Cost and Emissions impacts of Plug-In Hybrid Electric Vehicles on Ohio Power Grid

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ABSTRACT

This paper analyzes the impacts of plug-in hybrid electric vehicle (PHEV) charging on the Ohio power system to estimate the net cost and emissions impacts of PHEV use. We consider two charging scenarios—one in which the grid operator makes charging decisions and another in which these decisions are made by individual vehicle owners and consider cases with PHEV penetrations of between 1% and 5%. Results show that PHEV use would result in a close to 70% reduction in gasoline consumption compared to conventional vehicles and a 50% reduction in driving costs. The emissions impacts are more mixed, with some pollutants being reduced and other increased, due to use of coal-fired generation in Ohio.

Keywords: Plug-in Hybrid Electric Vehicle (PHEV), Grid, Charging, Emissions, Costs.

INTRODUCTION

Plug-In Hybrid Electric Vehicles (PHEVs) have been promoted as a potential technology that can reduce vehicle's fuel consumption and decrease transportation-related emissions, overall costs, and oil dependence. This is obtained by using electricity as a primary source of energy to run the vehicle, using gasoline as a secondary backup fuel. Several studies have found that by using electricity, PHEVs could emit less CO_2 and certain other pollutants over their entire fuel cycle than conventional vehicles (CVs) and hybrid-electric vehicles (HEVs) [1], [2], [3], [4], [5], [6]. This is because in many regions grid electricity is effectively a cleaner source of transportation fuel than gasoline. Furthermore, pollutants can be better-controlled in power generation plants and there are local benefits from shifting emissions away from population centers to point sources such as power plants. Emissions impacts of PHEVs will depend strongly on the generation mix present in the power system; clearly, a high penetration of cleaner sources of energy such as solar, wind, hydroelectric, or nuclear energy could lead to a great decrease in pollutants emissions while a predominance of coal as primary source of energy is less effective in this sense. Stephen and Sullivan [3] estimated average PHEV-related CO_2 emissions for the U.S., showing that a PHEV will emit 221 g/km of CO_2, about 51% of conventional vehicle's emissions. Similar results were obtained in a study on the Colorado electric system, which estimates that a PHEV will emit about 60% of the CO_2 normally produced by a conventional vehicle [2]. PHEVs could also help countries reduce oil dependence by decreasing gasoline consumption of vehicles running today [6], [7]. Since electricity is less expensive than gasoline, PHEVs could provide important operational cost savings, making them attractive for future buyers despite the additional initial cost compared to CVs and HEVs [7], [8], and representing a first step toward future transportation electrification.

MODELING ASSUMPTIONS

This paper describes an analysis of the effect of a PHEV fleet on the Ohio power system. This analysis helps determine how a PHEV fleet would affect net emissions and costs and whether PHEVs would be economically attractive for new customers. Two different scenarios are considered: a **controlled charging** scenario, which assumes that the utility co-optimizes the operation of generators and the charging of PHEVs to minimize the total cost of generation and vehicle driving; and an **uncontrolled charging** scenario in which PHEVs are recharged whenever they are connected to the grid (without regard to charging cost), and the utility must serve these loads. This scenario assumes that because electricity is a cheaper source of transportation energy, PHEV drivers will always opt to recharge their vehicles when they are not being driven.

PHEV data

For each set of model runs, the PHEV fleet is assumed to consist of a fixed number of vehicles. The total vehicle fleet size is taken from 2007 Ohio vehicle registration information reported by the U.S. Department of Transportation's Federal Highway Administration [9]. Simulations are carried out with three different PHEV penetration levels: 1%, 3% and 5% of the total vehicle fleet. Vehicle driving patterns are based upon empirical driving data collected from a sample of drivers with instrumented vehicles. Figure 1 represents some statistical information about drivers.

Driving data are coupled with the ADVISOR vehicle simulator model to estimate gasoline and electric consumption of an equivalent PHEV. Based on this empirical data different driver profiles were developed. The model assumes that the PHEV fleet is evenly divided into the driving profiles corresponding to the driving pattern data. Driving data were used to determine the hours in which the PHEVs are driven, the total distance traveled in that hour, and those in which they are grid-connected and could recharge their batteries. In doing so, it is assumed that a PHEV must be parked for an entire hour to be considered 'grid-connected' in that hour.

