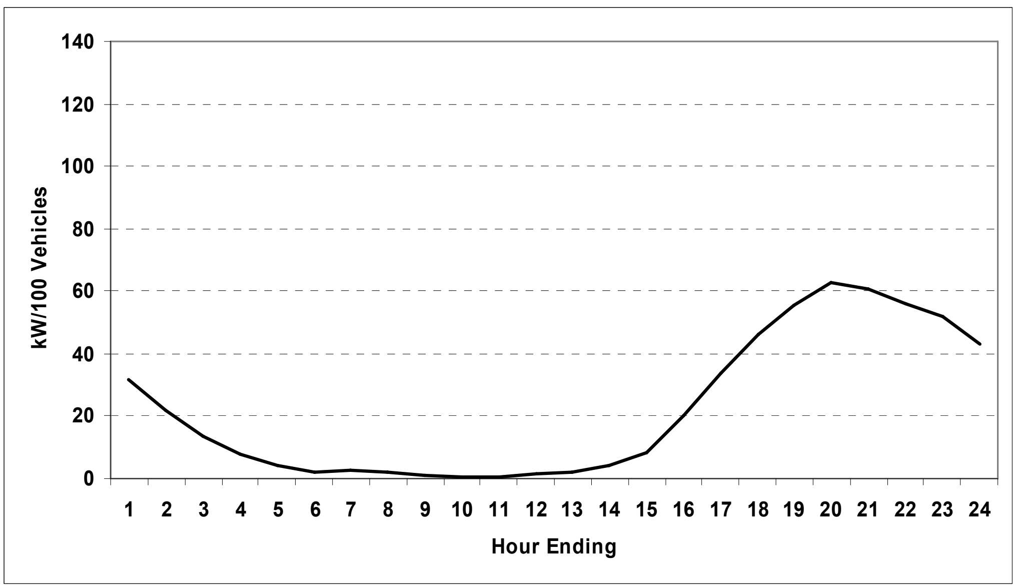


Figure 5: Fleet Average Charging Profile in the Uncontrolled Charging Case

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.[26] This requires only a modest increase in infrastructure, i.e., a timer in either the vehicle or in the household charging station. This case is considered a more likely scenario than the uncontrolled charging, given existing incentives for off-peak energy use – many utilities (including Xcel Energy) already offer time-of-use rates to residential customers, and several California utilities

[26] "Off-peak" is generally defined as the period of relatively low electricity demand, typically during overnight hours.

have previously initiated special time-of-use rates for electric vehicles.[27] The charging rate (1.4 kW) is identical to the uncontrolled case.

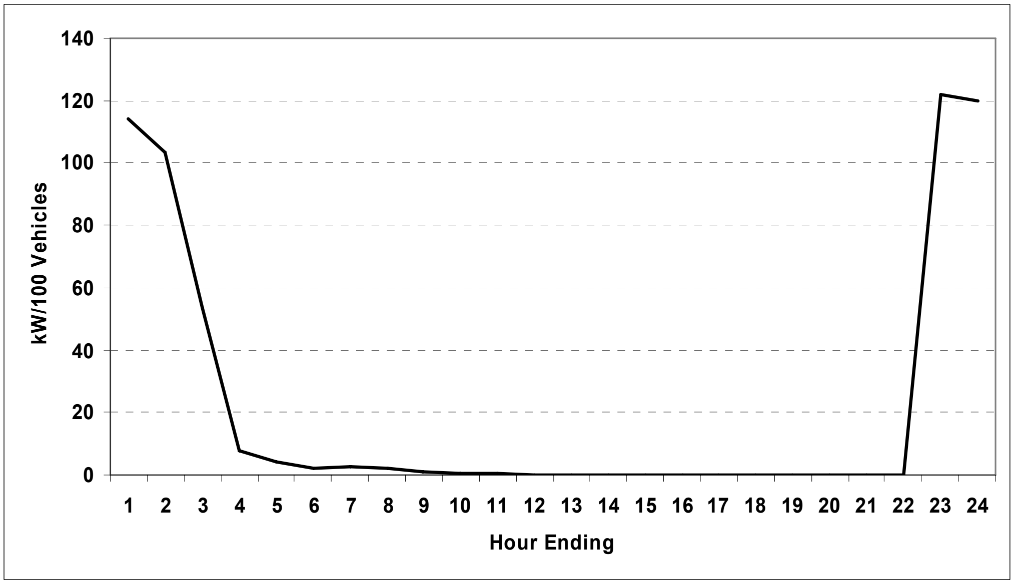


Figure 6: Fleet Average Charging Profile in the Delayed Charging Case

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. This allows the utility to precisely match the vehicle charging to periods of minimum demand, allowing the use of lowest-cost electricity, and improving overall utility system performance. With direct control, the utility would send a signal to an individual vehicle or a group of vehicles to start or stop charging as conditions merit. Such a concept is already in place through other load-control programs used for water heaters, air conditioners, etc. The direct control could also be established through an aggregator that sells the aggregated demand of many individual vehicles to a utility, regional system operator, or a regional wholesale electricity market.

An alternative option – indirect control – would have each vehicle responding intelligently to real-time price signals or some other price schedule to buy electricity at the appropriate time. In either control scheme, the vehicles would be effectively "dispatched" to provide the most economic charging and discharging.

We developed a separate charging algorithm that dispatches vehicle charging and "fills the valley" of minimum overnight demand.[28,29] All charging must be completed by 7 a.m.

---

[27] Pacfic Gas & Electric. Via http://www.pge.com/docs/pdfs/about_us/environment/electric_vehicles/ev4pt2.pdf#search=%22pge%20ev%20rate%22

To allow for maximum system optimization, we increased the allowable fleet average charge rate to 3.2 kW. This is greater than the continuous charge rate of a common household (120V) circuit, and assumes that at least 20% of all charging is on 240V 40A circuits. (These are also common household circuits used for heavy-duty appliances such as clothes dryers.)

Unlike the previous cases, the daily charging load pattern is not constant in this case – it varies in accordance with the weekly and seasonal load pattern. **Figure 7** illustrates the charging profile from one typical day in this case.

Figure 7: Fleet Average Charging Profile in the Off-peak Charging Case

This case is essentially a boundary case to contrast to Case 1, representing a likely "least-cost" charging scenario.

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. As a result, the vehicle is continuously charged whenever it is not in motion, (limited by the battery capacity). The advantage of this scenario is that it maximizes electric operation, and minimizes both petroleum use and vehicle emissions.

---

[28] Ideally, the production cost model would itself optimally dispatch the vehicle charging. However, PROSYM's optimization routines are based on a weekly dispatch instead of a 24-hour cycle. While PROSYM does include a pumped storage optimization routine, it was easier to perform the charging optimization in this separate routine.

[29] Denholm, P.; Short, W. (2006). "Evaluation of Utility System Impacts and Benefits of Optimally Dispatched Plug-In Hybrid Electric Vehicles." NREL Report No. TP-620-40293. Via http://www.nrel.gov/docs/fy07osti/40293.pdf

Figure 8 illustrates the daily charging pattern in the continuous charging case.

