POLITECNICO DI MILANO
Dipartimento di Ingegneria Energetica

Impact of Plug-in Hybrid Electric Vehicles (PHEV) in the Electricity Market Optimization

Relatore: Prof. Angelo Onorati
Correlatore: Dr. Vincenzo Marano

Tesi di laurea di:
Riccardo Fagiani Matr.719559

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Outline

Sommario

I Plug-In Hybrid Electric Vehicles (PHEVs) sono stati promossi come una possibile tecnologia per ridurre il consumo di carburante di veicoli terrestri, riducendo in questo modo le emissioni dovute ai sistemi di trasporto, i loro costi e la dipendenza dalle importazioni di greggio. Tutto questo è ottenuto utilizzando l'elettricità come fonte primaria di energia del veicolo, lasciando alla benzina un ruolo secondario di riserva.

L'impatto sulle emissioni e sui costi dei PHEVs è strettamente connesso a il mix energetico usato per generare elettricità, il quale a sua volta dipende da quando i PHEV sono ricaricati durante il giorno; permettendo ai PHEVs di ricaricarsi quando il carico sulla rete elettrica è più basso, controllati dall'amministratore della rete, si possono ottenere costi di ricarica inferiori e il carico massimo giornaliero sulla rete non viene incrementato. D'altro canto, permettendo ai propietari dei PHEVs di ricaricare le propie batterie quando ne hanno bisogno diminuisce ulteriormente il consumo di benzina ma provoca costi di ricarica superiori rispetto al caso precedente. Le emissioni inquinanti sono strettamente connesse al power mix del sistema elettrico, un grosso utilizzo di carbone per la produzione di corrente elettrica farà incrementare le emissioni di SO_2 con una leggera diminuzione delle emissioni di CO_2 ; al contrario, un sistema dove sono presenti impianti idraulici e nucleari può ottenere riduzioni delle emissioni inquinanti molto maggiori.

Questo lavoro si basa su un analisi compiuta sul sistema elettrico dell'Ohio per comprendere quale effetto avrebbe una flotta di PHEV sulla rete e il suo impatto ambientale. Sono stati analizzati due differenti scenari di carica, uno scenario di carica controllata dove l'amministratore della rete elettrica co-optimizza la carica dei PHEVs con il funzionamento della rete, e uno scenario di carica non controllata dove ogni veicolo viene ricaricato ogni qual volta è parcheggiato; per entrambi gli scenari sono stati considerati tre differenti livelli di penetrazione nel mercato di PHEVs, rispettivamente dell 1%, 3% e 5%. Il sistema elettrico dell'Ohio è stato formulato come un programma lineare misto intero (Mixed-Integer Program) scritto con AMPL e risolto con cplex 12.1 utilizzando l'algoritmo di risoluzione branch and cut. Il modello simula il dispacciamento dei generatori elettrici e decide quando le batterie dei veicoli sono ricaricate dello scenario controllato. Come avviene tipicamente nei mercati elettrici, il modello esegue i calcoli sul dispacciamento dei generatori per ogni giorno dell'anno con un intervallo orario.

Le simulazioni del modello sono poi state utilizzate per calcolare l'impatto economico e ambientale dei PHEVs, l'analisi considera tre differenti emissioni:

CO_2, SO_2 e NOx, e tiene conto delle emissioni di due differenti fonti: le emissioni prodotte dai generatori e le emissioni dei gas di scarico dei singoli veicoli. Le emissioni dei veicoli sono state calcolate considerando le normative vigenti e la composizione chimica della benzina mentre le emissioni dei generatori sono ottenute partendo dai dati del CEMS (Continuos Emissions Monitoring System) per l'anno 2007 misurati dall' Environmental Protection Agency (EPA). I costi di generazioni sono calcolati basandosi sul rendimento stimato per ogni generatore e sui costi dei combustibili bruciati da ognuno di essi, il rendimento è stato calcolato partendo dai dati del CEMS. Le caratteristiche di guida per ogni veicolo si basano su dati empirici, sono poi state elaborate con il modello di simulazione del veicolo ADVISOR per stimare il consumo di benzina e di elettricità che un PHEV avrebbe se guidato secondo queste caratteristiche.

L'analisi mostra che l'uso dei PHEVs può portare in entrambi gli scenari di carica ad una riduzione del consumo di benzina di circa il 70% per ogni veicolo se comparato con uno convenzionale, inoltre i PHEVs possono ridurre del 50% i costi di operazione di un singolo veicolo, in funzione dei prezzi di benzina ed elettricità. Da un punto di vista ambientale una strategia di carica non controllata otterrebbe i migliori risultati riducendo la quantità di CO_2 emessa in un anno da un singolo veicolo di più di una tonnellata. A cuasa del fatto che gran parte dell'elettricità in Ohio è prodotta bruciando carbone, le emissioni di NOx e SO_2 di un PHEV risulteranno maggiori rispetto a quelle di un veicolo convenzionale; in un anno un veicolo convenzionale emette circa 1 kg di NOx mentre le emissioni di SO_2 sono trascurabili, un PHEV ricaricato in modo non controllato emette intorno ai 5 kg di NOx e 10 kg di SO_2.

Parole chiave: Plug-In Hybrid Electric Vehicle (PHEV), ricarica, interazione, rete elettrica, emissioni, costi.

Abstract

Plug-In Hybrid Electric Vehicles (PHEVs) have been promoted as a potential technology that can reduce vehicles' fuel consumption, decreasing transportation-related emissions, overall costs and dependence on imported oil. This is obtained using electricity as primary source of power to run vehicle, leaving to gasoline a secondary backup role.

The net emissions and cost impacts of PHEV use are intimately connected with the electricity generator mix used for PHEV charging, which will in turn depend on when during the day PHEVs are recharged; allowing PHEVs to recharge during off-peak period controlled by the grid administrator, leads to lower charging costs without adding loads on the power grid when it could be difficult to supply them. On the other hand, allowing individual vehicles owners to recharge whenever they need it decrease oil consumption but leads to a generation cost increase compared to the controlled charging scenario. Pollutant emissions are tightly connected to the energy mix of the power system, a huge use of coal for power generation will increase SO_2 transportation-related emissions with a small diminution of CO_2; on the contrary, a power system where nuclear and hydroelectric plants are present can obtain a more important reduction of pollutants emissions.

This work is based on an analysis made on Ohio power system to estimate which effect would have a fleet of PHEV on the grid and its global environmental impact. It has been focused on two different charging scenarios, a controlled charging scenario where the grid administrator co-optimize PHEVs charging load with its operation, and an uncontrolled scenario where each vehicle is recharged whenever it is parked; for each of these two scenarios different levels of PHEV penetration in the market has been considered, 1%, 3% and 5%. Ohio power system is formulated as a mixed-integer program (MIP) 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 as well as the dispatch of PHEV to charge when not being driven in the controlled charging scenario. As is typical of day-ahead electricity markets, the unit commitment model has one hour day planning horizon with an hourly time-step for the commitment and dispatch variables.

The model simulations are then used to evaluate the cost and emissions impact of PHEV use, the analysis considers three different emissions: CO_2, SO_2 and NOx considering emissions from two different sources: generator emissions and vehicles tailpipe emissions. Tailpipe emissions are estimated using emissions regulations and gasoline chemical composition while generators emissions rates are estimated using 2007 Continuous Emissions Monitoring System (CEMS) data from the U.S. Environmental Protection Agency (EPA). Generation cost are calculated based on estimated generator heat rate and fuel cost, heat rate were estimated based on historical CEMS data. Vehicle driving pattern were based upon empirical driving data and then coupled with the ADVISOR vehicle simulator model to estimate gasoline and electricity that a PHEV would use if driven according to these profiles.

The analysis shows that PHEVs use could result in major reductions in gasoline consumptions of close to 70% per vehicle compared to a conventional vehicle under both charging scenarios, moreover PHEVs could obtain a decrease of about 50% in operation cost for a single vehicle, depending on gasoline and electricity prices. On the environmental side an uncontrolled charging strategy will obtain best results decreasing annual CO_2 emitted by a single vehicle more than 1 ton (around 24%). Due to a huge coal penetration in the Ohio energy mix, SO_2 and NOx emissions of a PHEV will increase compared to conventional vehicles; in one year a conventional vehicle emits around 1 kg of NOx and negligible SO_2 emissions, a PHEV charged in an uncontrolled way will emit around 5 kg of NOx and 10 kg of SO_2.

Key words: Plug-In Hybrid Electric Vehicle (PHEV), charge, interaction, power grid, emissions, costs.

Table of Figures

List of Tables

Terminology

AER: All Electric Range;
CD: Charging Depleting;
CEMS: Continuous Emissions Monitoring System;
CS: Charging Sustaining;
CV: Conventional Vehicle;
DOE: Department of Energy;
EIA: Energy Information Administration;
EM: Electric Motor;
EPA: Environmental Protection Agency;
ERCOT: Electricity Reliability Council of Texas;
EU: European Union;
EV: Electric Vehicle;
GHG: Greenhouse Gases;
GPS: Global Positioning System;
HEV: Hybrid Electric Vehicle;
ICE: Internal Combustion Engine;
IEA: International Energy Agency;
IPCC: Intergovernmental Panel on Climate Change;
LMP: Locational Marginal Price;
LP: Linear Programming;
LSE: Load Serving Entities;
MIP: Mixed Integer Program;
MISO: Midwest Independent System Operator;
NRC: National Research Council;
OPEC: Organization of the Petroleum Exporting Countries;
PHEV: Plug-In Hybrid Electric Vehicle;
SOC: State of Charge;
U.S.: United States;
V2G: Vehicle to Grid Services.

1. Introduction and motivation

Preface

Liquid hydrocarbon fuels derived from petroleum provide ninety-five percent of the primary energy consumed in the transportation sector worldwide. There is no other sector which is so dependent on a single source of primary energy. The transport sector as a whole is responsible for one-quarter of energy-related greenhouse gas emissions worldwide, the second largest sectoral contribution after power generation. Despite growing awareness of the dangers and causes of global warming, the climate change impacts of transport have, until now, played an extremely minor role in the development of alternative fuels (1).

In order to avoid the worst impacts of climate change, the global economy must as soon as possible change towards decarbonisation and sustainability. While for the power sector some sustainable low-carbon generating options exist, many of which are becoming increasingly competitive as climate change policies penalize carbon dioxide emissions worldwide, the transport sector looks set to increase its carbon footprint.

Energy efficiency is by far the cheapest and most immediate means to reduce primary energy consumption and greenhouse gas emissions, and will therefore be an important goal in all sectors and applications. In addition to energy efficiency, there is an urgent need to accelerate the development and commercialization of low-emissions technologies. However, while the automotive transport sector remains firmly stuck to the internal combustion engine, the only improvements can come from incremental vehicle efficiency.

Vehicles which are capable of receiving electricity from the grid will directly benefit from future emissions reductions and diversification of primary energy sources in the power sector. Thus grid-connected solutions such as battery-electric vehicles and plug-in hybrid electric vehicles will grow successively cleaner while the energy system as a whole becomes more secure. Even with today's carbon-intensive energy mix, the electrification of automotive sector can produce an immediate reduction of greenhouse gases, an improvement in urban air quality and noise levels, and lower operating costs (2). The widespread adoption of electric powertrain technology will transform automotive mobility by helping to reduce the world's dependency on liquid hydrocarbon transportation fuels. It will create an explicit link between the power generation and transport sectors, extending the range of sustainable renewable energy options which can propel the world's motor vehicles. Furthermore, the electrification of automotive sector will improve global security by substantially reducing the sector's ninety-five percent dependency on crude oil, which has such a highly destabilizing impact on the world today.

Geographically, a few key markets will be keen to adopt grid connected vehicles: North America, the EU and Japan. The U.S. represent the world's largest automotive market, number one consumer of crude oil, and currently are trying to reduce their import dependence; Europe is also a huge automotive market and like the U.S. is looking for ways to decrease crude oil import dependency. Japan imports one hundred percent of its crude oil supplies, and currently leads the world in hybrid vehicle technology, seen by many as an important step towards grid connectivity.

An environmentally sustainable transportation sector will not be achieved through electrification alone. Additional measures to reduce overall demand through smarter urban planning, encouraging mass transit, from road to rail and car sharing will make necessary and significant contributions. However, with around eight hundred million motor vehicles in the world today and this number growing inexorably, road-based transport will continue to play a vital role in the delivery of essential mobility services.

This work goal is to demonstrate how automotive electrification can lead to a decrease of oil consumption and to a more efficient transportation system with less pollutant emissions.

Oil transport domination and oil security

Oil's great advantage is its physical state at ambient conditions: it is a liquid. This property gives it a good energy density combined with ease of application, oil it is also incredibly cheap considering the extraordinary benefits human beings have enjoyed since the beginning of Oil Age. Today, crude oil is the most important source of primary energy in the world, about 40% of the total, and its supremacy looks unassailable for the future, as shown in Figure 1.1.

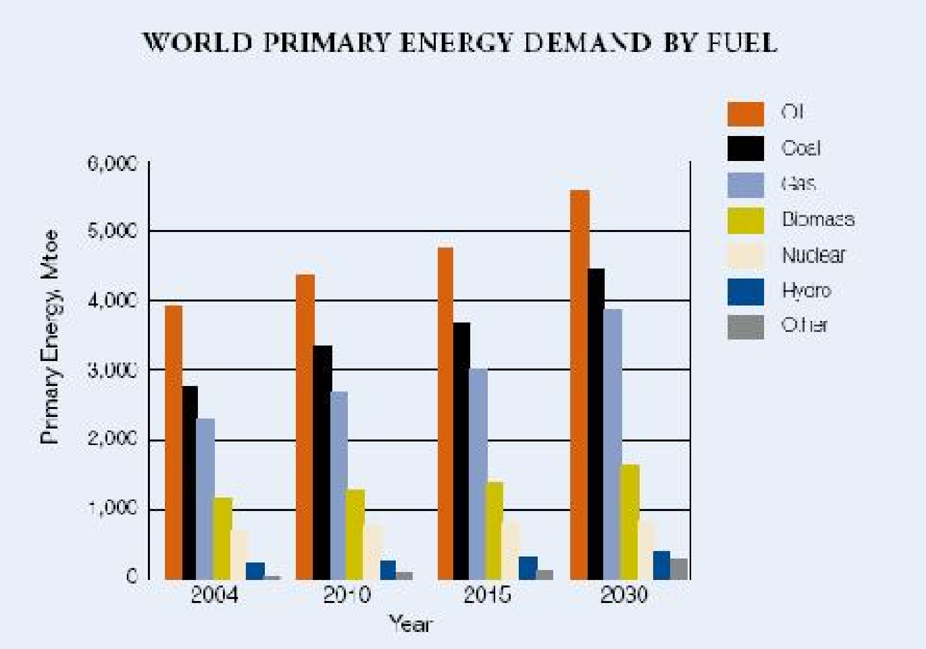


Figure 1.1: Projected evolution of the world's primary energy demand by fuel (1).