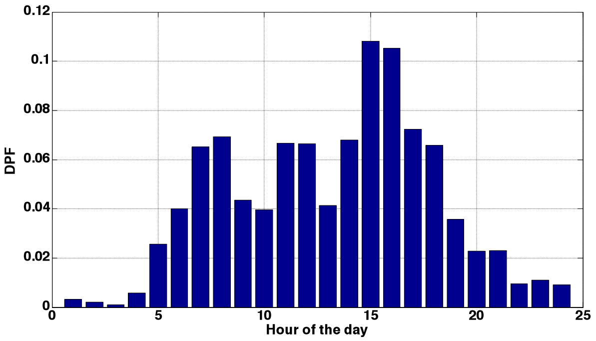

Figure 1: Average distribution of miles driven by drivers during the day

Depending on the state of charge (SOC) of a PHEV's battery, the vehicle will either be driven in charge-depleting (CD) mode, in which case the battery is the primary energy source and the gasoline engine is used only on a supplemental basis (for quick accelerations), or charge-sustaining (CS) mode, in which case the gasoline engine is used to maintain the same average SOC (driving like an HEV). The adopted control strategy is EV (electric vehicle) mode control—the vehicle is driven as an electric vehicle until the lower limit of SOC is reached, then the vehicle operates in CS mode as an HEV. The empirical driving data and ADVISOR model are used to estimate the average gasoline and battery energy usage for each PHEV driving profile in both CD and CS modes. The model also assumes that PHEVs always have sufficient gasoline to operate in either CS or CD mode. It is assumed that the charger has a power capacity of 1.875 kW and charging efficiency of 90%.

Generators data

Generation costs were calculated based on estimated generator heat rates and fuel costs. Heat rates were estimated starting from historical continuous emissions monitoring system (CEMS) data from the U.S. Environmental Protection Agency (EPA) [10]. CEMS data specifies the generation and total heat content of fuel burned by each generator in each hour. These data were used to estimate:

- *startup fuel* burned whenever the generator is brought online from an offline state;
- *spinning no-load fuel* burned whenever the generator is operating, independent of its generation output.;
- *variable fuel* burned depending on the electric output of the generator and was assumed as a step function.

Figure 2 shows the actual CEMS data for one generator in our sample set and the estimated variable fuel cost. CEMS data were also used to determine the minimum power output of each generator (when online), ramping limits, and minimum up and down times when each generator is started up and shutdown. Fuel costs were estimated based on purchase price data reported in form FERC-423, as reported by the U.S. Department of Energy's Energy Information Administration (EIA) [11]. Nuclear generators are assumed to be non-dispatchable and run at full capacity, thus their generating costs are modeled as constant values. Because Ohio is a part of the PJM system, the state may export or import energy from neighboring control areas, depending on the relative cost of energy that can be imported from or exported to the rest of the of the PJM system

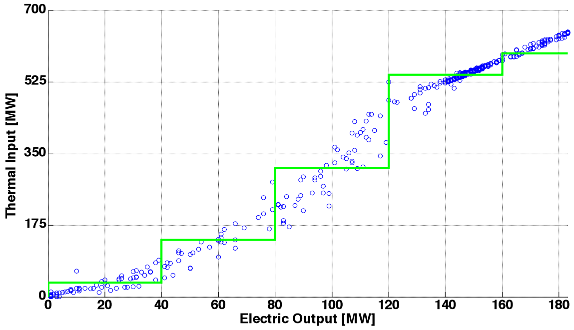

Figure 2: Heat rate data of one of the generators taken from EPA

The price at which energy can be bought and sold will generally vary depending on the volume of transactions, and this is captured in the model by assuming that the price of energy that is bought and sold from the rest of the market is a function of the transacted quantity. Specifically, historical PJM day-ahead market bid [12] data were used to estimate the relationship between price and load. As shown in Figure 3, the energy price function is derived from the bids based on their merit order. The actual historical PJM load is used to shift the market price function horizontally, and the shifted function is used to determine the price of net energy transactions between Ohio and the rest of the PJM market. Market energy transactions are then taken into account when calculating generator's emissions, as explained in the next section.