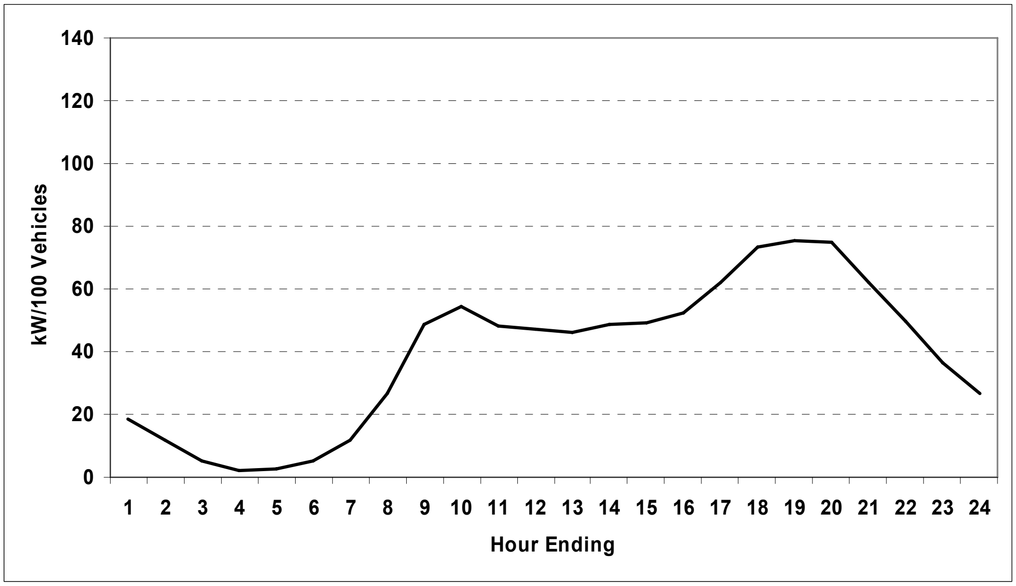


Figure 8: Fleet Average Charging Profile in the Continuous Charging Case

The charging pattern can be best understood starting at 4 a.m., when all vehicles are fully charged. Recharging begins after the morning commute and other morning activities, with the charging rate staying fairly uniform due to the large number of midday trips. Late-day charging peaks after the evening commute, but drops off more rapidly than in the uncontrolled charging case, because the midday charging results in a higher state of charge before the evening commute begins. As a result, there is even less off-peak charging than in the uncontrolled charging case.

2.5 Overall Vehicle Performance

The combined vehicle assumptions and charging scenarios describe the overall vehicle performance, including total electricity demand and gasoline consumption. **Table 3** summarizes the vehicle parameters for the four PHEV charging cases, compared to non-plug-in vehicles. The first three charging cases are considered "once per day" charging scenarios, and produce the same average-vehicle electricity demand and miles driven electrically. With continuous charging, a much larger fraction of miles are driven electrically, because the battery is "topped off" at the end of each trip.

Table 3: Vehicle Performance Under Various Charging Scenarios

Charging Scenario	Conventional Vehicle	HEV	PHEV Cases 1-3 (Charging Once per day)	PHEV (Continuous charging)[30]
Miles from Electricity (Daily/Annual)	0	0	14.6 / 5,356	19.9 / 7,260
Percent of Miles from Electricity	0	0	39%	52%
Electricity Requirement (kWh) (Daily/Annual)	0	0	5.3 / 1,944	9.4 / 3,530
Annual Gasoline Use (gallons)	535	386	237	145
Annual Fuel Cost[31]	$1,375	$993	$778	$614

The major benefit of PHEVs to owners (assuming no additional benefits from V2G operation) is the reduction in gasoline use and resulting reduction in operational costs. Compared to a base conventional vehicle, a PHEV can reduce gasoline consumption by more than 70%, given the availability of daytime charging. It is important to note that much of this efficiency gain is associated with the hybrid drivetrain. The annual gasoline savings associated with plug-in technology is equal to the HEV gasoline use minus the PHEV gasoline use, about 150 to 240 gallons per year using our vehicle assumptions. Assuming fuel prices of $2.57/gallon and 8.6 cents/kWh, the use of plug-in technology would save its owner from $200 to $450/year in fuel costs.

3. Results

Results were generated by first running a base case without PHEVs, and then running the individual PHEV cases. The difference between the base case and each PHEV scenario case establishes the net system impacts. Four general impact categories were examined: total electricity load and load shape, charging generation source, total charging costs, and emissions.

3.1 Net PHEV Load and Load Shape

The net PHEV loads provide a visual indication of the basic impacts on utility load patterns and provide some quantitative information such as the change in utility load factor, such as the need for additional capacity.

[30] The vehicle performance (fuel and electricity consumption rates) in the continuous charging case is slightly different than the performance described in Table 2. This is due to the increased use of blended mode operation made possible by continuous charging.

[31] Includes the cost of gasoline and electricity. Using the average price of gasoline for Denver in the year ending November 2006 ($2.57/gallon) and the average retail price of electricity during the same time periods (8.64 cents/kWh). The actual price of electricity purchased for vehicles is actually considerably less than this value since the average price includes fixed billing charges. Gasoline costs from http://www.eia.doe.gov/oil_gas/petroleum/data_publications/wrgp/mogas_history.html. Electricity costs from http://www.eia.doe.gov/cneaf/electricity/epm/table5_6_a.html.

Summer Load Impacts

Like most of the United States, the Xcel Energy system peaks in the summer, driven by midday and early evening air-conditioning demand. **Figure 10** illustrates summertime load patterns for three days, including the normal load and the load with PHEV charging. The overall annual peak occurs on day 3.