Approximately 95% of the primary energy used for transportation derives from crude oil, Figure 1.2; this level of fuel specificity is unique to the transportation sector, which is consequently immune to the type of competition that characterizes the power sector. The most important reason for automotive sector dependence on liquid hydrocarbon fuel is that the majority of vehicles in use today rely upon the internal combustion engine that uses liquid hydrocarbons to run.

The most important power source for transport is concentrated in relatively few countries as shown in Figure 1.3 more than 65% of proved reserves are located in the eleven OPEC (Organization of the Petroleum Exporting Countries) member states, with a further 7% in the Russian Federation (3). The International Energy Agency (IEA) projects that the US, China and India will be the top three oil consuming nations in 2030(1). Together they currently have just 4% of proved reserves, and all are significant net importers.

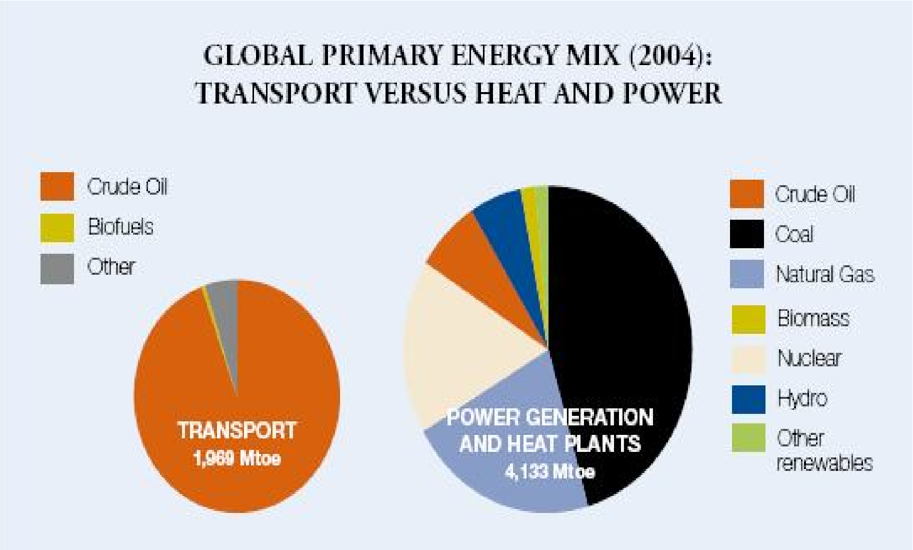


Figure 1.2: Comparison of the global primary energy demand mixes of the transport sector and heat and power plants (1).

Meanwhile, the European Union's share of proved reserves is less than 1%. Diversification of supply should be the only way to security of supply, but the uneven geographical distribution of conventional crude oil resources represents a considerable barrier to diversification. Furthermore in some of oil-rich countries were those resources have been discovered before the establishment of robust political institutions there are problems due to political instability; this geopolitical reality leads to market uncertainty and price volatility.

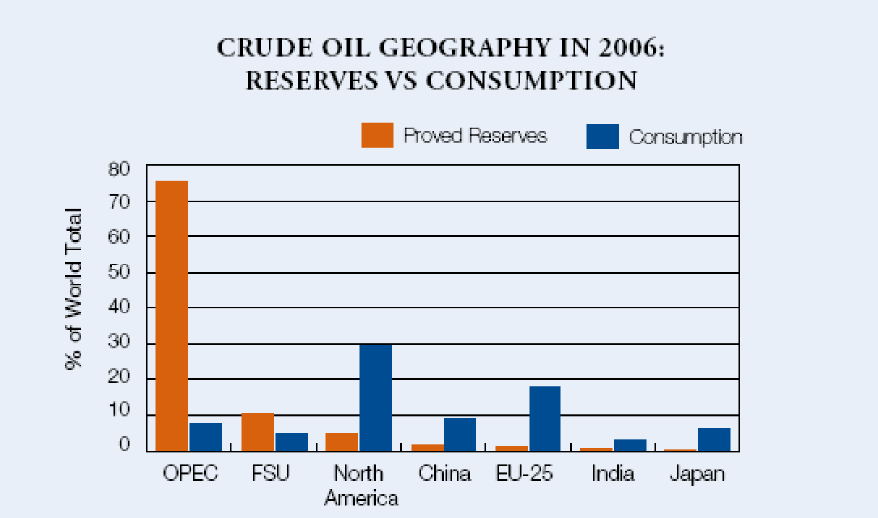


Figure 1.3: Geographical distribution of conventional crude oil resources (3).

Figure 1.4 illustrates how oil prices tend to fluctuate in response to significant events. Oil price shocks, such as that connected with the Iranian revolution of late 1970s, have historically stimulated massive increase in exploration and production and investment in alternative technologies.

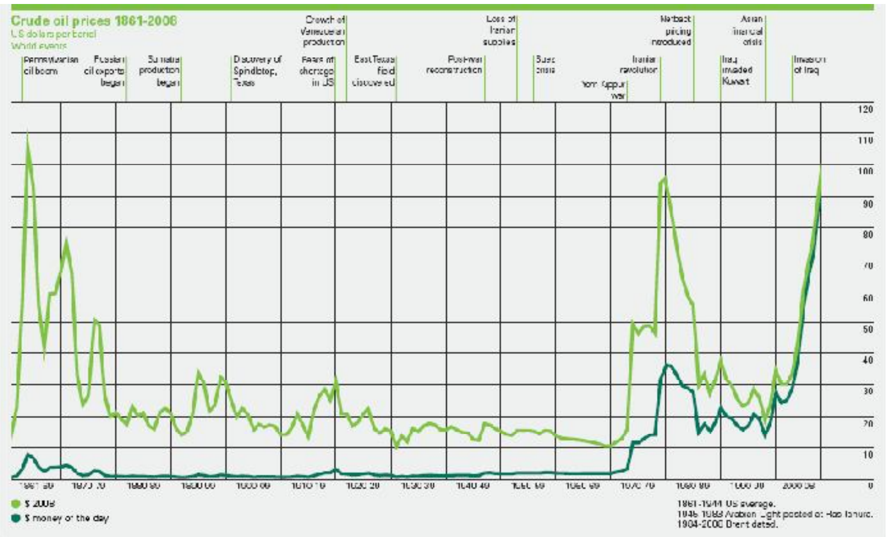


Figure 1.4: Evolution of post-WWII crude oil price (3).

Environmental aspects

Global warming is one of the biggest challenges facing the world today. Research strongly indicates that as the planet's average surface temperature climbs so will sea levels as glaciers and ice-sheets melt, potentially flooding coastal areas. The sea level has risen ten to twenty centimeters in the past century and scientists estimate that it will rise up to one meter by 2100(4). While some areas of the globe will have too much water, others will not have enough. In early 2007, the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) gathered together and summarized the results of hundreds of scientific studies since 2001 which have investigated the causes and the effects of global warming(5). The IPCC report drew the conclusion that in order to prevent huge climate changes, greenhouse gases (GHG) emissions that are currently rising at a rate of 3% per year has to decline before 2015. In order to maintain a safe climate, 85% of global CO_2 emissions must be eliminated by the middle of this century (5).

The small, widely dispersed, mobile nature of transportation emissions represents a challenge in the battle against CO_2 production that causes climate change. It also partly explains why the majority of efforts to reduce GHG emissions have focused on the bigger, stationary sources which characterize the power sector. However to better decrease global GHG emissions it has to be found an alternative to traditional internal combustion engine that can decrease oil consumption and emissions connected to transportation sector. Less emissions coming from transports combined with a huge penetration of renewable and sustainable energy sources in the power sector could lead to a global reduction of GHG emissions avoiding disastrous climate changes.

Different alternatives have been proposed to reduce pollutants emissions and oil dependence of the transport sector:

- Use less pollutant fuels like hydrogen or biofuels with the traditional Internal Combustion Engine (ICE), introducing minimal changes to it in order to work with a new fuel;
- Change the ICE with a different propulsion system like fuel cells, electric engine or compressed air engine.
- Run the vehicle with two different sources of energy and two different engines, for example placing together an electric engine with an ICE as it happens in Hybrid Electric Vehicles (HEVs).

This work focuses on Plug-In Hybrid Vehicles (PHEVs) that are hybrid electric vehicles with the ability to charge their batteries from the power grid. In the last years has been introduce in the market first HEVs that could obtain better fuel consumption; they are a first step to the electrification of the automotive sector that seems to be the best solution for decrease transportation related emissions. PHEVs are a further step in this direction giving the possibility to cover longer distance using electricity instead of gasoline. Unlike hydrogen fuel cell vehicles, PHEVs can be deployed in the marketplace without simultaneously building an infrastructure to supply the energy to operate them, and unlike all-electric battery vehicles, drivers will not have to worry about charging the batteries on a long trip.

PHEVs represent the most promising approach to introducing the significant use of electric transportation that has three important aspects:

- Potentially offers consumers a lower-cost alternative gasoline;
- Decrease greenhouse gas emissions from the transportation sector;
- Reduces dependence on imported petroleum.
- Improve the reliability of the power grid.

Unlike battery-only electric vehicles (EVs), PHEVs do not require on-demand recharging; if the driver misses a charge, the vehicle can run burning gasoline as a standard hybrid vehicle. The main issue against PHEVs starting to be spread in the market is the additional investment cost needed to buy this kind of vehicles; today for a battery pack of 10kWh capacity, that allow a PHEV to run completely electric for about 60 km, a cost of 17500$ is estimated (2). Also if the battery is smaller and less costly for a PHEV than for an EV, the cost of Li-ion batteries is currently very high, and PHEVs need a breakthrough in battery technology to become economically competitive.

A low PHEV penetration in the market will add a low charging load on the grid that could easily managed by the grid administrator, however if a large number of vehicles start run on electricity there could be some issues for the power grid; more generation capacity will be required to satisfy charging loads of each vehicle, in particular if charging is done during the afternoon when load on the grid is already high. If transportation related emissions will decrease, on the other side there will be an increase in generators pollutants emissions, this emissions then will be strictly depending on which kind of generator is used to produce electricity. For these reason the automotive and the electric power sector as to be considered as a single system, and analyze them together to verify the global impact that a PHEV fleet will have on it.

This study focuses on the impact that a fleet of PHEVs would have on the Ohio electric power system. Using electricity instead of burning gasoline will shift the production of pollutants from the vehicle's internal combustion engines to the big power plants; so the environmental impact of PHEV use and its dependence on the power mix generation present in Ohio will be analyzed.

Finally will be considered the economical aspect of these vehicles and if they will be profitable for a future customer or if financial aids will be needed to spread them in the market.

2. Plug-In Hybrid Electric Vehicles

A Plug-in hybrid vehicle is a hybrid vehicle with ability to be recharged from the grid; Figure 2.1 shows PHEV schematics. The battery is discharged while driving and then it is recharged from the grid when the vehicle is parked. The ability of recharging allows the vehicle to be run in pure electric mode; the Department of Energy (DOE) defines All Electric Range (AER) as the distance traveled in electric mode (engine switched off) on standard driving cycles (6). A hybrid typically has AER of 2-5 miles (3-8 km) while a PHEV can provide AER from 10 to 40 miles (16 to 64 km) kilometers (6). PHEVs are defined PHEV-10, PHEV-20, PHEV-30 or PHEV-40, based on the AER meaning that they could be driven for 10, 20, 30 or 40 miles (16, 32, 48, 64 km) without burning gasoline. The external charging ability also allows using battery and the electric motor more frequently and sharing more power with the engine. Thus, the engine is used at its best operating region for more time as compared to hybrid vehicle. Therefore, the PHEV can provide better fuel economy. Plug-in hybrid vehicle architecture is exactly same as a hybrid vehicle consisting of an electric drive, and engine except the size of engine is smaller, and motor and battery are bigger. A typical hybrid would carry a battery of 1-3 kWh energy where a PHEV with 30 kilometers range would require a 6 kWh battery (7). Use of larger battery also allows reducing the engine size and giving more flexibility for tuning the engine in its best operating region. Apart from the power train requirements, a PHEV requires charging unit for the battery and interface for the grid. Similar to hybrid, PHEV can be designed using many combinations available; principal configurations used are:

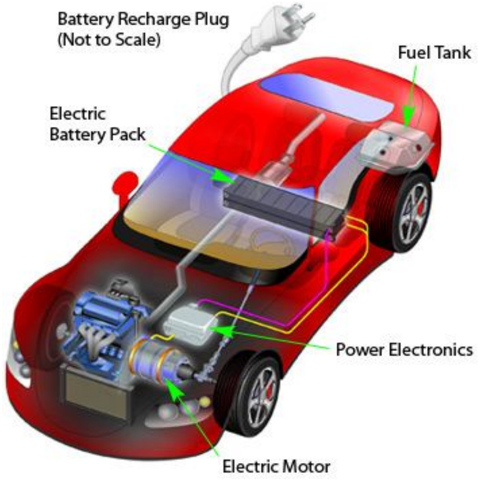


Figure 2.1: PHEV schematics.

- series Hybrid;
- parallel Hybrid;
- series-parallel Hybrid.

Hybrid configurations

Series Hybrid

The series configuration, see Figure 2.2, is considered to be closer to a pure electric vehicle. In fact, the electric motor drives individually the vehicle while the internal combustion engine is connected to a generator and is operated as an auxiliary power unit to extend the driving range of a pure electric vehicle. In this configuration, the engine output is first converted into electricity trough a generator that can either charge the battery or bypass the battery to propel the wheels via the same electric motor. Regenerative braking is possible using the electric motor as a generator.