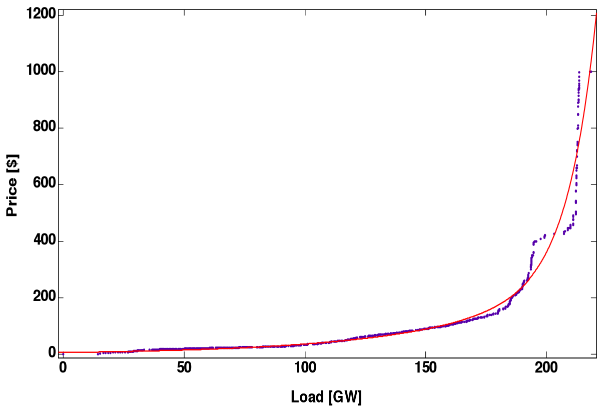

Figure 3: Price of market transactions as a function of transacted energy

Power system model

The analysis is based upon a unit commitment model of the Ohio electric power system, which is formulated as a mixed-integer program using the AMPL and solved using the branch and cut algorithm in cplex 12.1. The model simulates the commitment and dispatch of conventional generators and PHEV charging behaviors. The unit commitment model has a one day planning horizon (typical of day-ahead electricity markets) with an hourly time-step for the commitment and dispatch variables. Each of the 365 days in the sample is simulated independently, except that the commitment and dispatch of each conventional generator and the charge level of each PHEV battery at the beginning of each day is fixed based on the ending values from the previous day's run. Each day's unit commitment is solved in two steps. First a unit commitment model with a two-day planning horizon and a four-hour timestep for the commitment variables (the dispatch variables still have an hourly timestep in this first commitment problem) is used to determine and fix the ending commitment and dispatch of each generator and charge level of each PHEV battery. After these variables are fixed, the one-day problem is solved with hourly timesteps for all of the variables.

PHEV charging decisions are modeled differently in the controlled and uncontrolled charging scenarios. In the controlled charging scenario, the grid operator makes all charging decisions and coordinates these with power system operations. The grid operator's model consists of both the power system and PHEV models, and the grid operator's objective is to minimize the sum of generation costs and the cost of gasoline used by the PHEVs (the cost of electricity used by the PHEV fleet is accounted for in the total generation costs). The controlled charging model also includes a constraint to ensure that each PHEV battery is fully recharged in time for the first vehicle trip of each morning. In the uncontrolled charging scenario, PHEV owners are assumed to make charging decisions on their own without any regard for the impact of vehicle charging on the power system.

Model simulations are used to evaluate the cost and emissions impacts of PHEV use. The analysis considers three different emissions: CO_2, NO_x and SO_2, and considers emissions from two different sources: generator emissions and PHEV tailpipe emissions. Input-based generator emissions rates are estimated using 2007 CEMS data. These emissions rate estimates are combined with the simulated commitment and dispatch for Ohio generators to determine total emissions for the Ohio generator fleet. Energy that is imported into or exported from Ohio will also have an emissions impact—imports will result in greater emissions from generators outside of Ohio, and exports will reduce generator emissions outside of Ohio due to the fact that less energy needs to be supplied by the rest of PJM market. These emissions are estimated based on the hourly marginal fuel mix data (which specifies the mix of generating technologies that are marginal in each hour), reported by PJM, and estimates (based on the CEMS data) of generator emissions rates for each generation technology.

Tailpipe emissions are estimated using emissions regulations and gasoline chemical composition. CO_2 emissions are estimated at 8.87 kg/gallon. For SO_2 emissions, we assume that emissions will exactly comply with EPA's Tier2 requirement of 0.17 g/gallon. Tier2 also requires NO_x emissions to be less than 0.07 g/mile. We assume that CVs and HEVs will be designed to exactly meet these requirements and PHEV emissions are estimated from HEV emissions based on the proportional reduction in gasoline consumption.