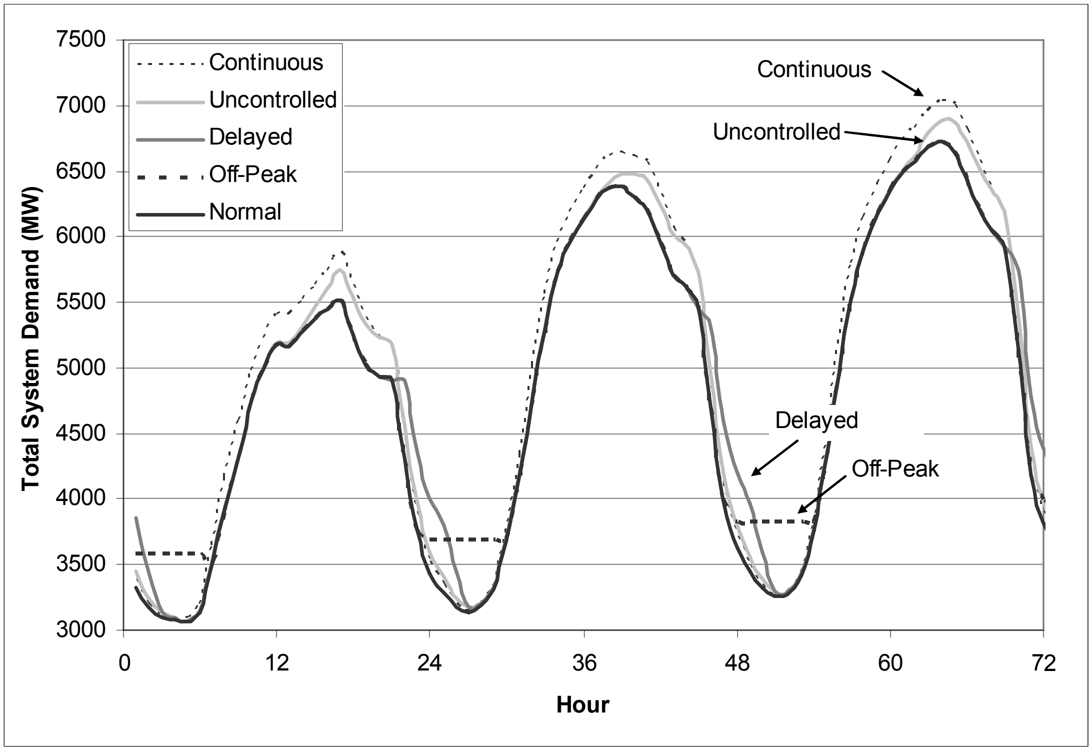


Figure 10: Summertime Load Patterns with PHEV Charging

The uncontrolled and continuous charging cases add considerable load coincident with periods of high demand, and add to the peak capacity requirements. Delayed charging dramatically improves the situation by avoiding charging during the peak demands in late afternoon and early evening, while the optimal charging case fills the overnight demand minimum. As a result, delayed or optimal PHEV charging avoids any need for additional generation capacity.

Winter Load Shape Impacts

Figure 11 illustrates the impact of PHEV loading on wintertime demand patterns. Wintertime peak demand is driven largely by heating and lighting requirements. There is a strong evening demand peak, largely coincident with the time when PHEVs would begin charging in the uncontrolled charging scenario. As with the summer case, delayed charging and optimal charging avoids charging during the evening lighting peak.

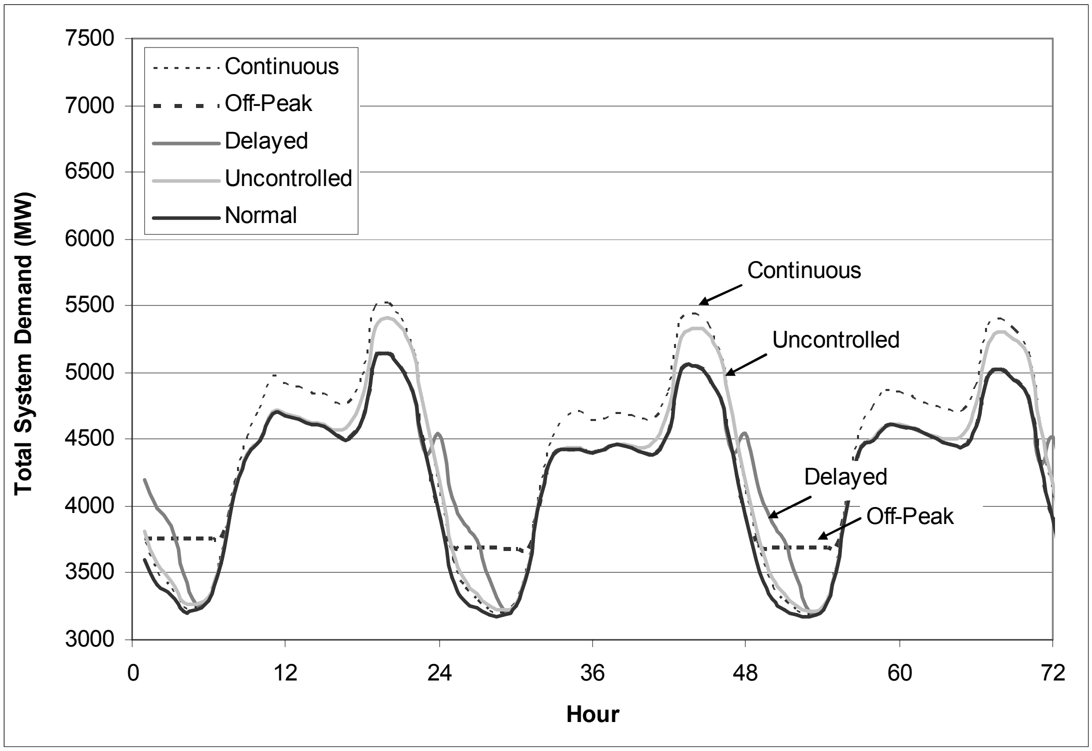


Figure 11: Wintertime Load Patterns with PHEV Charging

Total Load Impacts

The total impact of PHEVs on an annual basis can be observed in a load duration curve (LDC). An LDC is created by reordering the hourly demand data from greatest to least demand for all 8,760 hours in a year, and provides insight into the overall utilization of a utility's power plant fleet.

Figure 12 illustrates the LDCs for each of the four charging scenarios.