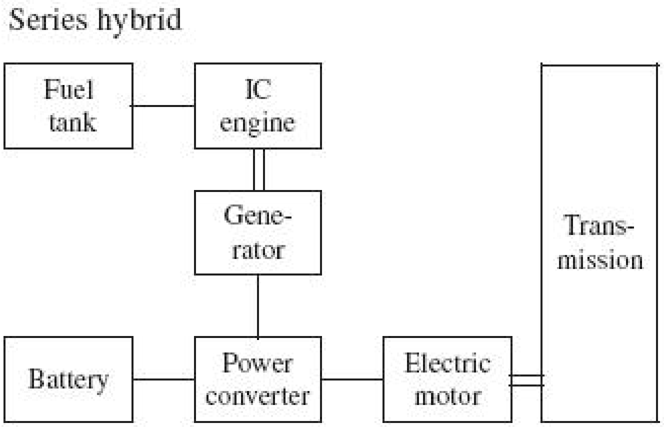


Figure 2.2: Series hybrid configuration.

Due to the decoupling between the engine and the transmission, the engine operations are not related to the vehicle power requirement, thus it can be always operated in its most efficient region. In addition, because the engine is mechanically disengaged, the transmission does not require a clutch. The drawback of series configuration is the need of three propulsion devices, namely the Internal Combustion Engine (ICE), the generator and the electric motor. In addition, in series architectures, at least the Electric Motor (EM) has to be sized in order to satisfy alone the maximum power request. Therefore, series hybrids show high vehicle mass and need for expensive components.

Parallel Hybrid

Differing from the series hybrid, parallel hybrids are ICE-based vehicles with an additional electric path. As shown in Figure 2.3, in parallel architecture only two propulsion devices are needed, namely the ICE and the electric motor and both ICE and EM can satisfy the power request at the wheels either alone or combined. This capability is extremely useful to optimize the power distribution between the paths.

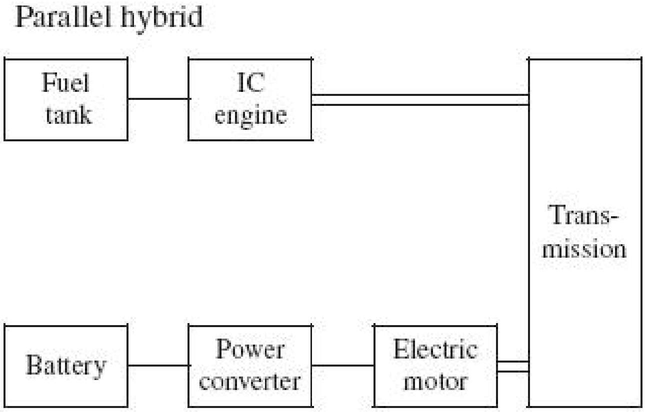


Figure 2.3: Parallel hybrid configuration.

In addition, the engine can be turned off at idle and the electric motor can assist in case of high power demand, such as during the acceleration phases. Both the engine and the electric motor can be sized for half of the maximum power, allowing for downsizing the engine and further reducing fuel consumption. Since the engine is mechanically coupled to the drivetrain and works on the same shaft, the architecture includes a clutch that reduces the energy conversion efficiency.

Series-parallel Hybrid

The series-parallel configuration, see Figure 2.4, put together the features of both series and parallel hybrids. As in parallel hybrid, one electric machine is used as prime mover or for regenerative braking while the second and smaller electric motor is principally used to recharge the battery or for start-stop operations. This allows for more degree of freedom in the optimization of the energy management strategy.

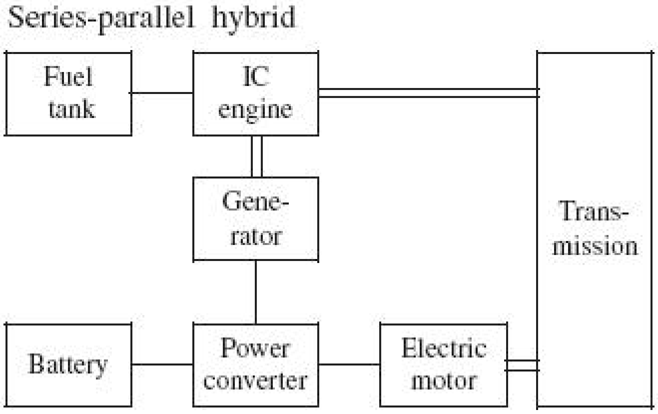


Figure 2.4: Series-parallel hybrid configuration.

PHEV energy management

The energy management algorithms for PHEVs are crucial for vehicle performance; the capability to operate in pure electric mode and to recharge the battery from an external source increases the complexity of the energy management problem. PHEV control problem is similar to the hybrid vehicle control, with the main difference being that the batteries used for PHEV applications are almost completely depleted (usually 95-25 % SOC) and then charged from external sources. These constraints create many difficulties in the optimization; trip length and initial SOC are key factors to determine fuel economy: while conventional and hybrid vehicles have a constant fuel economy at increasing distance over the same driving pattern, results for PHEVs show a decrease in fuel economy at increasing distance.

The control of PHEV follows same trends as a hybrid vehicle but includes more constraints and different objectives. Both the controllers decide the power sharing between internal combustion engine and electric motor by deciding the engine on/off timing. One common objective is to reduce fuel consumption and emissions. Controllers for PHEV are designed to operate in two modes, charge depleting (CD) when battery state of charge (SOC) is greater than some minimum value and charging sustaining (CS) when battery SOC is at minimum value or the electric motor cannot supply the required demand. The basic controllers vary mainly in the strategy used to choose these modes. The charge depleting mode is selected when motor can supply the request power, or when zero emission modality is required by law, and battery SOC is greater than a minimum. The charge sustaining mode is necessary when battery SOC drops to certain minimum value or to preserve battery charge for future use.

PHEV control can be classified in two main categories:

- EV mode control
- Blended mode control

In EV mode control, the vehicle operates in charge depleting mode as long as the electric motor can supply the requested power and battery SOC is greater than a designed threshold. Once the battery depletes to a minimum SOC the controller switches to charge sustaining mode. In blended mode control, the engine is used consistently with the electric motor during the entire driving trip. The power sharing between the motor and the engine is optimized such that the SOC decreases during the driving trip and reaches the minimum value only at the end of the trip.

Figure 2.5 shows a comparison of SOC profiles for EV and blended mode control strategies along with the SOC for a hybrid architecture;

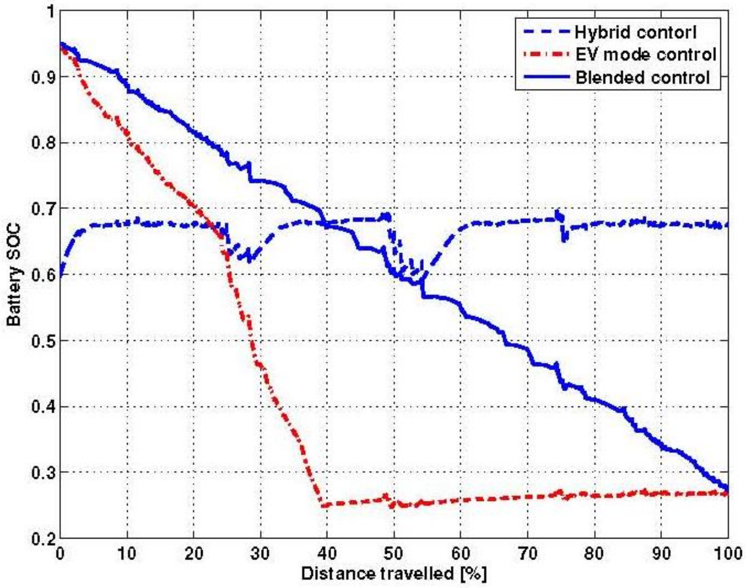


Figure 2.5: Comparison of battery SOC profile for different control strategy.

Figure 2.6 shows the engine "on time" for these two modes. It is clear that the engine is used consistently in the blended mode control, while it is used extensively only at the end of trip for EV mode control. Obviously, the blended mode requires a priori knowledge of the driving pattern, thus needing sophisticated control algorithms, using GPS information and historical traffic data to characterize the driving pattern and using it for control strategy optimization (8).

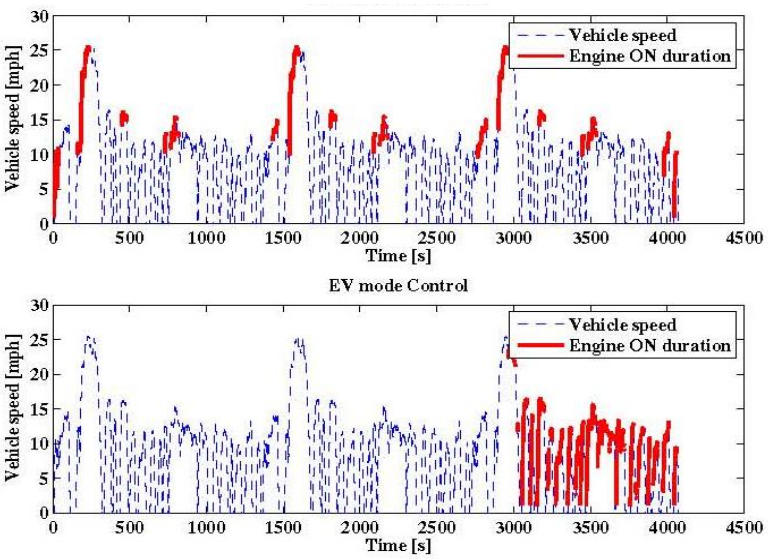


Figure 2.6: Engine on time. Comparison between EV mode control and Blended mode control.

Apart from the constraints and optimization issues for hybrid, PHEV requires more sophisticated algorithms and constraints. The controller may need to consider fuel and electricity prices, availability of charging station, requirement of all electric range, etc. Thus, PHEV control is a more complex issue to solve.

PHEV batteries

Energy storage is fundamental for PHEVs, hybrid and electric vehicles operation; the prospects for large scale market introduction of these vehicles are tied closely to the availability of energy storage systems that has to provide high performance, be durable and safe, and meet severe cost constraints.

The electrical energy storage units must be sized so that it could store sufficient energy (kWh) and provide adequate peak power (kW) for the vehicle to have a specified acceleration performance and the capability to meet appropriate driving cycles. For those vehicle designs intended to have significant AER, the energy storage unit must store sufficient energy to satisfy the range requirement in real-world driving. In addition, the energy storage unit must meet appropriate cycle and calendar life requirements.

In the case of the charge sustaining hybrid-electric vehicle using an engine as the primary energy converter and a battery for energy storage, the energy storage unit is sized by the peak power from the unit during vehicle acceleration. In most cases for the charge sustaining hybrid vehicle designs, the energy stored in the battery is considerably greater than that needed to permit the vehicle to meet appropriate driving cycles. However, the additional energy stored permits the battery to operated over a relatively narrow SOC range (often 5%–10% at most), which greatly extends the battery cycle and calendar life. In principle, determination of the weight and volume of the battery for a charge sustaining hybrid depends only on the pulse power density (W/kg) of the battery.

Sizing the energy storage unit for plug-in hybrids is more complex than for charge sustaining hybrids. This is the case because of the uncertainty regarding the required all-electric range of the vehicles. In simplest terms, AER means that the hybrid vehicle can operate as a battery powered vehicle for a specified distance without ever operating the engine. In this case, the power of the electric drive system would be the same as that of the vehicle if it had been a pure electric vehicle and the energy storage requirement (kWh) would be calculated from the energy consumption (Wh/km) and the specified AER. Hence, for large AER, the battery would likely be sized by the energy requirement, and for short AER the battery would be sized by the power requirement.

For plug-in hybrids, battery cycle life also becomes an important issue. The battery will be recharged from a low state-of-charge (after deep discharges); as a result, the battery cycle life requirement for plug-in hybrids will be more demanding than for an electric hybrid vehicle, and minimum of 2000–3000 cycles will be required. So both in terms of power and cycle life, the plug-in hybrid applications are more demanding for the battery than the electric hybrid vehicle.

Status of battery technology

The following technologies are analyzed:

- Nickel metal hydride (NiMH);
- Lithium ion (Li-Ion).

Most of the HEV tested and marketed to date have used nickel metal hydride batteries. The development of lithium–ion batteries has progressed to the state that strong consideration is being given to the use of those batteries in both PHEVs and HEVs; however this technology is still studied to verify batteries behaviors during their complete working life.

Li-Ion batteries can be constructed from a wide variety of materials, allowing battery developers to pursue several different paths. The main Li-Ion cathode material used for consumer applications (e.g. laptop computers and cell phones) is lithium cobalt oxide. However, due to safety concerns with using this chemistry for automotive applications, several alternative chemistries are being testing for PHEVs; NiMH batteries instead are used for most HEVs currently sold in the market. The primary advantage of this chemistry is its proven longevity in calendar and cycle life, and overall history of safety. However, the primary drawbacks of NiMH are limitations in energy and power density, and low prospects for future cost reductions.

Of the chemistries currently being considered for PHEV application, Li-Ion is best suited for the power and energy density goals of PHEV. Although NiMH batteries may be suitable for a less ambitious PHEV design with lower AER, Li-Ion technologies are still superior to NiMH in potential for lower cost in the future. However, Li- Ion is not yet firmly established for automotive applications, and development must overcome issues of longevity and safety in order to achieve commercial success. Li-Ion battery has more than double the power density and more than 50 percent greater energy density than NiMH battery. Figure 2.7 shows that Li-Ion batteries could be the preferable for PHEV combining a energy density with power density.

The NiMH battery is nearing fundamental practical limits (estimated at ~75 Wh/kg on a pack level). Over the next several decades, lithium-ion chemistries instead have been predicted to be capable of achieving specific energies as high as 200 Wh/kg on a cell basis (9).