RESULTS

PHEV charging scenario will influence the power demand on the grid and the dispatch of generators during the day. As shown in Figure 4, in the controlled charging scenario, the peak load is typically not increased by vehicles charging, since most of the charging is done in the morning (to exploit the availability of lower-cost energy). In the uncontrolled scenario, by contrast, the peak load is increased since PHEVs are plugged in during peak hours, as shown in Figure 5.

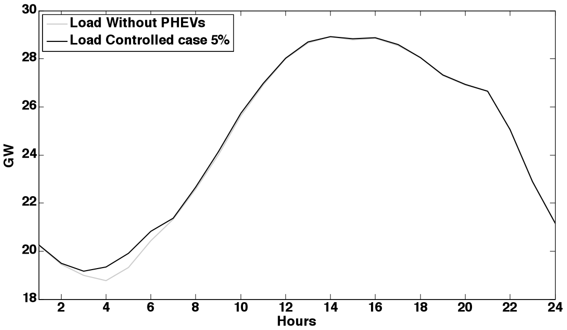

Figure 4: Total load on the grid with a controlled charging strategy on August 6th, summer peak

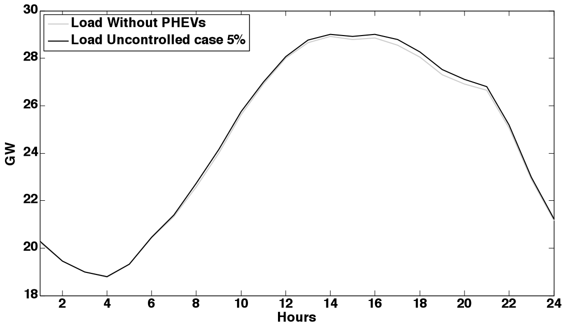

Figure 5: Total load on the grid with an uncontrolled charging strategy on August 6th, summer peak

Figure 6 and Figure 7 show that controlled charging would add a peak of 600 MW on the grid (due to the delaying of vehicle charging overnight), while uncontrolled charging would yield a less-intensive load of between 100 MW and 250 MW distributed during the afternoon. These differences in the PHEV charging load peak could have important implications for distribution-level constraints, since the more-concentrated PHEV charging that would occur with controlled charging may present challenges at the distribution-level for utilities and load-serving entities. A 5% fleet penetration in the uncontrolled charging scenario will add about a 300 MW load in the afternoon, less than 1% of total load; uncontrolled charging could add a more considerable load if the PHEV fleet grows in the future.

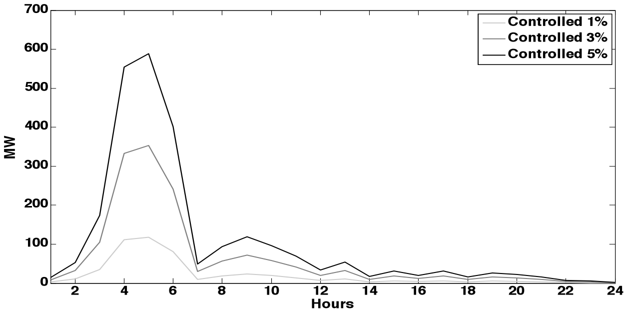

Figure 6: Total charging load on the grid with controlled charging on August 6th

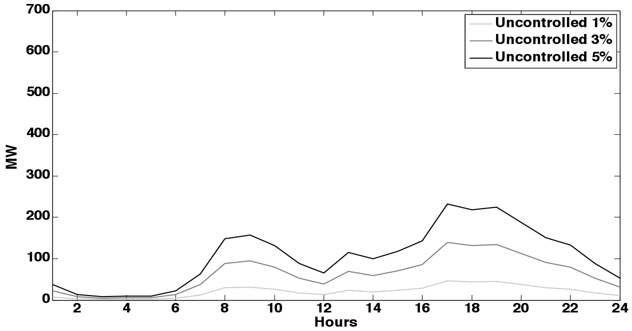

Figure 7: Total charging load on the grid with uncontrolled charging on August 6th

According to the National Research Council, PHEV market penetrations of up to 30% of the total vehicle fleets could be seen by 2050 [13]. Figure 8 shows that a 30% PHEV market penetration charged without any control from the grid operator would increase the Ohio system peak load by about 1.5 GW, shifting it later in the afternoon. This higher load could create problems to grid stability (assuming there is enough capacity to satisfy it).