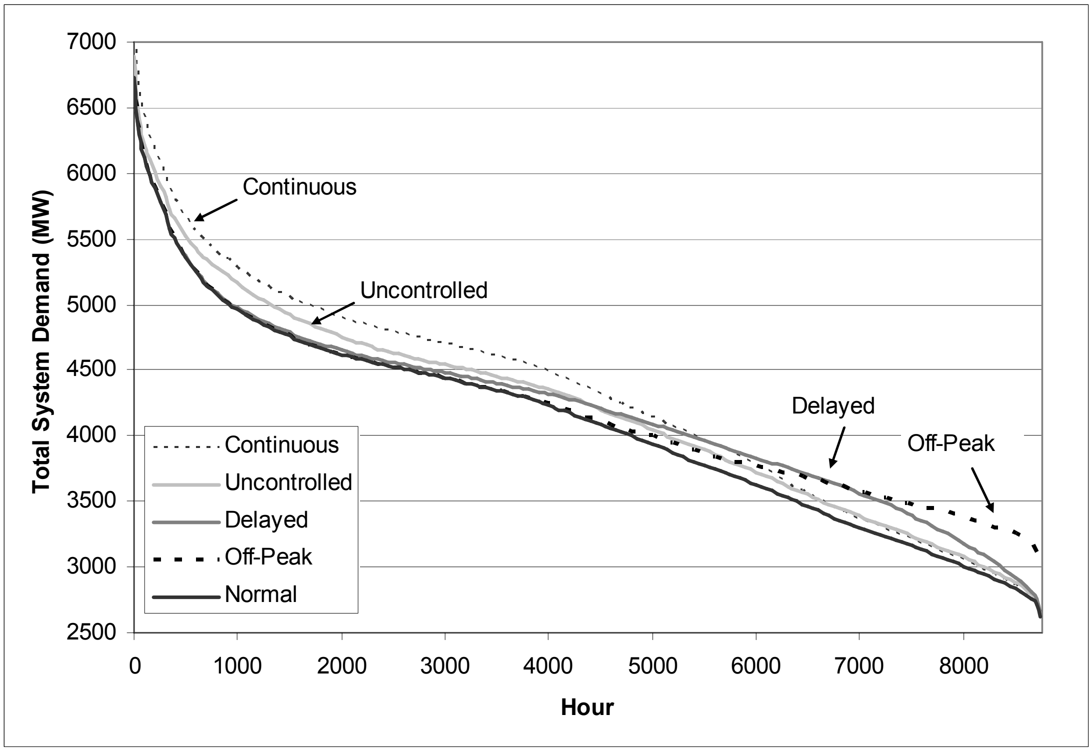


Figure 12: System Load Duration Curve with PHEV Charging

Figure 12 demonstrates that, on an annual basis, the uncontrolled charging and continuous charging cases require a large fraction of PHEV charging to occur during periods of moderate to high loads. The time-delayed and off-peak charging cases show an improvement in the distribution of additional charging. The majority of the increased load occurs in the lower demand region. A noticeable benefit of off-peak charging is the increased minimum load.

Table 4 summarizes several of the load impacts resulting from the 500,000 PHEV scenario.

Table 4: Impacts of Various Charging Cases on System Capacity and Energy Requirements

Charging Scenario	Increase in Total Load (%)	Increase in Peak Demand (%)
Uncontrolled	2.7	2.5
Delayed	2.7	0
Off-peak	2.7	0
Continuous	4.8	4.6

3.2 Generation Source

Because PROSYM tracks each generation unit on an hourly basis, it is possible to determine exactly which generators would likely provide the incremental generation necessary for PHEV charging. Generators of each type (coal, gas combined cycle, etc.)

can be aggregated to provide a breakdown of the generator or fuel type providing energy for PHEVs.[32]

Figure 13 provides an estimate of the fraction of energy provided for incremental energy for each of the charging scenarios.

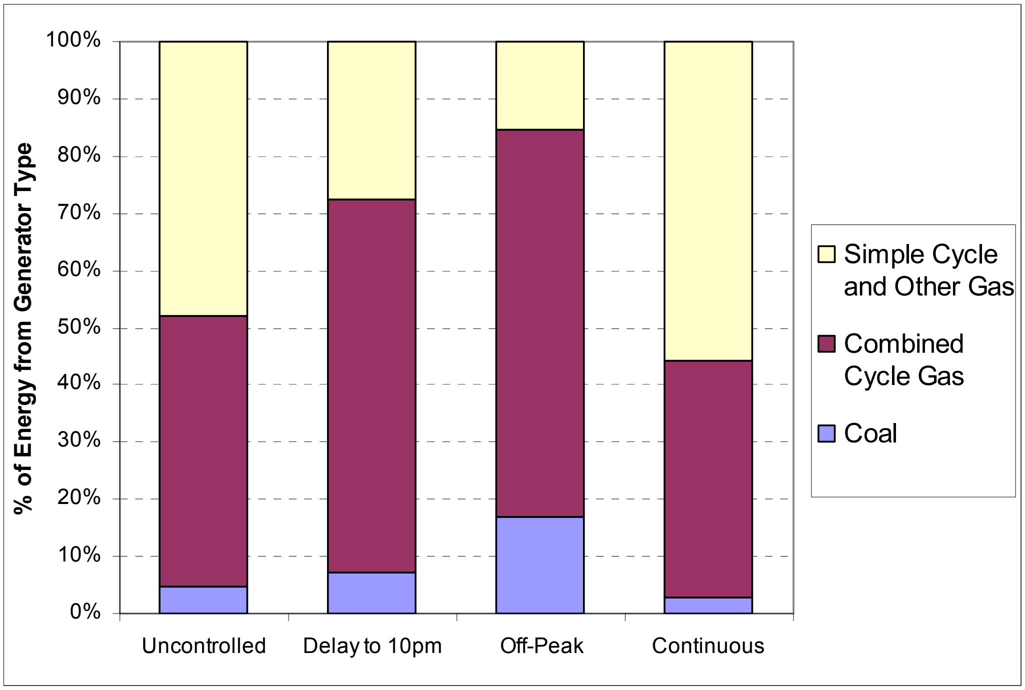


Figure 13: Generation Mix Serving Additional Load of 500,000 PHEVs[33]

In each case, the distribution graph represents the fractional source of energy for all PHEV charging. The marginal generation mix is the most important factor in both the overall charging costs and the net emissions. In this particular case, natural gas provides the marginal fuel more than 80% of the time, due to the particular characteristics of the current Xcel Energy system. It should be emphasized that the marginal fuel mix is very system dependent, and can change over time. While natural gas is "at the margin" for most of the West, coal may provide a greater fraction of the marginal fuel in the Eastern United States, especially during off-peak periods.[34] While moving to off-peak charging in the Xcel Energy system allows a modest increase in coal use, the greatest benefit to delayed and off-peak charging cases is increased use of more efficient combined-cycle units.

---

[32] Certain resources such as wind and hydro are considered "must run" units, and do not contribute to the incremental generation requirements of PHEV charging. PHEVs could provide a dispatchable load that allows increased use of wind in the long term, but that application is not considered in this work. For additional discussion of this application, see: Short, W.; Denholm, P. (2006). Preliminary Assessment of Plug-in Hybrid Electric Vehicles on Wind Energy Markets. 41 pp.; NREL Report No. TP-620-39729. Via http://www.nrel.gov/docs/fy06osti/39729.pdf

[33] "Other Gas" refers to reciprocating and steam units.

[34] Global Energy. *Coal: America's Energy Security Insurance*. Global Energy Monthly Briefing, March 2005. Via http://www.globalenergy.com/BR05/BR05-coal-americas.pdf

3.3 Charging Costs

Figure 14 illustrates the incremental generation costs associated with vehicle charging for each of the four charging scenarios. Costs are broken out in the three evaluated categories: fuel costs, variable operation and maintenance (O&M), and unit starts.