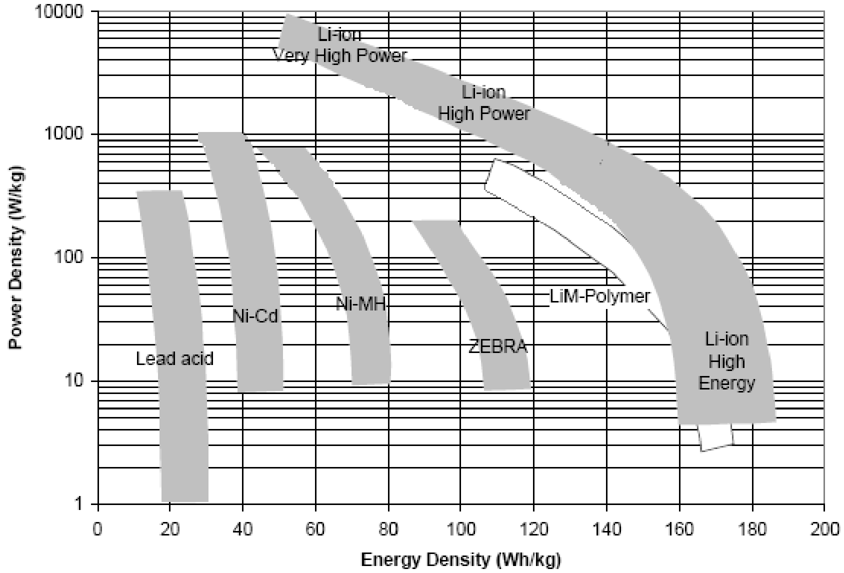


Figure 2.7: Potential of battery technology.

PHEV state of the art

Nowadays there are no PHEVs sold in the market, the only PHEVs produced are for investigation purpose and are still concept cars. In the near future many car industries are going to introduce in the market some PHEVs, the first to do that will be General Motor followed by Toyota; they seems the most ahead with their prototype at this time and will lunch Chevy Volt and the Prius PHEV in the next two years.

Nevertheless some companies like Hymotion offer the possibility to convert a conventional hybrid Toyota Prius to a PHEV with an additional investment of around 10000$. Hymotion aftermarket kit is composed by an additional pack of batteries of 5kWh that can be recharged from a 120V outlet in 5 hours shown in Figure 2.8, and in some modification to the vehicle's control system. This second pack of batteries allows the Prius to run on electricity improving the fuel consumption of the vehicle; the control strategy is different from a designed PHEV and uses both the internal combustion engine and the electric motor until the battery is completely discharged, at that point the control system switches to a charging sustaining modality as it works for the no-modified Prius (10).

Figure 2.8: Hymotion additional battery pack.

Some Prius have been converted in the U.S. in the last years using these aftermarket kits, many of these were converted for research purpose as it was done at the Center for Automotive Research (CAR) at the Ohio State University, as shown in Figure 2.9.

Figure 2.9: The plug-in Prius at the Ohio State University.

Chevy Volt

Chevy Volt will be the first PHEV entering the market by the end of 2010 by General Motor; it will be a series hybrid with an All Electric Range (AER) of 60 kilometers guaranteed by a lithium-ion battery pack of 16kWh. Chevy Volt will be use an EV mode control, when batteries will reach the end of their charge the 1.4 liter engine will be switched on to recharge them; being a series hybrid the engine will be used just to recharge batteries and will not help the electrical motor run the vehicle as it happens in parallel hybrid configuration (11).

General Motors announced on January 2010 that Volt will be sold initially in California, Michigan and in the suburbs of Washington; General Motor has also developed an agreement with District of Columbia utility companies Pepco and

Dominion to take delivery Chevy Volt fleet test vehicles. These vehicles will join a total fleet of 100 cars in the U.S that will remain in the hands of utility companies for a demonstration and learning project funded by a 30$ million Department Of Energy (DOE) grant (11).

Figure 2.10: Chevy Volt as presented on Chevrolet web site.

General Motor also reports they have tested the 80 pre-production Volts on over 400,000 test kilometers, and that some of those cars are in 24 hour/7 day per week operation. Cars have been tested in the extreme heat of Death Valley and the extreme cold of northern Canada. 300 pre-production battery packs have already been built. Pricing of Volt has not been announced by General Motor yet.

Toyota Prius Plug-in Hybrid Concept

On December 2009, a Plug-In version of Toyota Prius made his debut in the United States at the Los Angeles Auto Show. Based on third generation Prius, the vehicle expands Toyota's Hybrid Synergy Drive technology with the introduction of a first generation lithium-ion battery that enables all-electric operation at higher speeds and for longer distances than the conventional hybrid Prius. The vehicle is target to achieve an AER of 20 kilometers and will be capable to run at 90 km/h in electric mode. The strategy control used will be the EV mode control, so that for longer distance the future PHEV Prius will revert to a conventional hybrid running in charge sustaining mode.

Figure 2.11: Prius PHEV Concept presented at Los Angeles Auto Show, December 2009.

During 2010 350 vehicles will begin delivery between Europe and Japan while other 150 will arrive in the US in support to government programs for market and costumer analysis and technical demonstration. On the costumer side this program will allow Toyota to gather real world vehicle-use feedback to better understand costumer expectations for plug-in technology. On the technical side, the program aims to confirm the overall performance of first-generation lithium-ion batteries technology. All vehicles will be equipped with data retrieval devices which will monitor activities such as how often the vehicle is charged and when; whether the batteries are depleted or being topped off during charging; trip duration, all-EV driving range, combined mpg and so on.

"This program is a necessary first step in societal preparation, in that it allows us the unique opportunity to inform, educate and prepare customers for the introduction of plug-in hybrid technology," said Irv Miller, TMS group vice president, environmental and public affairs. "When these vehicles come to market, customers must understand what to expect and if this technology is the right fit for them."

The battery powering the Prius PHEV is the first lithium-ion drive-battery developed by Toyota and its joint venture battery production company, Panasonic Electric Vehicle Energy (PEVE). In the end of 2009, PEVE began producing the first of more than 500 lithium batteries on a dedicated assembly line at its Teiho production facility in Japan. This first-generation lithium battery has undergone more than three years of coordinated field testing in Japan, North America and Europe in a wide variety of climatic environments and driving conditions. Using approximately 150 conventional hybrids (mostly Prius), the field test vehicles logged well over a million combined miles. In the end, the battery was deemed both reliable and durable, confirming that it could indeed be used in conventional hybrid applications in the future, depending on further developments in cost reduction. The battery will now be placed into service in the 500 Prius PHEVs dedicated to Toyota's global demonstration program which begins in December. Operating in a more severe charge-depleting mode, the battery's overall performance in a broad range of vehicle-use applications will be confirmed (12).

Future market penetration forecast

For future analysis it is important to know how many PHEVs will be sold in the market to estimate the impact they could have on the power grid and their global environmental benefits. In a previous analysis the National Research Council (NRC) proposed two possible future PHEVs market penetration scenarios (2):

1. Maximum practical penetration scenario;
2. Probable penetration scenario.

Maximum practical penetration case

This scenario assumes that manufacturers are able to rapidly increase production and that consumers find these vehicles acceptable. The Maximum Practical scenario would lead to approximately 240 million PHEVs on the road in the U.S. by 2050, the end of the scenario, period as shown in Figure 2.12. Such rapid penetration would require strong policy intervention because PHEVs will cost significantly more than comparable conventional and hybrid vehicles. At current gasoline prices, the fuel savings will not offset the higher initial cost. This policy intervention could be made in a variety of ways: mandates to vehicle manufacturers; subsidies to the purchasers of PHEV to offset the additional costs of the vehicles; and taxes or restrictions on fuel.

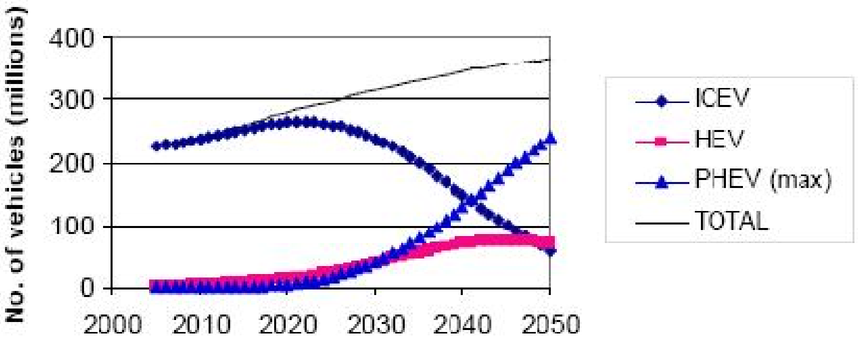


Figure 2.12: Number of vehicles in the market for each kind, maximum practical penetration scenario.

This scenario uses optimistic technology costs (for the year 2030 the additional investment cost need to buy a PHEV with an electric autonomy of 60 km is supposed of 8,800$) if costs fail to decline to those levels, this scenario would be prohibitively expensive.

Probable penetration case

The Probable scenario represents a PHEV market penetration that is more likely in the absence of strong market-forcing policies to supplement the policies already in place. Market penetration is slower than in the Maximum Practical scenario, PHEVs rise to 3 percent of new light-duty vehicles entering the U. S. vehicle fleet by 2020 and to 15 percent by 2035. This pace would lead to 110 million PHEVs on the road by 2050 as shown in Figure 2.13.

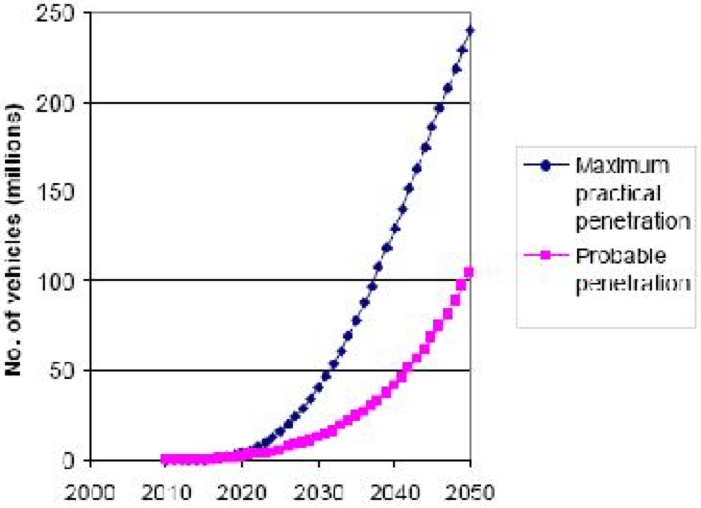


Figure 2.13: Number of PHEV sold in the market in the two different scenarios proposed.

3. PHEV grid interaction

The U.S. is currently the largest consumer of energy, although at current levels of growth, it is possible that in the future China could become the leading energy consumer. The U.S. department of energy categorizes national energy use in four broad sectors: transportation, residential, commercial and industrial as shown in Figure 3.1. It is clear that energy usage in the transportation and residential sectors is largely controlled by individual domestic consumers. Commercial and industrial energy usage is controlled by businesses. National energy policy has a significant effect on energy usage across all four sectors.

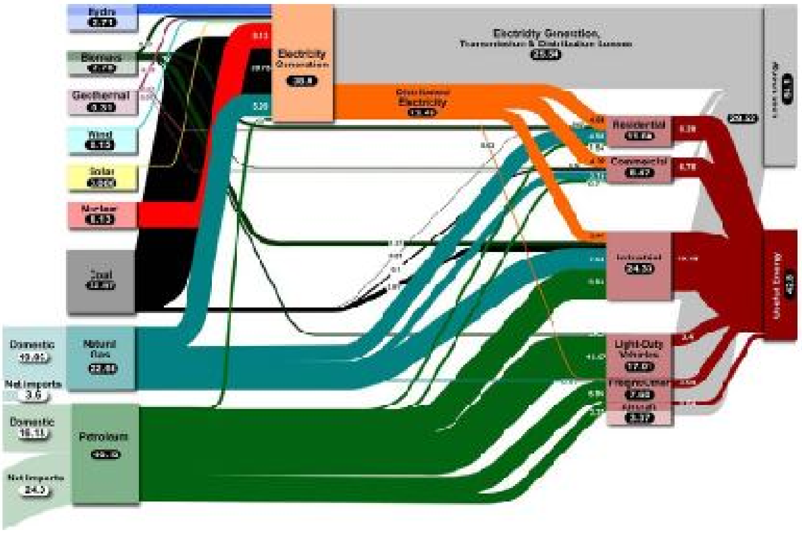


Figure 3.1: U.S. Energy flow trends in 2005 (units in quadrillion Btus).

It is worth noting that:

- the overall energy conversion efficiency in the electric power sector is quite low (around 31%). Part of the reason for such low efficiency is the difference between peak and off-peak operation, due mostly to much lower demand at night;

- the contribution of fuels from biomass which includes wood, waste, alcohol, geothermal, solar and wind to the transportation sector is virtually negligible;
- energy used for transportation shows the worst overall energy efficiency (around 20%);
- approximately 62% of the petroleum used in the U.S. is imported, and it is used almost exclusively for transportation.

In the near future with a low market penetration probably there will not be technical problems for PHEV to be recharged, they can use the existing power system infrastructure without any control on when charging is done by each single driver. PHEVs benefit from an existing infrastructure that could directly use renewable energy: they do not require energy supply infrastructure developments and could obtain substantial public benefits:

- more rapid introduction of zero-emissions vehicles;
- electric system reliability increase;
- lower transportation costs;
- higher penetration of renewable resources in the electric power system;
- lower dependence on oil importations;
- lower pollutant emissions.

However it is important to understand the ramifications of introducing a number of plug-in hybrid vehicles into the grid. Depending on when and where the vehicles are plugged in, they could cause local or regional constraints on the grid. They could require both the addition of new electric capacity along with an increase in the utilization of existing capacity. Local distribution grids will see a change in their utilization pattern, and some lines or substations may become overloaded sooner than expected. Furthermore, the type of generation used to recharge vehicles will be different depending on the region of the country and timing when PHEVs recharge and that will strongly effect PHEV emissions and cost impacts.

In the future power grid administrators will probably need to control when vehicles charging is done to minimize their impact on the power grid. For doing that a complex system of communication between power grid administrator and PHEV owners has to be built; with such a system of communication power grid administrator could start use the electric energy stored in vehicles batteries to help meet peak demand when power generation costs are higher, and recharge these batteries when load on the grid is lower, PHEV battery packs could also provide vehicle to grid services (V2G) improving the overall generation efficiency and could be used as a distributed energy storage system (13). However if power grid administrators want to decide when to charge and discharge vehicles batteries, they will have to concede some economical benefits to PHEV owners.

Vehicle to grid services

Recent studies (14), (15), (16) have proved that PHEVs could become a useful asset also for the electrical power grid providing with a distributed resource of energy stored in their batteries ancillary services. PHEVs batteries could also be used as distributed energy storage system that can minimize the effect of intermittent nature of renewable resources (17).

Ancillary services

In the electric power system, ancillary services are necessary for maintaining grid reliability, balancing the supply and demand, and supporting the transmission of electric power from seller to purchaser.