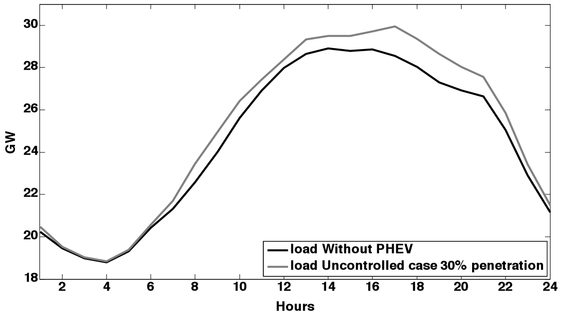

Figure 8: Estimated load on the grid with 30% PHEV fleet penetration

Emissions impact

Results show that the high penetration of coal plants in Ohio leads to in an increase of total SO_2 emissions, a decrease of total CO_2 emissions, and minimal variation of NO_x emissions. Figure 9 shows PHEV use can reduce CO_2 emissions by about 25% on an annual basis in an uncontrolled charging case, while benefits are negligible for the controlled charging scenario.

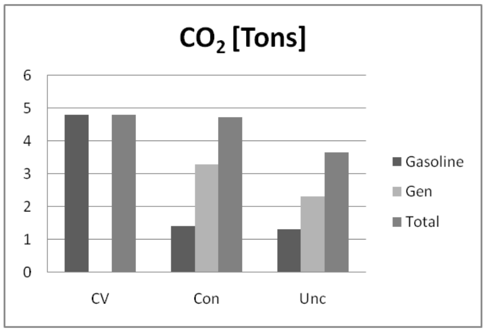

Figure 9: Annual per-vehicle CO2 emissions

Annual NO_x emissions will increase around 5 kg in both cases because emissions connected to power generation are higher than the emissions reductions from reduced gasoline use, as shown in Figure 10. Figure 11 further shows that due to the high penetrations of coal and heavy oil as generation fuels in Ohio, annual per-vehicle SO_2 emissions will increase by between 10 and 12 kg with PHEV use.

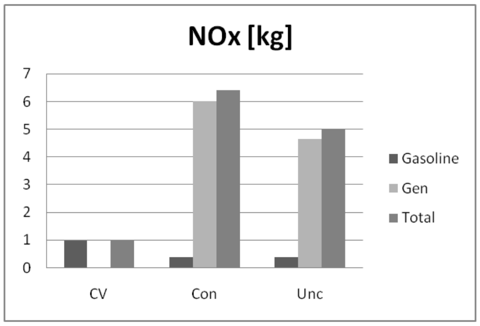

Figure 10: Annual per-vehicle NOx emissions

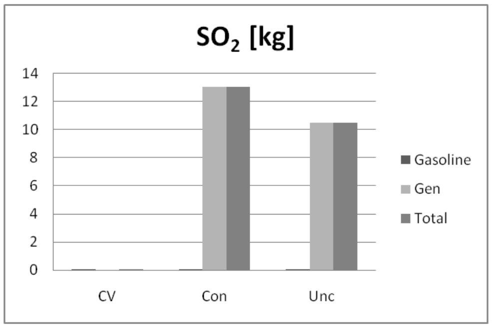

Figure 11: Annual per-vehicle SO2 emissions

Ownership cost

The architecture of a PHEV is differentiated from that of an HEV by its ability to further displace fuel usage by charging off-board electrical energy from the electric utility grid while not being driven. To accommodate the increased dependence on electric power while maintaining an appropriate vehicle weight, the PHEV uses a battery pack with a larger capacity and a smaller internal combustion engine and fuel tank. Also, an inverter-integrated charging plug is needed to connect the enhanced battery pack to a standard electrical socket for recharging purposes. Since all PHEVs produced in the future are expected to offer at least 220 V charging capability, the estimated cost to install an additional outlet in an accessible location to the PHEV is included in this cost analysis.