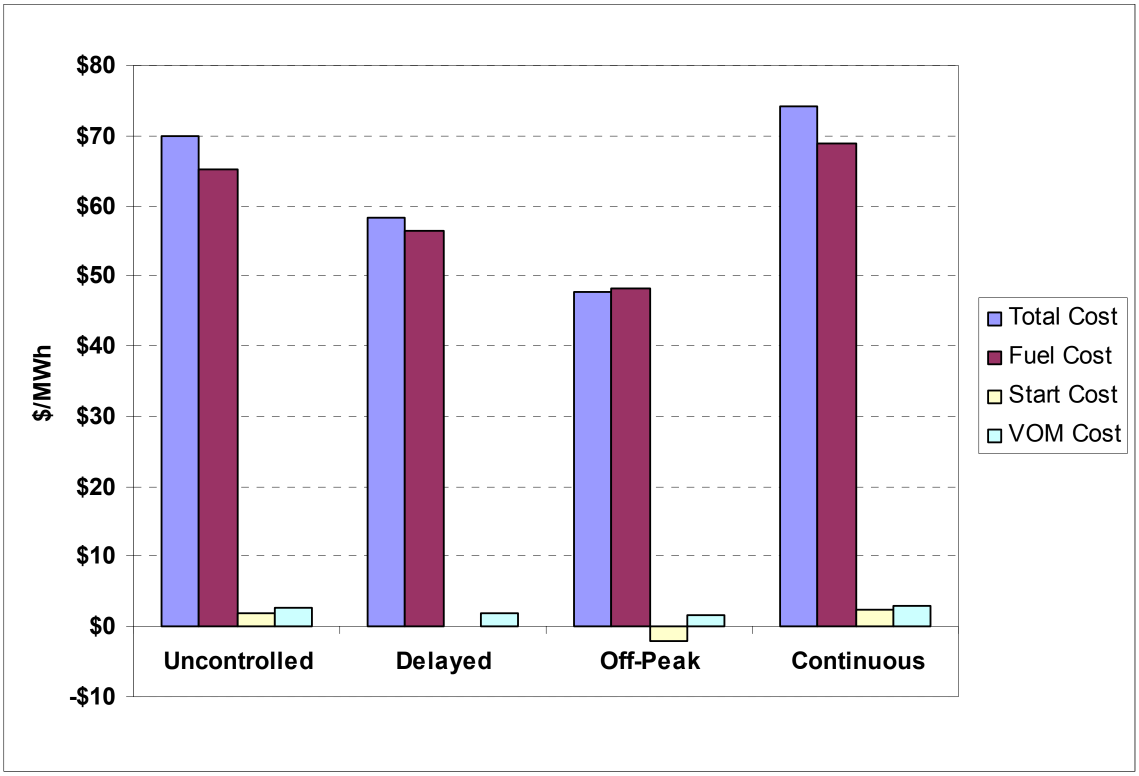


Figure 14: Incremental Cost of Electricity for PHEV Charging

From the uncontrolled charging to the delayed charging cases, the reduction in fuel cost occurs by moving from lower efficiency units to higher efficiency combined-cycle units. Moving to the off-peak charging case reduces costs further by shifting some generation to coal units. The large fuel costs associated with continuous charging results from the extensive use of the low efficiency gas units.

The actual decrease in cost associated with off-peak charging is limited in a system with natural gas at the margin during the majority of hours. Much greater cost savings are available in systems with available coal generation. The variable fuel cost associated with coal generation (assuming $1.60/mmBTU fuel and a 10,500 BTU/kWh heat rate) is $17/MWh. This value represents the potential lower bound of generation costs in an optimal charging scenario, excluding the additional benefits of avoided starts.

The negative cost associated with avoided starts is an interesting benefit associated with PHEV charging. By filling the valley of overnight off-peak demand, PHEVs reduce the number of times plants must be shut down, only to be restarted in the morning. In the modeled scenarios, the change in power plant startups ranged from about 30 fewer

startups per month in the off-peak charging case to about 130 additional startups per month in the continuous charging case.[35] This increases motivation for utilities to implement a program of off-peak vehicle charging. In addition to the lower fuel costs, the vehicle owner that allows for (or demands) utility-controlled charging incurs a system benefit of about 0.2 cents/kWh due to improved system performance.

Figure 15 translates the cost of electric generation into more common vehicle equivalents. The cost of generating PHEV-charging electricity is somewhat analogous to the "wholesale" cost of gasoline, or the cost of producing electric fuel. Assuming the vehicle parameters in **Table 2**, a PHEV requires about 13 kWh to displace 1 gallon of gasoline used in an HEV. As a result, the electric equivalent of gasoline is produced for as little as 62 cents per gallon, equivalent to fuel costs of less than 2 cents per mile in the off-peak charging case.

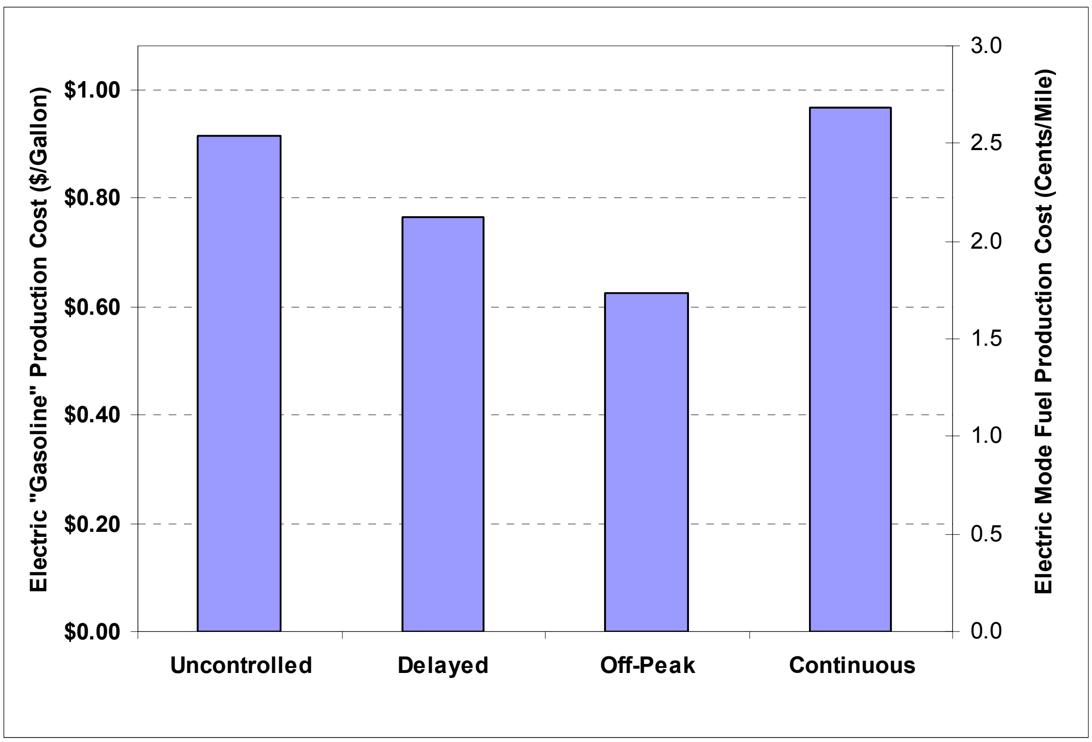


Figure 15: PHEV Electric-Mode Fuel Production Costs

The annual savings associated with moving from the uncontrolled charging to controlled charging scenarios could be compared with the cost of implementing charging-control technologies. Using previously stated vehicle assumptions, compared to uncontrolled charging, the annual benefit of delayed charging is about $23/vehicle, while off-peak charging reduces annual generation cost by about $44/vehicle. As mentioned before, the benefits of optimal charging in the Xcel Energy system are largely due to the efficiency gains associated with more efficient gas generation. The ability to switch from natural gas

[35] The ability to optimally control PHEV charging and limit power plant starts depends on a number of factors, including accurate forecasting of the amount of charge remaining in the PHEV fleet each evening.

to coal during off-peak hours could potentially double the annual savings associated with optimal charging.[36] These values also can be expressed as an equivalent to a gasoline "discount" equal to about 15 cents per gallon for delayed charging, and about 29 cents/gallon for off-peak charging, both compared to uncontrolled charging.