Regulation is one of ancillary services that PHEVs could provide; the main purpose of regulation is to adjust the grid to the target frequency and voltage. Regulation helps maintain interconnection frequency, balance actual and scheduled power flow among control areas, and match generation to load (18). The required amount of regulation service is determined as a percentage of aggregate scheduled demand. Regulation is provided continuously by generators that are online, equipped with automatic control and will respond within minutes to control center requests to decrease or increase power output.

Vehicle to grid power as a source for ancillary services

The basic concept of V2G is that PHEVs provide power to the grid while they are parked. Each vehicle must have three essential elements for V2G:

1) A power connection to the grid for electrical energy flow
2) Control connection necessary for communications with grid operators
3) Precision metering on-board the vehicle

The control signal from the grid operator is shown in Figure 3.2 schematically as a radio signal, but this might be through direct internet connection or other communication media. In order to schedule dispatch of power, a grid operator needs to rely that enough vehicles are parked and potentially plugged-in at any minute during the day. In the U.S., an average personal vehicle is on the road only 4-5% of the day, which means that a great majority of the day the vehicles are parked, and also during peak traffic hours almost 90% of personal vehicles are parked (16).

Unlike large generators, PHEVs energy storage and power electronics are already designed to provide large and frequent power fluctuations over short time periods, due to the nature of driving. This makes these vehicles especially well engineered for regulation. Once a signal is received, the vehicle can respond in less than a second to change its power output. A “regulation up” signal would cause the vehicle to provide power to the grid (V2G) and a “regulation down” signal would cause a decrease in the power output or even draw power from the grid (the regular battery charging mode). It has been successfully demonstrated the use of a single battery electric vehicle to respond to a regulation signal in previous studies (19).

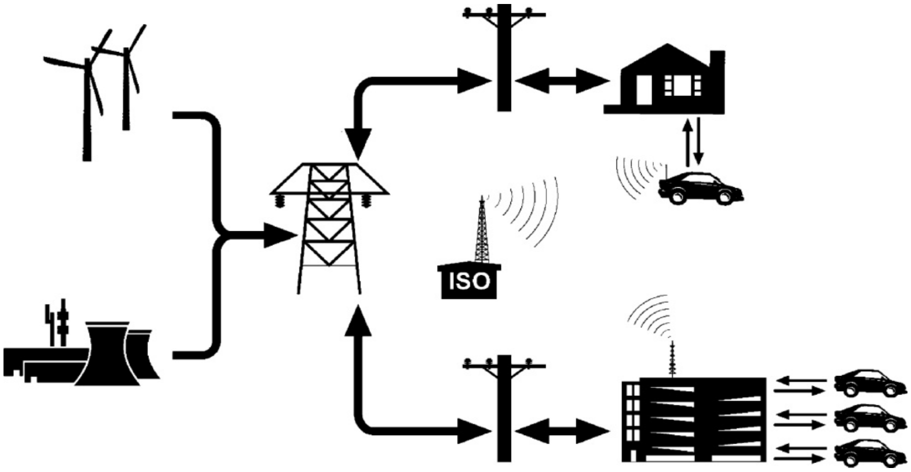


Figure 3.2: Schematic of power lines and control connections between the electric power grid and vehicles.

V2G services include acting as an energy storage device that can be charged off-peak and discharged on-peak as well as providing ancillary services, such as regulation, thereby reducing the need of the system to rely on conventional generators. More important is regulation, which reduces the dependence on conventional generators for capacity and allows the grid administrator to commit fewer generators.

PHEV can provide regulation of higher quality than currently available for three reasons:

- can assure a fast response to a signal;
- it is available in small increments;
- it is distributed.

From the perspective of the electric power sector, this is a new source of high quality grid regulation (14), in addition to these saving to the system, PHEV owners can obtain a value from making their vehicles available to the system for V2G services, this value comes from energy and ancillary services payment and also from reduced vehicle driving cost due to conventional generators having more capacity available to charge PHEV batteries since the grid operator does not have to rely on generators for ancillary services (15). In this way V2G services could give to PHEV owners an additional income, which would reduce their lifetime ownership cost.

PHEV and grid interaction literature review

Before entering the details of this work and its results, here some previous studies regarding the interaction of PHEVs with the power grid are presented to give an overview on previous studies on this topic.

Environmental and Energy Implications of Plug-In Hybrid-Electric Vehicles (20)

In this study, published in 2008 by Ford Motor Company, the effect of charging of a significant number of PHEVs in the U.S. is analyzed using presently available night-time spare electric capacity in the short term and new base-load capacity in the long term.

Conventional and hybrid vehicles fuel consumption were based on EPA city cycle fuel economy data, while for PHEV was considered that in all-electric mode energy efficiency was equal to the electric Toyota RAV4 efficiency. The number of PHEV that could be recharged during off-peak periods was calculated estimating the night-time spare capacity and dividing it for the daily energy consumption of a single PHEV obtaining a total number of PHEV in the U.S. of around 74 millions. Two different scenarios were considered, the first representing the initial penetration of PHEV into the fleet during which the utility would supply energy using their available night-time spare capacity and a second future scenario were new power plants were built to supply new load due to vehicles charging. To estimate CO_2 emissions authors used average emissions rates for each region and the associated elasticity coefficient, which relates the fractional increase in emissions to a given fractional increase in load. In a short term scenario results show that a PHEV could emit an average value of 221 g/km of CO_2, around 50% less of a normal conventional vehicle considered in the study; while a larger number of PHEV would decrease the average emissions toward a lower bound of 150 g/km. In a long term scenario authors considered that utilities will build some additional low cost base load plants to serve the additional load due to PHEV charging their batteries. New plants will have lower fuel consumption due to improving in technology, so PHEV emissions will decrease in the long term scenario reaching 157 g/km of CO_2.

To finish their analysis authors proposed to compare saving in CO_2 emissions due to PHEV use with savings obtained by replacing inefficient coal plants with same state of the art generating capacity. They calculated vehicles emissions on an energy basis instead of a distance basis to compare them with emissions of utilities. The scenario offering the greatest CO2 savings depends upon the type of vehicles displaced. If the replaced vehicles are conventional ones, it is more effective to use PHEV instead to replace coal plants; if they are Hybrid vehicles or more efficient vehicles, a significant fraction of coal plant capacity could be replaced before greater savings would be obtained using PHEVs.

Cost and Emissions Associated with Plug-In Hybrid Electric Vehicle Charging in the Xcel Energy Colorado Service Territory (21)

This study focuses on the Xcel Energy Colorado area; this utility serves about 55% of the state’s population including Denver and its suburbs. Figure 3.3 shows that in Colorado energy production is covered by coal for the 71%, followed by natural gas that covers 24% of energy production, generation capacity data were taken from the Department Of Energy for the year 2007.

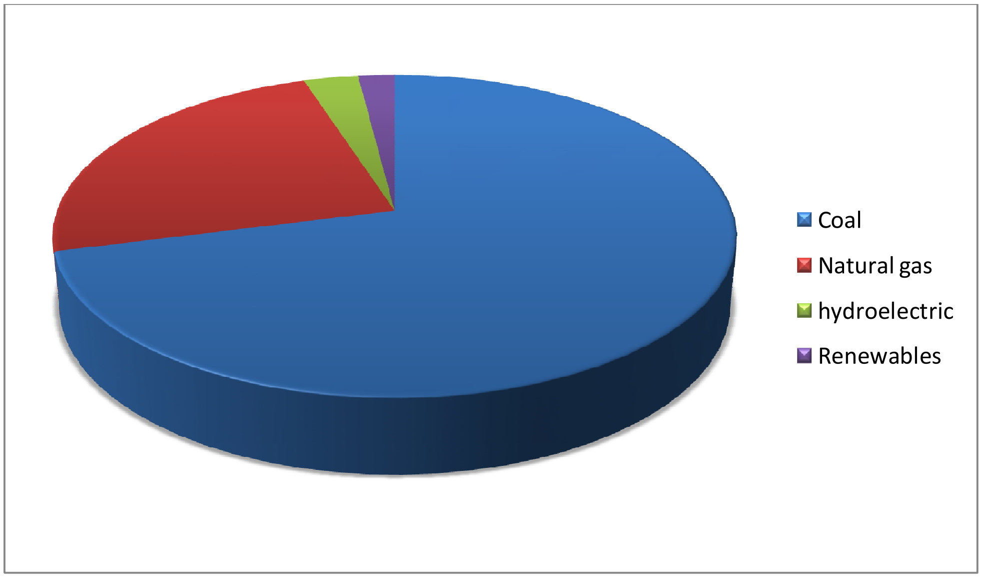


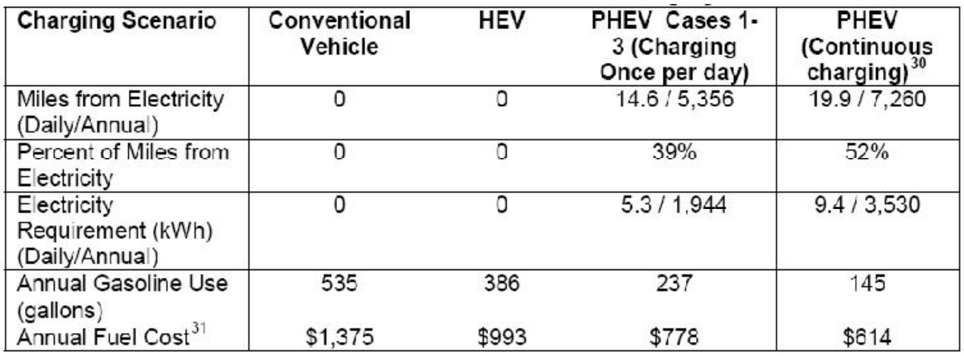
Figure 3.3: Colorado energy production divided for power sources.

To simulate charging of PHEVs a model that simulates the dispatch and operation of the Colorado electric power system for an entire year was used. The model optimally dispatch generators considering their variable cost and startup cost, it considers also constraints on emissions permit, ramping limits and transmission system limits. PHEV were considered with a 30 kilometers electric autonomy and their performance were calculated with ADVISOR simulator starting from empirical driver's data. A total fleet size of 500,000 vehicles was assumed, around 30% of the total light-duty vehicles in the area.

Four different scenarios were simulated:

1. an uncontrolled charging scenario where vehicles owners charge their batteries exclusively at home without any control on them;
2. a delayed charging scenario where the charging is done at home but delaying it after 10 PM;
3. an off-peak charging scenario were the grid administrator decide when charging vehicles batteries to minimize charging cost;
4. a continuous charging scenario that assumes that public charging station are available wherever the vehicle is parked, so that charging is done whenever a vehicle is parked.

The first three charging cases are considered 'once per day' charging scenarios and produces the same average electric demand for charging and miles driven electrically; with continuous charging a much larger fraction of miles are driven electrically. Table 3-1 summarizes PHEV performances compared to non plug-in vehicles; from results obtained it is clear how a PHEV could save more than 70% of gasoline consumption compared to a conventional vehicle if could be recharged during the day.



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

Table 3-1: Vehicle performance under various charging scenarios in Colorado.

Like most of the United States, the peak load on Colorado electric system is during the summer, driven by midday and early evening air-conditioning demand. Figure 3.4 illustrates the summertime load patterns for three days, including the normal load and the load 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 results, delayed or optimal PHEV charging avoids any need for additional generation capacity.

This study permits to track which type of fuel is used to recharge PHEV batteries; the marginal generation mix is the most important factor in both the overall charging costs and net emissions. In Colorado natural gas provides the marginal fuel in more than 80% of the time, due to particular characteristics of the system, so the greatest benefit to delayed and off-peak charging cases is increased use of more efficient combined-cycle units. Charging vehicle's battery during off-peak periods conduces also to lower charging costs compared with uncontrolled and continuous charging saving 0.2 cents/kWh due to improved system performance.

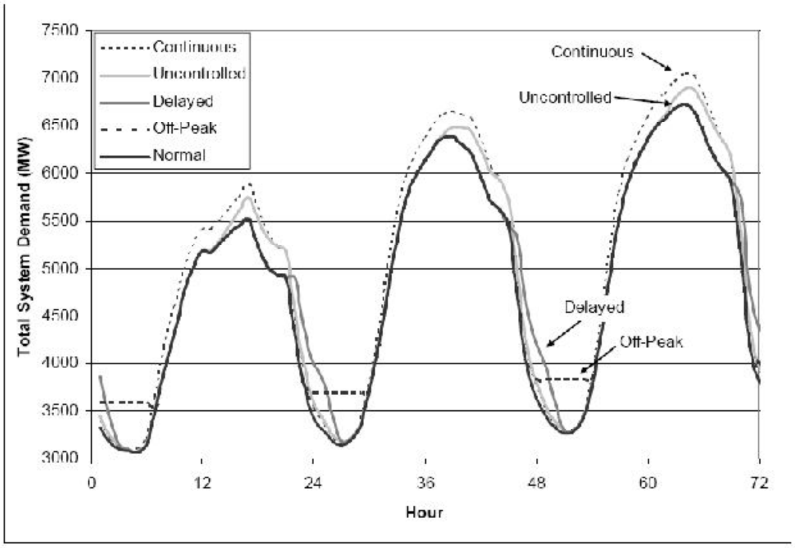


Figure 3.4: Summertime load on the Colorado grid with PHEVs.

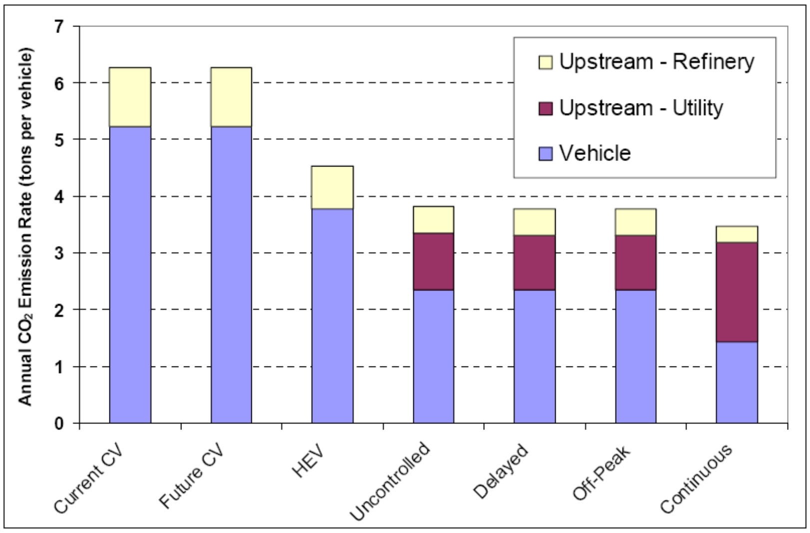


Figure 3.5: Net vehicles CO_2 emissions rates.