Currently, conventional vehicles exhibit the least-expensive initial cost of about $21,390, which is not expected to vary significantly in the future (in terms of real cost, excluding inflation). PHEVs will experience a more dramatic cost reduction from current cost estimates of $51,388 to about $27,668. With these cost reductions, PHEVs are expected to have a price premium of approximately $6,200 in the future as compared to conventional vehicles [14]. Our analysis of vehicle operating costs focuses on the cost of fuels—gasoline and electricity—used in driving PHEVs and compares this to the driving costs of CVs. PHEVs will clearly have lower gasoline costs, due to the use of electricity. The average daily trip of drivers considered in the model is about 38 miles and the PHEVs considered have an all-electric range of approximately 22 miles if they operate using the electric vehicle control strategy assumed. Figure 12 shows that gasoline savings can reach more than 70% and one single PHEV will reduce annual gasoline consumption by an average of around 385 gallons compared to a CV.

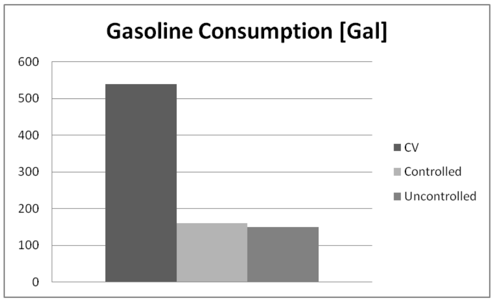

Figure 12: Average annual per-vehicle gasoline consumption (gallons)

Although fuel consumption is reduced through the use of PHEVs, there will be an increase in electricity demand. Retail residential electricity rates averaged about $0.111/kWh in Ohio in 2007, based on values reported by the EIA [14]. While the cost of energy contributes to determining this retail rate, there are non-energy related charges, such as fixed cost recovery, transmission and distribution costs, and metering that are included as well. Our simulations show that adding the PHEV charging loads increases the annual cost of generation by about $0.0032/kWh and $0.0024/kWh in the uncontrolled and controlled cases, respectively. Since utilities would need to recover these additional generation costs, it is plausible to assume that retail rates would increase by this amount above the $0.111/kWh average. It is worth noting, however, that policy makers may opt to levy a different rate on PHEV charging for a number of reasons. One is that it may be desirable to charge a lower rate, as an incentive or subsidy for adoption of PHEV technology. Indeed, in a controlled charging scenario, utilities may opt to give preferential rates in exchange for vehicle owners allowing the utility to control charging. On the other hand, it may also be desirable to charge higher prices in order to recover gasoline taxes, which are typically used for road construction and maintenance, which PHEV owners do not pay due to reduced gasoline consumption. For this reason, we do our cost analysis by parameterizing the cost of electricity. Similarly, although the average retail price of gasoline in Ohio in 2007 was $2.27/gallon [16], gasoline prices soared to much higher levels in 2008. Although prices have dropped from the highs seen then, this is largely attributed to the recent global recession with many expecting prices to rebound as economic activity increases.

It is worth noting that this cost analysis focuses on the uncontrolled charging scenario, since this is the most likely scenario when PHEVs first enter the vehicle fleet. Figure 13 summarizes the effect of gasoline and electricity prices on the relative operating cost savings of PHEVs over CVs.

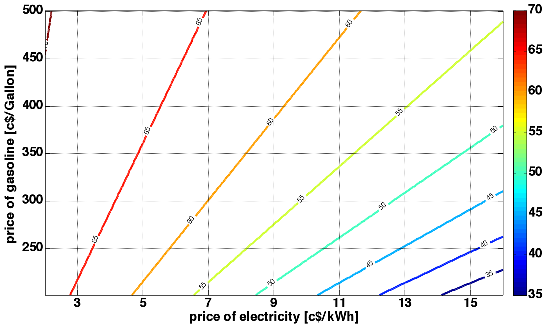

Figure 13: Savings in operation cost [%] of PHEV with respect to CV

Payback time

Payback time is an important factor in determining whether future consumers will decide to buy a PHEV. The basic tradeoff that the consumer faces is the higher upfront capital cost of a PHEV relative to the stream of driving cost savings due to reduced gasoline costs. Figure 14 and Figure 15 summarize the effect of gasoline and electricity prices on the payback time of a PHEV, relative to a CV, with a capital cost difference of $6,000 and $10,000 between the PHEV and CV. As discussed above, this analysis assumes a future scenario in which mass production of PHEVs and their batteries (which is expected to be the major driver of the higher cost of PHEVs) bring the price difference between a PHEV and CV to these levels.