It should be noted that all costs in this section are variable generation costs, and do not include the cost of transmission and distribution. The costs associated with PHEV charging also do not consider the capacity costs associated with increased peak demand. Both the uncontrolled charging case and the continuous charging case increases peak demand – about 0.3 kW per vehicle in the uncontrolled case and about 0.7 kW per vehicle in the continuous charging case. If PHEV owners were responsible for this incremental capacity, charging costs would increase. Alternatively, charging could be restricted during the few hours per year when PHEVs would add to peak demand. – about five hours/year in the uncontrolled charging case and 20 hours/year in the continuous case. If PHEVs were unable to charge during these times, their annual electric miles would be reduced by less than 1%.

3.4 Emissions

We examined major sources of emissions of nitrogen oxides (NO_X), sulfur dioxide (SO_2), and carbon dioxide (CO_2). These sources include vehicles, electric generation, and refinery operations; but do not include all life-cycle factors, such as fuel extraction and transport, vehicle manufacturing, etc.

NO_X emission results from high-temperature combustion processes and is produced by both coal and gas-fired plants. SO_2 is emitted as a result of the oxidization of sulfur contained in coal and petroleum, with about 67% of SO_2 emissions originating in the electric sector.[37] CO_2 is emitted as the result of the oxidization of carbon in all fossil fuels.

Figure 16 illustrates the electricity-related emissions rates for the various PHEV charging scenarios.

[36] We did not examine any potential "feedback" effects on the cost of electricity due to the increased use of natural gas for PHEV charging.
[37] U.S. EPA. "SO_2: What is it? Where does it come from?" http://www.epa.gov/air/urbanair/so2/what1.html

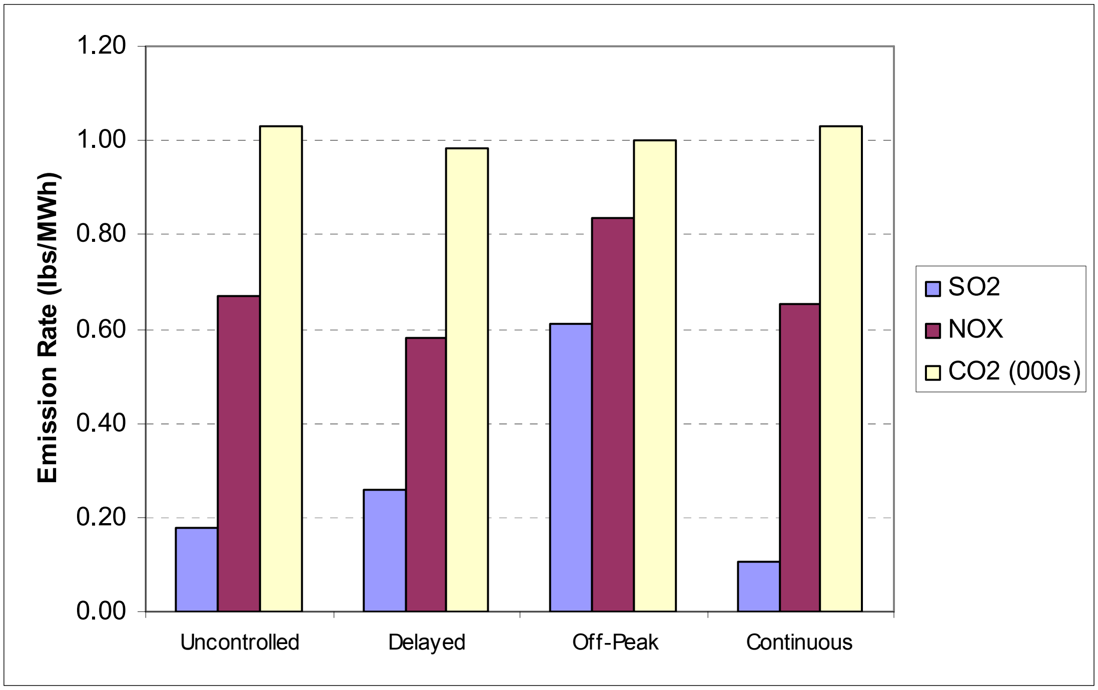


Figure 16: Emission Rates of SO_2, NO_X, and CO_2 Associated with PHEV Charging

The SO_2 emission rate associated with PHEV charging is strongly correlated with the amount of coal generation, because natural gas combustion produces very little SO_2 emissions. As a result, the off-peak charging case produces the highest SO_2 emission rate. The NO_X emission rate also correlates strongly with the amount of coal generation, although significant NO_X emissions may be produced by natural gas units. The increased use of coal in the off-peak case is balanced by the increased use of more efficient combined-cycle units, resulting in approximately equal CO_2 emissions rates in all four charging scenarios. In all cases, incremental generation for PHEV charging is much less dependent on coal than the system average, resulting in much lower emission rates. The Xcel Energy system average emission rates in 2004 were about 2.9 lbs/MWh for NO_X, 3.1 lbs/MWh for SO_2, and 1,950 lbs/MWh for CO_2.[38]

Figure 17 illustrates the total net NO_X emissions from several vehicle types including conventional vehicles and PHEVs under various charging scenarios. The net NO_X emissions include vehicle tailpipe emissions, power plant emissions, and refinery-related emissions.[39] The composite per mile emissions can be estimated by dividing by the annual number of miles traveled – in this case, equal to 13,900.

[38] U.S. EPA eGRID2006 Version 2.0. http://www.epa.gov/cleanenergy/egrid/index.htm

[39] Vehicle CO_2 emissions from U.S. Environmental Protection Agency. *Compilation of Air Pollutant Emission Factors, AP-42*, 5th ed.; U.S. Environmental Protection Agency, U.S. Government Printing Agency: Washington, D.C., 1996; Volume I: Stationary Point and Area Sources. AP-42. Vehicle NOx from tier 1 and tier 2 stds, equal to 0.3 gms/mile and 0.7 gms/mile. From: Transportation Energy Data Book: Edition 25, (2006). Stacy C. Davis, Susan W. Diegel, Oak Ridge National Laboratory, ORNL-6974. Refinery emissions from GREET at http://www.transportation.anl.gov/software/GREET/