On an environmental side, Figure 3.5 shows how PHEV in Colorado could emit less CO_2 with all the charging strategies.

Emissions Impacts and Benefits of Plug-In Hybrid Electric Vehicles and Vehicles to Grid Services.

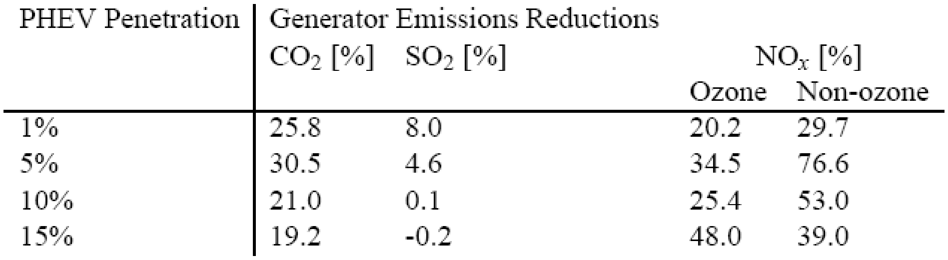
This study (22) is based upon a model of the Electricity Reliability Council of Texas (ERCOT) electric power system, this model simulates the commitment and dispatch of generators as well as the dispatch of PHEV to charge and discharge their battery, PHEV could also provide ancillary services when not being driven. It shows how V2G services could improve environmental impact of PHEVs.

All generators that were in operation in ERCOT in the year 2005 were considered and analyzed, generation costs were estimated based on heat rates, fuel costs and variable operation and maintenance costs data from Ventyx and Platts Energy, cost of SO_2 permits was also taken into account. Hourly wind availability was considered to estimate wind plants generation. PHEV market penetration was considered between 1 and 15% of the total light duty fleet.

Vehicle driving patterns were based on empirical data and then used to estimate the energy and gasoline consumption of PHEVs. V2G services were dispatched considering constraints on the power capacity of the plug used in the charging station and on the energy stored in the battery, as for the charging vehicles could provide V2G services only when parked.

Discharging a PHEV battery for V2G services results in three costs and that was also considered in the analysis. The first is the cost of recharge the energy used from the battery, the second is the increase in cost for gasoline consumption because having less energy stored in the battery PHEV will be run more in charging sustaining modality, and the last cost is the reduction in the usable cycle life of the battery. The lithium-ion batteries used for PHEV have a usable cycle life that is a decreasing function of how much the batteries are discharged. For that reason, the dispatch of a PHEV to provide energy back to the power grid imposes a cost on the vehicle owner because it will obtain a shorter lifetime of his battery pack. This cost was calculated modeling the expected battery life lost from each discharging of a PHEV battery and the associated expected battery replacement cost. An important question is whether sufficient benefits from providing V2G services occur to PHEV owners to ensure that they make their vehicle available for V2G.

The model minimize total costs considering all the costs associated with generators and PHEV operation as gasoline, electricity used to recharge batteries and costs associated with reduction in battery cycle life. Analysis was focused on three different pollutants: CO_2, SO_2 and NOx; generation-related emissions were broken into generator emissions and upstream emissions from fuel extraction and transportation while vehicle emissions were considered divided in tailpipe emissions and upstream refinery emissions. NOx emissions were divided in two different periods, an ozone season and a non-ozone season.



PHEV Penetration	Generator Emissions Reductions			
	CO_2 [%]	SO_2 [%]	NO_x [%]	
			Ozone	Non-ozone
1%	25.8	8.0	20.2	29.7
5%	30.5	4.6	34.5	76.6
10%	21.0	0.1	25.4	53.0
15%	19.2	-0.2	48.0	39.0

Table 3-2: Reduction in PHEV charging emissions from V2G services.

Table 3-2 summarizes the generator emissions impact of V2G services by showing the reduction in emissions when PHEV provide V2G services as a percentage of the increase in emissions from introducing the PHEV fleet. A large difference in the reduction of CO_2 and NOx emissions compared to SO_2 emissions was found. The reason of that is that spinning reserves is typically provided by natural gas-fired generator, so if PHEVs provide this services they will reduce emissions due to natural gas burning that does not emit SO_2. PHEVs do not burn any fuel if their battery is used for spinning reserves so in the complex V2G services provide an emissions reduction.

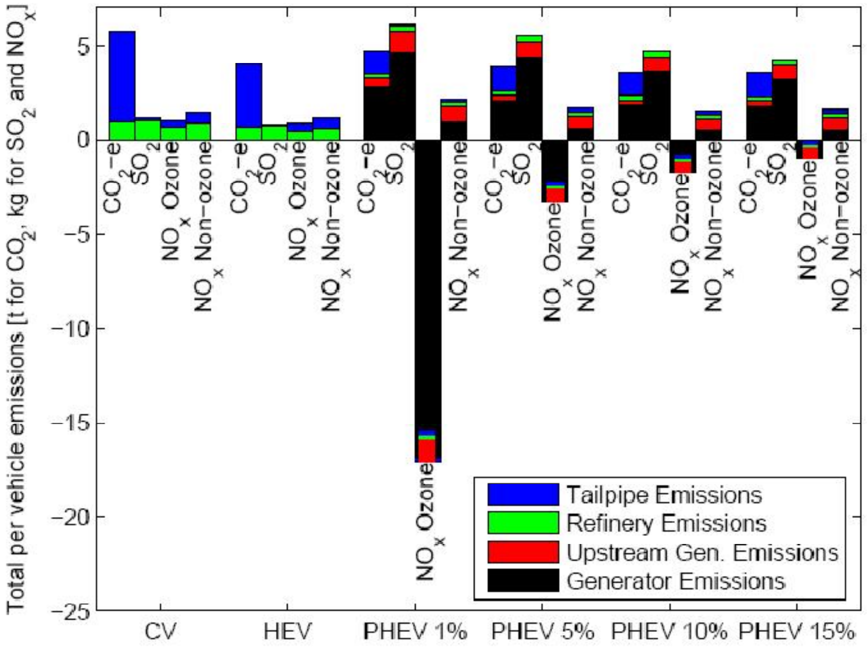


Figure 3.6: Total annual per vehicle emissions without V2G services.

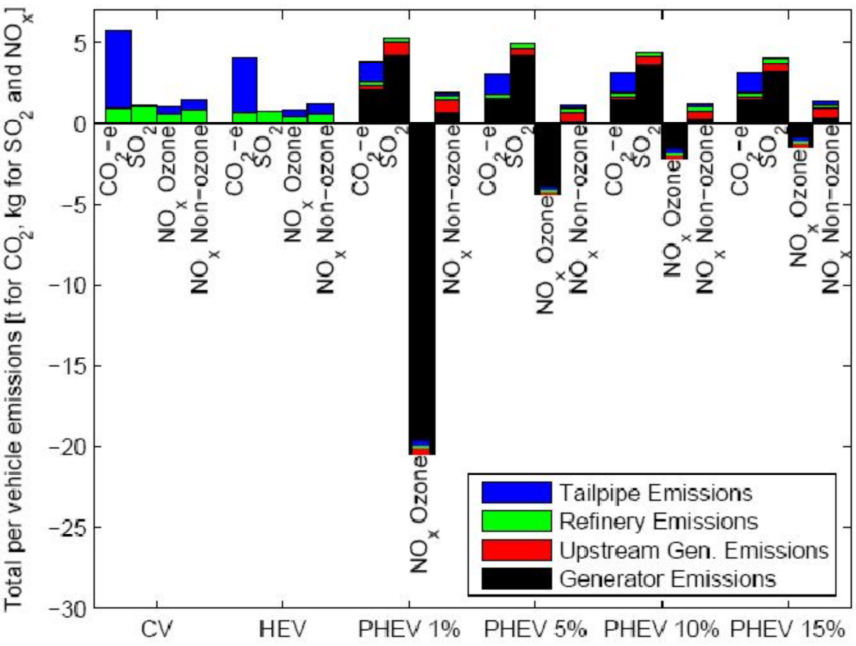


Figure 3.7: Total annual per vehicle emissions with V2G services.

Figure 3.6 and Figure 3.7 compare total annual per-vehicle emissions from PHEVs to those from CVs and HEVs. The generation emissions have been calculated on the incremental change in the generator emissions divided by the size of the PHEV fleet. The NOx emissions for PHEVs in the ozone season are negative because their use can decrease global emissions from generators instead of increasing it also if more electricity is produced, that is due to the fact that load on the grid has switched from less to more efficient generators using PHEVs. The increasing in SO2 emissions with PHEVs is attributed to the great use of coal that is done in Texas to produce electricity, in all the scenarios analyzed coal generators provide between 22% and 33% of the incremental load. It is possible to see how also with a great use of coal as generating fuel CO2 emissions are decreased with PHEV use in both cases.

Comparing figures shows a drop in generator emissions of PHEV with V2G services, which has obtained using PHEV batteries to provide spinning reserves instead of leaving on-line generators above their maximum generation level; in this way generators have more capacity available to recharge PHEV batteries during the day, so more distance can be covered without burning gasoline by PHEVs.

Literature review conclusions

Looking at these studies it is clear that the configuration of the electric system, in particular which kind of generator is used to produce electricity is a fundamental aspect of the problem and will influence PHEV environmental and costs impacts. Driving behaviors are another important variable that has to be considered in the analysis, especially how driving distances are distributed during the day to see when vehicles will need to be recharged between two trips.

This analysis focuses on the future impact that a PHEV fleet could have on the state of Ohio, so it was decided to model all the generators present in the state and the electric market. Real electric demand data were obtained from Ohio electric utility PJM (23), to have a more realistic load profile on the grid, changing during the days of the year depending on customers' behaviors. Drivers' behaviors were taken from a previous study that tracked real driving patterns, in this way more realistic statistical driving data were used for the simulation. Unfortunately more detailed data on the grid scheme and load distribution over it were not available, for that reason limits on transportation lines were not taken into account.

4. Modeling

The model has to be able to decide which generator switch on and off during the day to satisfy the electric load on the grid, it has also to be able to decide when charge PHEVs minimizing their impact on the grid. Because of the fact that integer variables (as variable indicating if a vehicle is parked or a generator is on-line) have to be considered in the model with linear variables (as that representing the electrical output of each generator) the system was modeled as a Mixed Integer Program.

Two different charging scenarios were considered to take into account how charging strategy could change PHEV global impact, both assuming the presence of public charging stations allowing each driver to recharge vehicle whenever it is parked; a first scenario where the model optimize the charging profile with the functioning of the power system and a second scenario where charging profile was imposed by drivers behaviors and simply added to the already existing load on the grid.

Mixed integer linear programming

Linear programming (LP) is concerned with maximizing or minimizing an equation over certain constraints, for example:

$$\max \quad z = 3x_1 - x_2 + 2x_3 \tag{1}$$

With the following constraints:

$$x_1 + 2x_2 \leq 5 \tag{2}$$

$$x_1 + 5x_3 \geq 0 \tag{3}$$

Problems like this one are used in business to maximize profits or optimize other aspects; however some part of the solution may be restricted to integers. Mixed integer linear programs are linear program which require some of all the variables to be integer. For example if x_1 represents the amount of cars sold by an industry it has to be an integer value; rounding the solution will often compromise the optimality and the rounded solution could be not in the feasible region. One way to solve this kind of problems is to enumerate all the integer solutions in the feasible region and individually check each one for optimality.

Mixed integer linear programs are very hard to solve, there are two different solving methods that can be used:

- The branch and bound method.
- The cutting planes method.

The branch and bound method first of all resolve the problem as it were no integer restrictions with the simplex method, then if there is a non integer variable, it is pick and branched creating two subproblems or nodes. Each node must be solved and checked for optimality, if other non integer variables are presented in one node it could be eventually brunched or pruned. A node could be pruned when is optimal solution exceeds constraints, or when its optimal solution is worse than the optimal solution of the other branch. The process ends when all the nodes are pruned, at that time the optimal solution will be associated with the last node left.

The cutting planes method is based on the idea of cutting pieces of the feasible region, in order to do that starting from the information of the optimal dictionary has to be deduced an inequality that could cut out a part of the feasible region. Than the system has to be solved with the simplex method with this new inequality until all variables are integer.

While cutting planes can solve very fast, the process could be unreliable, on the other end branch and bound is very reliable but can be extremely slow. Cut and brunch method starts using cutting planes until new cutting planes can be found and then solves the remaining system with the branch and bound method.

Simplex method

In order to solve the linear relaxation the simplex method has to be used, which is the algorithm for solving normal linear programs. First of all the problem is initialized adding slack variables:

$$ax_1 + bx_2 + cx_3 \leq d \tag{4}$$

There will be for sure a variable x_4 such that:

$$ax_1 + bx_2 + cx_3 + x_4 = d \tag{5}$$

A stuck variable is added for any constraint of the problem, than a starting solution of problem that satisfies $Ax = b$ has to be found. An easy way to find one is to set all the stuck variables equal to b, it always satisfies $Ax = b$. Than A has to be separate into $[A_B\ A_N]$ where A_B is the columns of A corresponding to the basic variables, which are the part of x not given to be zero. A_N is the columns of A corresponding to the non basic variables.

Than the simplex method solves:

$$A_B^T y = c_B \tag{6}$$

And computes:

$$S_N = C_N - A_N^T y \tag{7}$$

If $S_N \leq 0$ the problem is solved, in the other case if $S_N(i) > 0$ for any i the solution can be improved by increasing one of the values of x. If i is the index equal to max $S_N(i)$, than $x(i)$ acts as pivot variable and is called the entering non basic variable. The simplex method than solves $A_B d = A_N$ for d, than computes $\theta = \min[\, x_B(i)/d(i)]$ such that $d(i) > 0$.

Let

$$\theta = x_B(l)/d(l) \tag{8}$$

Then x_B is the leaving basic variable and has to be switched with the entering non basic variable. Doing that the simplex method slides the solution x by decreasing $x_b(l)$ to zero, and putting the slack created by this into $S_N(i)$. Doing that z is increased.