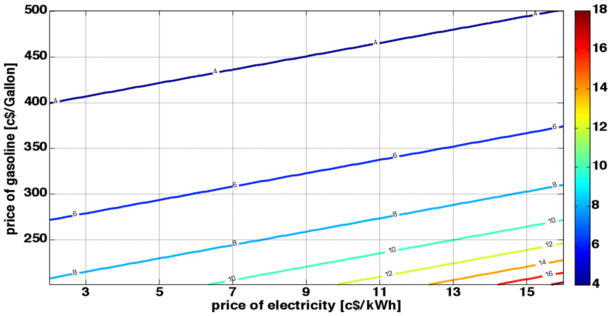

Figure 14: Payback time of a PHEV as a function of gasoline and electricity prices with PHEV costing an additional $6000 compared to a CV

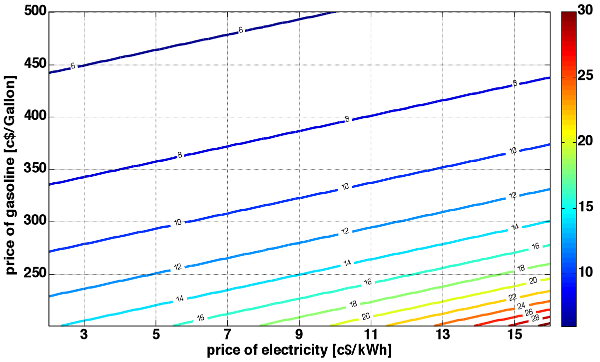

Figure 15: Payback time of a PHEV as a function of gasoline and electricity prices with PHEV costing an additional $10000 compared to a CV

CONCLUSIONS

In this study the Ohio power system has been modeled as a mixed integer program to analyze the impact that a PHEV fleet would have on it. Two different charging scenarios, a controlled charging and an uncontrolled one, have been modeled to estimate effects of the timing of PHEV charging. This analysis has focused on how PHEVs would affect net emissions and costs, and what impacts they would have on the grid load profile.

Results show that in the near future, the uncontrolled charging scenario is preferable—obtaining better gasoline saving and environmental impact. Furthermore, this scenario does not require complex communication and control systems between the power grid operator and vehicles to control the charging process. If in the future PHEVs reach a bigger market penetration, it will be necessary to verify if power grid capacity is sufficient to satisfy higher peak loads during afternoons and if transportation and distribution infrastructures will be able to transport energy from power plants to where vehicles will be plugged-in. Results also show how PHEVs could lead to substantial reductions in gasoline consumption of close to 70% relative to CVs, providing a initial step towards transportation electrification. Since electricity is less expensive than gasoline, the additional investment required to buy a PHEV could be repaid by great savings in operation costs. Nevertheless, federal and state incentives could be necessary to help PHEVs gain a foothold in the market due to their long payback-time.

Looking at environmental impact it is clear that even with a high penetration of coal in the Ohio power system, it could be possible to decrease greenhouse gasses (CO_2 emitted by a single vehicle in one year decreases by about 25%), as shown in other studies. Using cleaner sources of energy for electricity production will improve this benefit (for example, an analysis of PHEVs in Colorado showed a 40% reduction in per-vehicle emissions of CO_2 [2]) and avoid increases in SO_2 and NO_x emissions.

Future studies will have to focuses on smaller scale cases to verify what influence PHEVs will have on local infrastructures and what benefits could be achieved by vehicle to grid and other services. These types of services could also further increase the economic justification of a potential PHEV purchase. Other important aspects to be analyzed are how PHEV use can help support renewable integration and the effects of increased electricity demand due to PHEV charging on electricity prices.

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