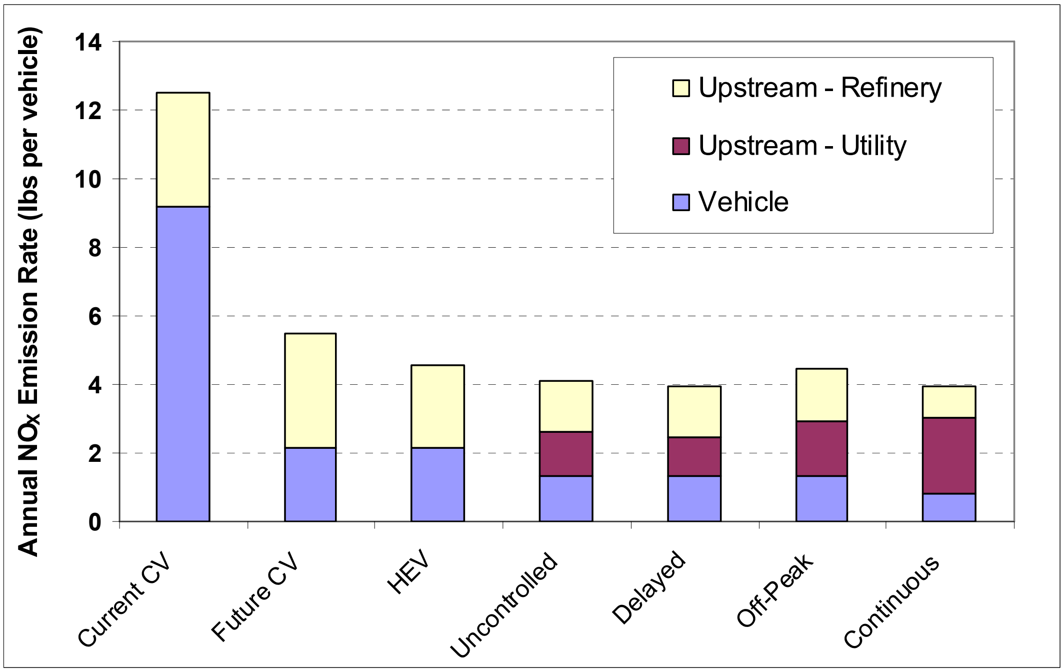


Figure 17: Net Vehicle NO_X Emissions Rates

Among the more important aspects of this chart is the dramatic reduction in new vehicle NO_X emissions mandated by current regulations. Currently, about 55% of all NO_X emissions nationwide are from motor vehicles, with only about 22% emitted from electric utilities.[40] As a result of reduced future vehicle emissions, net emissions from PHEVs could be somewhat higher than from conventional vehicles or HEVs, especially if more coal generation was available for charging. This also means NO_X emissions from refinery operations will become a greater fraction of vehicle-related emissions, although relatively small on an absolute basis. The refinery emissions are based on current national average, and rates are expected to decrease under existing and pending EPA regulations. There are also regulations that will substantially reduce NO_X emissions from the electric sector.[41] Ultimately, a meaningful net comparison of NO_X emissions is difficult, given the issues associated with emissions transport and air quality modeling. Major air quality issues and health concerns related to NO_X are from emissions in populated areas. Many of the upstream NO_X emissions do not occur in populated areas, reducing their impact. Also, "blended mode" PHEV NO_X emissions are less likely to occur in populated areas, and PHEVs are far more likely to be operated almost exclusively in zero-emissions EV-only mode in urban centers. In addition, because many of the marginal generators used for PHEV charging do not currently have post-combustion controls, there are significant opportunities to reduce generation-related NO_X emissions.

Because there is so little sulfur in motor gasoline, gasoline vehicle SO_2 emissions are very small, and net vehicle related emissions are largely from the upstream processes,

[40] U.S. EPA "NOx: What is it? Where does it come from?" Via http://www.epa.gov/air/urbanair/nox/what.html

[41] U.S. Environmental Protection Agency. Clean Air Interstate Rule. Available at http://www.epa.gov/cair

either from the refinery or the power plant. This is illustrated in **Figure 18**, which shows the net SO_2 emission rates for various vehicle types and charging scenarios.

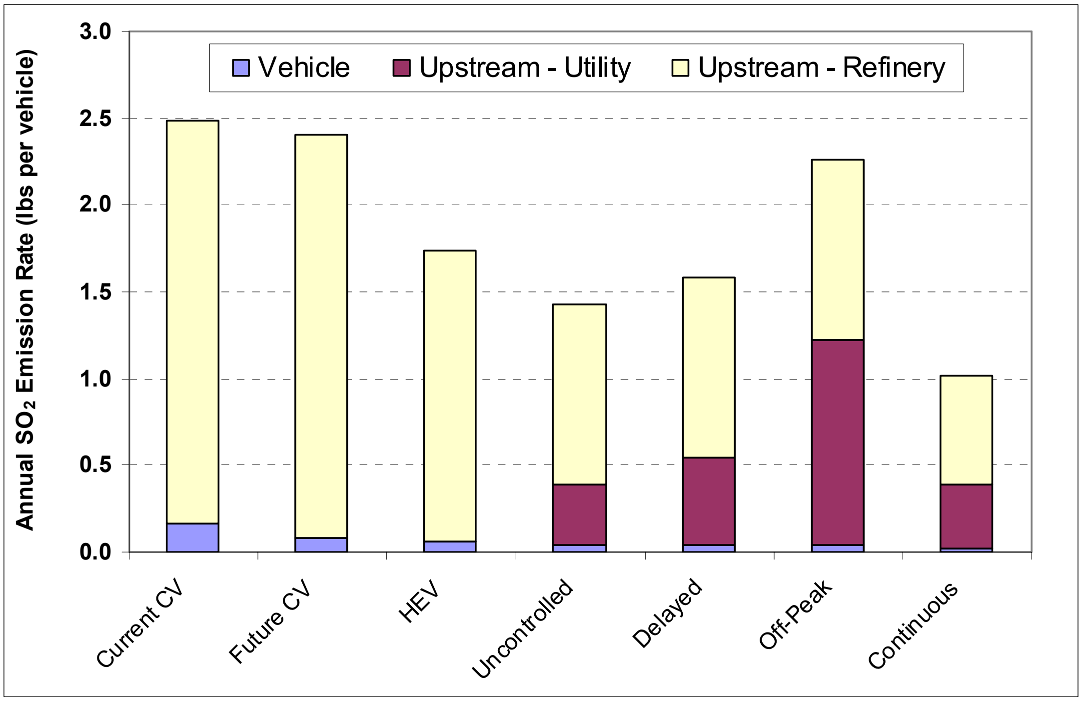


Figure 18: Net Vehicle SO_2 Emissions Rates

Depending on the amount of coal in the marginal generation mix, net SO_2 emissions from a PHEV may be greater than a conventional vehicle or HEV. This comparison is clearly very sensitive to both assumed refinery emissions rate and the use of coal for PHEV charging. However, any SO_2 comparison must be placed in context of the national cap on SO_2 emissions, which does not allow a net increase in SO_2. As a result, any increase in SO_2 emissions resulting from additional load created by PHEV charging must be offset by a decrease in emissions elsewhere – so while PHEVs will not increase the amount of SO_2 emissions, they could slightly increase the cost of coal-generated electricity.

Figure 19 illustrates the net CO_2 emissions on a per-vehicle basis. In all cases, there are significant reductions in net CO_2 emissions from PHEVs.