The following step is to update B and N, the list of basic and non basic variables and the update x_B in the following manner:

$$x_B = x_B - \theta d \tag{9}$$

and

$$x_B(l) = \theta \tag{10}$$

This procedure is repeated until $S_N \leq 0$.

Unit commitment model

This analysis is based on a model developed by Professor Ramteen Sioshansi for a previous similar study on Texas power grid (24); the model was then modified and adapted to the case of Ohio. The model is based upon a unit commitment model of the Ohio electric power system, which is formulated as a mixed-integer program (MIP) using the AMPL and solved using the branch and cut algorithm in cplex 12.1 (25).

The model simulates the commitment and dispatch of conventional generators as well as the dispatch of PHEVs to charge when not being driven. As is typical of day-ahead electricity markets, the unit commitment model has a one day planning horizon with an hourly timestep for the commitment and dispatch variables. Each day in the sample, which consists of the 365 days in 2007, 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 upon the ending values from the previous day's run.

Inputs for the model are:

- Non-PHEV electricity Loads
- Driving data
- Vehicle data
- Gasoline prices
- Generator data
- PHEV fleet size
- PHEV charging behavior

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 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. Because PHEV owners face fixed electricity tariffs, it is optimal for PHEV owners to recharge their vehicles whenever they are plugged in, since electricity is a significantly less costly source of transportation energy than gasoline (when accounting for the relative efficiency of the vehicle's internal combustion engine and electric motor).

The outputs of the model for each hour of the year are:

- PHEV charging profile
- Total load
- Total emissions
- Driving cost
- Generation cost

Figure 4.1 presents a schematic flow diagram of the model.

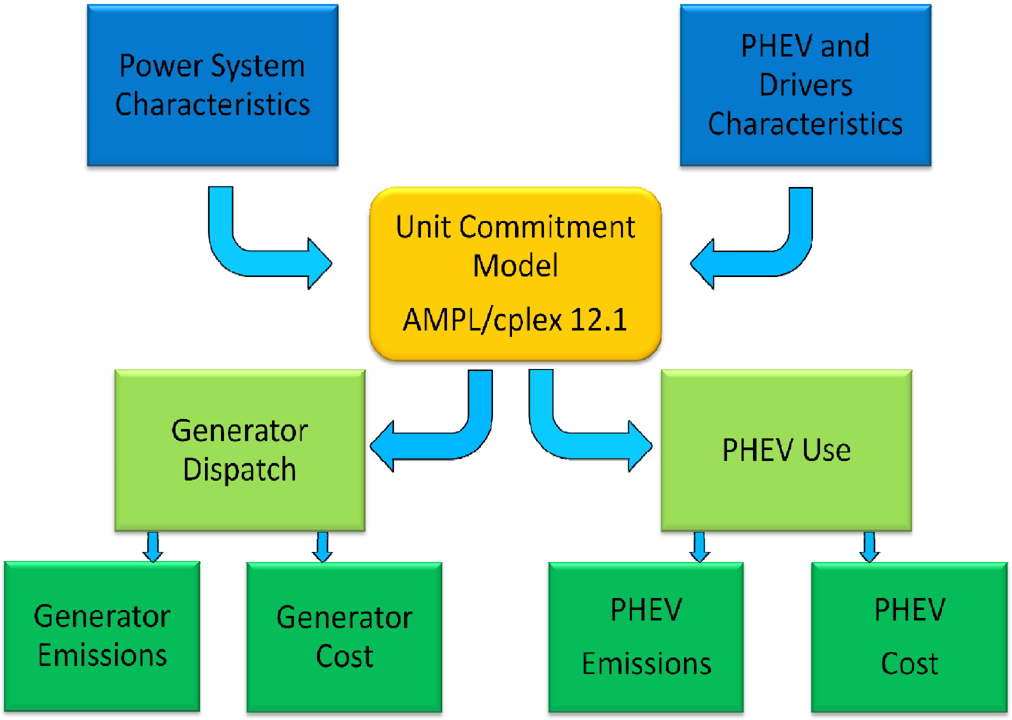


Figure 4.1: Schematic model flow diagram.

Mathematical formulation of the model

The model in the controlled charging case minimizes total cost of power generation and gasoline consumed by PHEVs:

$$\sum_{t=1}^{T}\Big[\sum_{g=1}^{G}\sum_{s=1}^{gen\_cost\_steps} gen\_fuel\_cost(g) * gen\_hr(g,s) *$$
$$gen(g,s,t) + g=1Ggen\_fuel\_cost(g)*startup\_heat(g)*startupg,t+$$
$$spinning\_heat(g)*upg,t+$$
$$p=1PHEVsnumPHEVs*gasoline\_cost*cd\_gal(p)*cd\_milesp,t+$$
$$cs\_gal(p,t)*cs\_miles(p,t)+$$
$$m=1market\_price\_stepsmarket\_dir(m,t)*market\_price(m,t)*market\_tr$$
$$ans(m,t) \tag{11}$$

The model has these data inputs:

Total number of hours in optimization horizon:

$$T$$

Number of generators:

$$G$$

Number of steps in generation cost functions:

$$gen\_cost\_steps$$

Number of PHEV driving profiles:

$$PHEVs$$

Number of steps in market price functions:

$$market\_price\_steps$$

Generator heat rate:

$$gen\_hr(g, s)$$

Generator fuel cost:

$$gen\_fuel\_cost(g)$$

Amount of fuel burned by generator when switch on before to get on-line:

$$startup\_heat(g)$$

Amount of fuel burned by generator to remain on-line independently of his generation output:

$$spinning\_heat(g)$$

Number of PHEV for each driving profile:

$$numPHEVs$$

Gasoline cost:

$$gasoline\_cost$$

Gasoline consumed in CD modality:

$$cd\_gal(p)$$

Gasoline consumed in CS modality:

$$cs\_gal(p)$$

Price of the electricity exchanged in the market:

$$market\_price(m,t)$$

Direction of energy in the market, 1 if energy is purchased by Ohio, -1 if is sold:

$$market\_dir(m,t)$$

The variables that are decided by the model and it change in his optimization are:

Generator power output:

$$gen(g,s,t)$$

Binary variable indicating if generator is on-line:

$$up(g,t)$$

Binary variable indicating if a generator has been switched-on:

$$startup(g,t)$$

Miles run in CD modality:

$$cd\_miles(p,t)$$

Miles run in CS modality:

$$cs\_miles(p, t)$$

Energy exchanged in the market:

$$market\_trans(m, t)$$

The model has to satisfy some constraints in his optimization that represent physical behavior of generators and PHEVs:

- Balance on power generation and power consumption:

$$\sum_{g=1}^{G} \sum_{s=1}^{gen\_cost\_steps} gen(g, s, t) + undergen(t) - overgen(t) = load(t) +$$
$$p{=}1PHEVsnumPHEVs{*}PHEV\_charge(p,t)charge\_eff-$$
$$m{=}1market\_price\_stepsmarket\_dirm,t{*}market\_trans(m,t) \qquad \forall t$$

(12)

- Limits on ramp up of generators:

$if\ t > 1$

$$\sum_{s=1}^{gen\_cost\_steps} gen(g, s, t) - \sum_{s=1}^{gen\_cost\_steps} gen(g, s, t-1) \leq ramp_{up(g)} +$$
$$\left(mincap(g) - ramp_{up(g)}\right) * startup(g, t) \qquad \forall t, g$$

(13)

$else$

$$\sum_{s=1}^{gen\_cost\_steps} gen(g, s, t) - init\_gen(g) \leq ramp_{up(g)} + \big(mincap(g) -$$
$$rampupg{*}startupg,t \qquad \forall t,g$$

(14)

- Limits on ramp down of generators:

$if\ t > 1$

$$ramp_{down(g)} - \left(mincap(g) + ramp_{down(g)}\right) * shutdown(g,t) \leq \sum_{s=1}^{gen_{cost_{steps}}} gen(g,s,t) - \sum_{s=1}^{gen\_cost\_steps} gen(g,s,t-1) \quad \forall t,g \tag{15}$$

$else$

$$ramp_{down(g)} - \left(mincap(g) + ramp_{down(g)}\right) * shutdown(g,t) \leq \sum_{s=1}^{gen_{cost_{steps}}} gen(g,s,t) - init\_gen(g) \quad \forall t,g \tag{16}$$

- Limits on generators minimum and maximum output;

$$\sum_{s}^{gen\_cost\_steps} gen(g,s,t) \leq maxcap(g) * up(g,t) \qquad \forall t,g \tag{17}$$

$$mincap(g) * up(g,t) \leq \sum_{s}^{gen\_cost\_steps} gen(g,s,t) \qquad \forall t,g \tag{18}$$

- Balance of energy in PHEVs batteries;

$if\ t > 1$

$$PHEV\_SOC(p,t) = PHEV\_SOC(p,t-1) + PHEV\_charge(p,t) - cd\_discharge(p) * cd\_miles(p,t) \quad \forall p,t \tag{19}$$

$else$

$$PHEV_{SOC(p,t)} = init\_SOC(p) + PHEV\_charge(p,t) - cd\_discharge(p) * cd\_miles(p,t) \quad \forall p,t \tag{20}$$

- Satisfaction of drivers requirement;

$if\ driving_{distance(p,t)} > 0$

$$cd\_miles(p,t) + cs\_miles(p,t) = driving\_distance(p,t) \qquad \forall p,t \tag{21}$$

- No recharge of batteries while vehicles is driven;

$$if\ driving\_distance(p,t) > 0 \qquad PHEV\_charge(p,t) = 0 \qquad \forall p,t \tag{22}$$

For the uncontrolled case the objective function minimized by the model is lightly different and does not include PHEVs gasoline cost because they are considered as a constant of the problem.

$$\sum_{t=1}^{T}\left[\sum_{g=1}^{G}\sum_{s=1}^{gen\_cost\_steps} gen\_fuel\_cost(g) * gen\_hr(g,s) * gen(g,s,t) + g=1Ggen\_fuelcost(g)*startup\_heat(g)*startupg,t+ spinning\_heat(g)*upg,t + m=1market\_price\_stepsmarket\_dir(m,t)*market\_price(m,t)*market\_trans(m,t)\right. \tag{23}$$

Data inputs for this scenario are the same as in the controlled one, except that PHEV charging is no more optimized by the model but vehicles are recharged whenever they are parked for at least one hour.

Constraints for this case are need just for the power system and are the followings:

- Balance on power generation and power consumption;
- Limits on ramp up and down of generators;
- Limits on generators minimum and maximum output.

Generators characteristics

Ohio electric power system

The U.S. electrical infrastructure is divided into regions under the supervision of the North American Electric Reliability Council (NERC) (26).

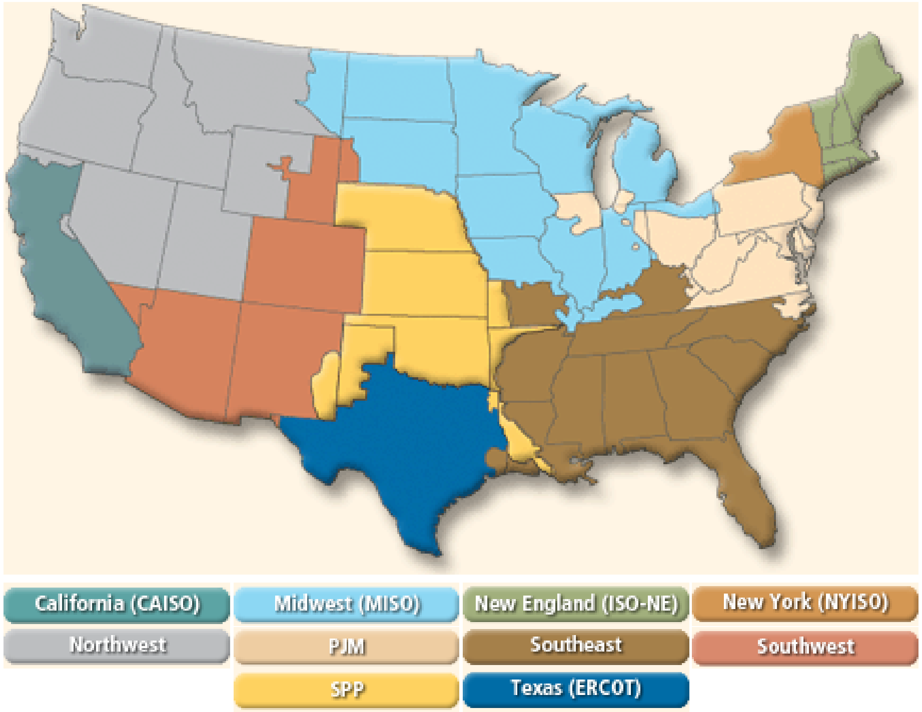


Figure 4.2: An overview of U.S. power markets.

The state of Ohio is covered by two different energy markets that are administrated by PJM and the Midwest Independent System Operator (MISO). Figure 4.2 shows the geographic regions covered by different system operators; most of Ohio is covered by PJM. This analysis will focus on the portion of the state of Ohio that is part of the PJM service territory. PJM administers a two-settlement energy market (27). The two-settlement system consists of a day-ahead and a real-time market. The day-ahead market is a forward market in which hourly clearing prices are calculated for each hour of the next operating day based on generation offers, demand bids, self schedules of bilateral transactions, and generation increment and decrement offers that are submitted into the market. The balancing market is the real-time energy market in which the clearing prices are calculated at a finer five-minute interval based on the actual system operations.

Separate accounting settlements are performed for each market; the day-ahead market settlement is based on scheduled hourly quantities and on day-ahead hourly prices whereas the balancing settlement is based on actual deviations from the day-ahead schedule and on real-time prices integrated over the hour. The day-ahead and real-time prices are locational marginal prices (LMPs); which capture differences in the marginal cost of generation at different locations within the power system and prices the scarcity of transmission capacity. In this way, the day-ahead market enables participants to purchase and sell energy at binding day-ahead prices, while also allowing transmission customers to schedule bilateral transactions at binding day-ahead congestion charges based on the differences in LMPs between the transaction source and sink. Load serving entities (LSEs) may submit hourly demand schedules, including any price-sensitive demand, for the amount of demand that they wish to lock-in at day-ahead prices. Any generator that is a PJM-designated capacity resource must submit a bid schedule into the day-ahead market even if it is self-scheduled or unavailable due to outage. Other generators have the option to bid into the day-ahead market. Transmission customers may submit fixed, dispatchable or 'up to' congestion bid bilateral transaction schedules into the day-ahead market and may specify whether they are willing to pay congestion charges or wish to be curtailed if congestion occurs in the real-time market. All spot purchases and sales in the day-ahead market are settled at the day-ahead prices. After the daily quote[1] period closes, PJM will calculate the day-ahead schedule based on the bids, offers and schedules submitted based on a least-cost security constrained unit commitment and dispatch for each hour of the next operating day. The day-ahead scheduling process will incorporate PJM reliability requirements and reserve obligations into the analysis. The resulting Day-ahead hourly schedules and day-ahead LMPs represent binding financial commitments to the market participants.