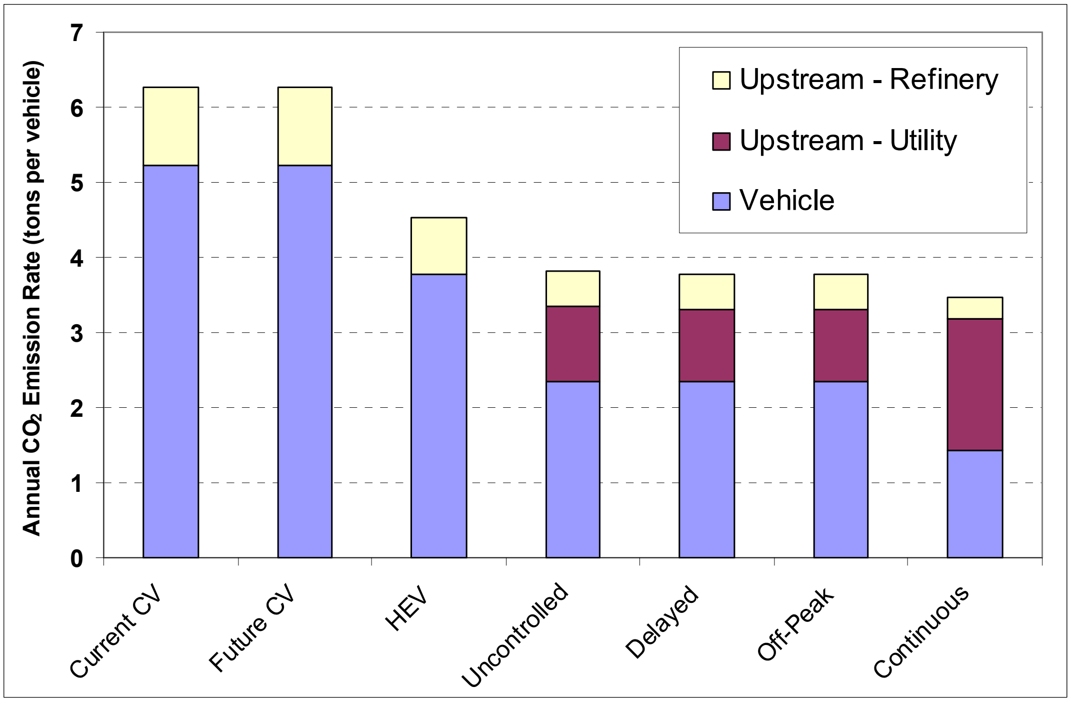


Figure 19: Net Vehicle CO_2 Emissions Rates

4. Conclusions

- The actual electricity demands associated with PHEV charging are quite modest compared to normal electricity demands. Replacing 30% of the vehicles currently in the Xcel Energy service territory with PHEV-20s deriving 39% of their miles from electricity would increase total load by less than 3%.

- A very large penetration of PHEVs would place increased pressure on peaking units if charging is completely uncontrolled. There is a large natural coincidence between the normal system peaks and when significant charging would occur during both the summer and winter seasons.

- No additional capacity would be required for even a massive penetration of PHEV if even modest attempts were made to optimize system charging. Simple time-of-day charging could easily place all end-of-day charging requirements into off-peak periods. Utility-controlled charging would create additional net benefits in terms of utilization of existing plants.

- In the near term, the Xcel Energy system uses gas for marginal generation most of the time. Coal is used for less than 20% of all PHEV charging, even in scenarios that use exclusively “off-peak” electricity.

- Because most near-term PHEV charging will likely be derived from gas units in the evaluated scenarios, the cost of natural gas drives the cost of PHEV charging.

- The incremental cost of charging a PHEV fleet in the overnight charging cases ranges from $90 to $140 per vehicle per year. This translates to an equivalent production cost of gasoline of about 60 cents to 90 cents per gallon.

- Total NO_X emissions from PHEVs in the evaluated scenarios are equal or slightly less than from non-plug-in HEVs. Although total NO_X reductions may be relatively small, tailpipe NO_X is significantly reduced as more miles are electrically driven. Without the use of an air quality model, it is difficult to quantify the net benefit of reducing tailpipe NO_X while increasing generator NO_X emissions. In addition, there are significant opportunities for further NO_X reductions in the electricity sector as many units are not fitted with the latest emission control technology.

- Because gasoline contains little sulfur (having been taken out at the refinery), the most important factors for net SO_2 emissions are emissions from refinery operations and from marginal coal generation. For the evaluated daytime and delayed charging scenarios, total PHEV-related SO_2 emissions are expected to be less than from conventional and hybrid vehicles. In the off-peak charging case, or any case where coal is at the margin a large fraction of the time, SO_2 emissions are expected to be greater. Any emissions comparison must be placed in context of the national cap on SO_2 emissions, which does not allow a net increase in SO_2. As a result, any increase in SO_2 emissions resulting from additional load created by PHEV charging must be offset by a decrease in emissions elsewhere.

- In all cases, there are significant reductions in net CO_2 emissions from PHEVs.

- Further analysis is needed to design and analyze several potentially improved charging scenarios. A more optimal charging scenario would likely combine off-peak charging to minimize costs, while including some midday (continuous) charging to increase gasoline savings. This would potentially provide both Xcel Energy and its customers with the greatest overall mix of PHEV benefits.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
May 2007	Technical Report	

4. TITLE AND SUBTITLE
Costs and Emissions Associated with Plug-In Hybrid Electric Vehicle Charging in the Xcel Energy Colorado Service Territory

5a. CONTRACT NUMBER
DE-AC36-99-GO10337

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
K. Parks, P. Denholm, and T. Markel

5d. PROJECT NUMBER
NREL/TP-640-41410

5e. TASK NUMBER
WR61.2001

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/TP-640-41410

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
The combination of high oil costs, concerns about oil security and availability, and air quality issues related to vehicle emissions are driving interest in "plug-in" hybrid electric vehicles (PHEVs). PHEVs are similar to conventional hybrid electric vehicles, but feature a larger battery and plug-in charger that allows electricity from the grid to replace a portion of the petroleum-fueled drive energy. PHEVs may derive a substantial fraction of their miles from grid-derived electricity, but without the range restrictions of pure battery electric vehicles. As of early 2007, production of PHEVs is essentially limited to demonstration vehicles and prototypes. However, the technology has received considerable attention from the media, national security interests, environmental organizations, and the electric power industry. The use of PHEVs would represent a significant potential shift in the use of electricity and the operation of electric power systems. Electrification of the transportation sector could increase generation capacity and transmission and distribution (T&D) requirements, especially if vehicles are charged during periods of high demand. This study is designed to evaluate several of these PHEV-charging impacts on utility system operations within the Xcel Energy Colorado service territory.

15. SUBJECT TERMS
NREL; plug-in hybrid electric vehicles; PHEVs; vehicle technologies; Xcel Energy Colorado; electric charging; transmission and distribution; T&D; transportation; vehicle emissions; utility system; electric generation; Paul Denholm; Keith Parks; Tony Markel

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			
Unclassified	Unclassified	Unclassified	UL		**19b. TELEPHONE NUMBER** (*Include area code*)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

F1146-E(12/2004)