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[1] Many interruptible and curtailable programs have separate ”quote” and “call” options. A “quote” program allows the customer to specify when and at what price they are willing to reduce load. A “call” option requires the customer to reduce load when called upon or face penalties.

The Real-time Energy Market is based on actual real-time operations. Generators that are designated PJM capacity resources that are available but not selected in the day-ahead scheduling may alter their bids for use in the real-time energy market during the generation rebidding period from 4:00 PM to 6:00 PM (otherwise the original bids remain in effect for the balancing market). Real-time LMPs are calculated based on actual system operating conditions as described by the PJM state estimator. LSEs will pay real-time LMPs for any demand that exceeds their day-ahead scheduled quantities (and will receive revenue for demand deviations below their scheduled quantities).

Generators are paid Real-time LMPs for any generation that exceeds their day-ahead scheduled quantities (and will pay for generation deviations below their scheduled quantities). Transmission customers pay congestion charges based on real-time LMPs for bilateral transaction quantity deviations from day-ahead schedules. All spot purchases and sales in the balancing market are settled at the real-time LMPs (28).

Generators data

The model includes all of the thermal, hydroelectric, and nuclear generators that were in operation in Ohio in 2007. Figure 4.3, Figure 4.4, Table 4-1 and Table 4-2 give an overview of the generation mix in terms of generating capacity and actual energy production in 2007.

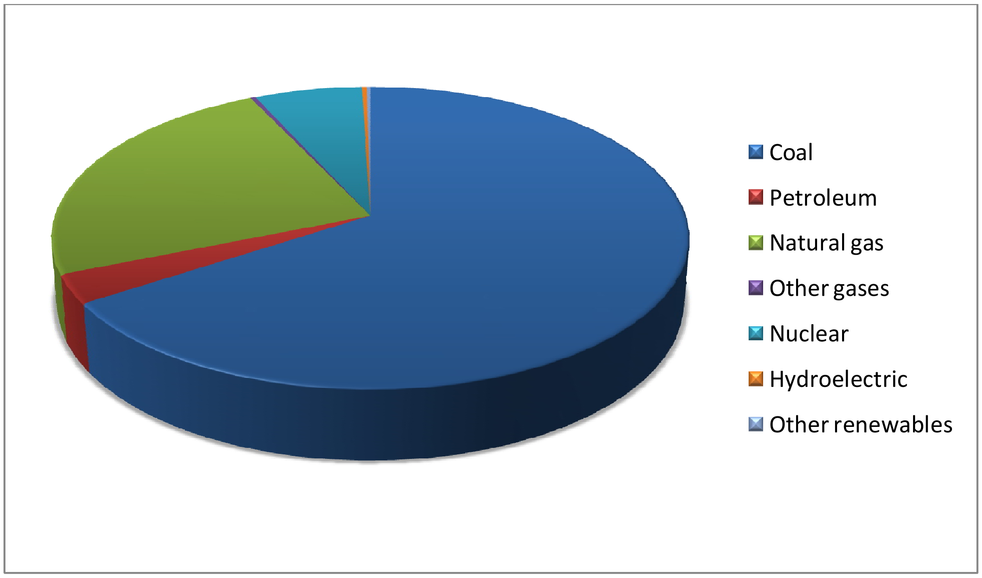

Figure 4.3: Generation mix in terms of installed capacity.

	Generating Capacity	
Energy Source	MW	%
Coal	22,074	65.9
Petroleum	1,075	3.1
Natural Gas	8,169	24.1
Other Gases	100	0.3
Nuclear	2,124	6.3
Hydroelectric	101	0.3
Other renewable	112	0.2

Table 4-1: Generation mix in terms of installed capacity.

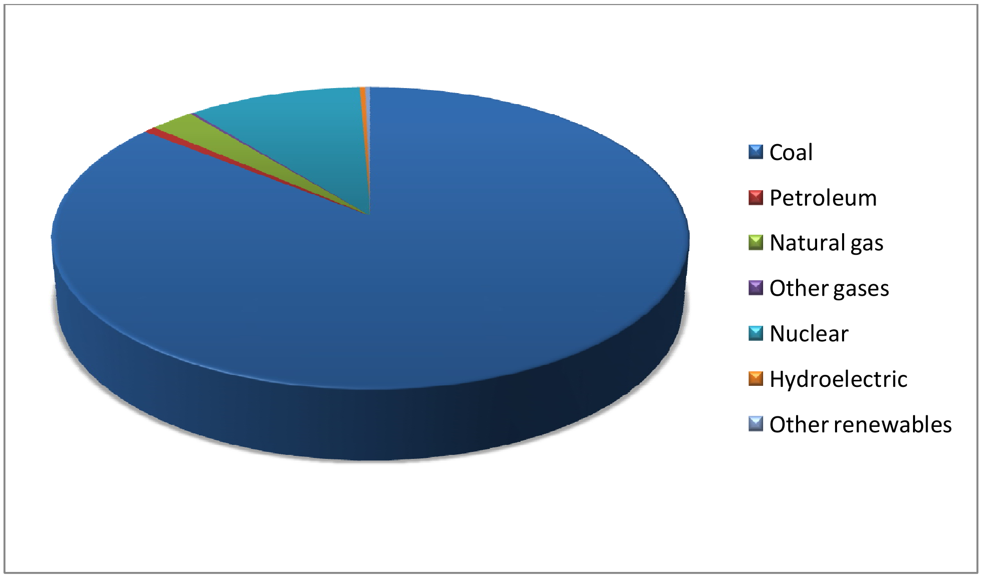

Figure 4.4: Generation mix in terms of energy produced.

The tables and figures show that the most abundant generation fuel in Ohio is coal, which produced almost 86% of energy in the state, followed by nuclear that produced more than 10%. More expensive natural gas-fired generators, which represent 24% of the installed capacity, are used rarely only to cover peak loads accounting for only 2.6% of generation.

	Actual Generation	
Energy Source	MWh	%
Coal	133,130,679	85.8
Petroleum	1,147,746	0.7
Natural Gas	3,974,897	2.6
Other Gases	289,273	0.2
Nuclear	15,764,049	10.2
Hydroelectric	410,436	0.3
Other renewable	435,143	0.3
Other	3,322	0.0

Table 4-2: Generation mix in terms of energy produced.

Generation costs were calculated based on estimated generator heat rates and fuel costs. Heat rates were estimated based on historical continuous emissions monitoring system (CEMS) data from the U.S. Environmental Protection Agency (EPA) (29). The CEMS data specifies the generation and total heat content of fuel burned by each generator in each hour. This data was used to estimate the startup, spinning no-load and variable fuel burned by each generator. The startup fuel is burned whenever the generator is brought online from an offline state; it is used to slowly warm up the plant without procuring thermal shocks to its components. The spinning no-load fuel is burned whenever the generator is operating, independent of its generation output. The variable fuel is burned depending on the electric output of the generator and its efficiency. To consider the real behavior of each generator and how its efficiency changes depending on the electrical output, was fitted to CEMS data a polynomial function that represented generator heat rate curve as represented in Figure 4.5; in order to reduce model complexity the polynomial functions were converted to step functions as shown in Figure 4.6.

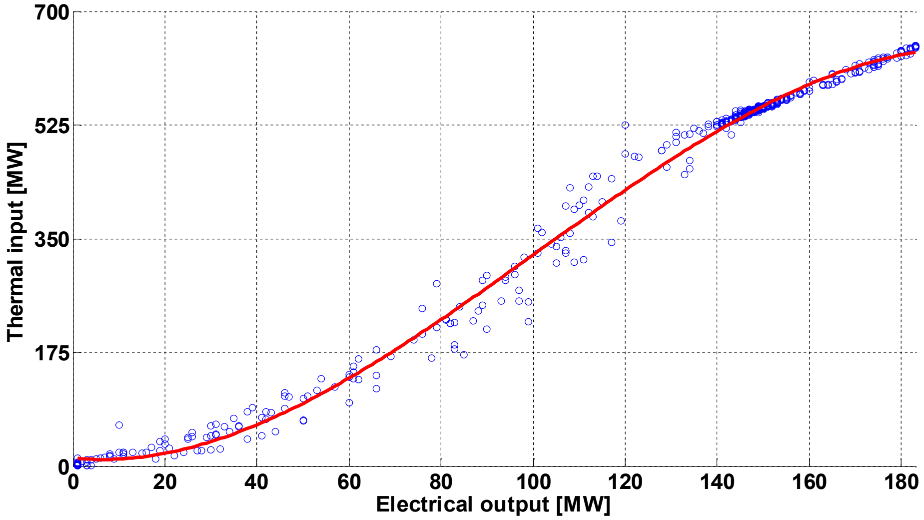

Figure 4.5: Heat rate curve of one generator.

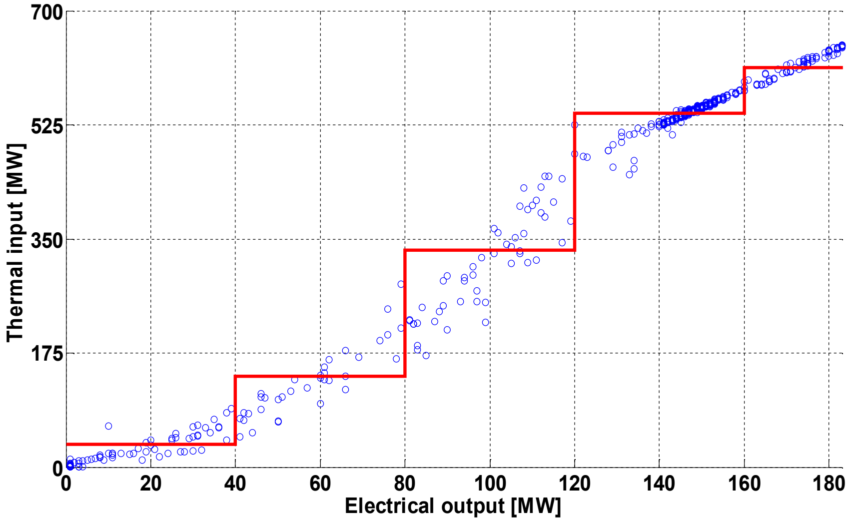

Figure 4.6: Heat rate curve of one generator approximated as step function.

The CEMS data was also used to determine the minimum output of each generator when it is 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). Nuclear generators are assumed to be non-dispatchable and run at full capacity and as such their generating costs are not modeled.

Because Ohio is a part of the PJM system, the state may export or import energy from neighboring control areas. These imports and exports will be economic depending on the difference between the cost of energy in Ohio and in the other control areas; imports are economics if energy from Ohio is more expensive and vice versa. The price at which energy can be bought and sold will 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 quantity transacted. Specifically, historical PJM (23) day-ahead market bid data were used to estimate the relationship between price and load, as shown in Figure 4.7. In order to reduce the complexity of the power system model, this price/load relationship is represented in the model as a step function.

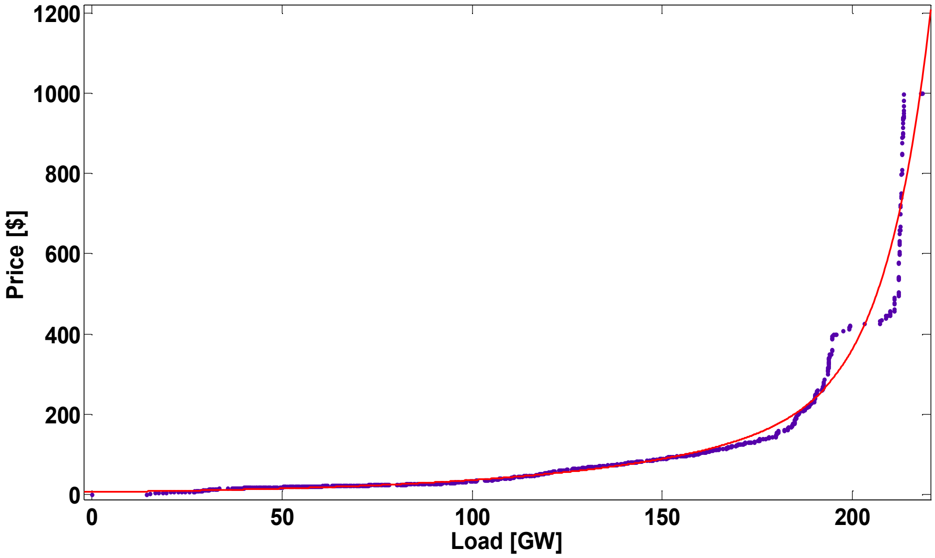

Figure 4.7: Price of market transactions as a function of energy transacted.

Starting from generators dispatch pollutants emissions were calculated; to calculate them was multiplied the amount of fuel burned by each generator for its emissions rate estimated using Continuous Emissions Monitoring System (CEMS) data for the year 2007; In emissions calculation was taken into account also the amount of energy exchanged in the market, imports will result in greater emissions from generators outside Ohio while export will reduce generator emissions outside Ohio. These emissions were calculated starting from hourly marginal fuel data of PJM, that specifies the mix generation technology used for each hour of the year, and then estimating from CEMS data the emissions rate for each technology in the others regions of PJM.

Drivers and PHEV characteristics

The PHEV model captures the driving and charging of the PHEV fleet. In both the controlled and uncontrolled charging scenarios, the driving decisions are assumed to be made by the vehicle owners. In the controlled charging case, the grid operator is assumed to make PHEV charging decisions, subject to constraints on when vehicles can be recharged depending on the driving decisions. In the uncontrolled charging scenario, vehicle owners are assumed to make charging decisions.

For each set of model runs, the PHEV fleet is assumed to consist of a fixed number of vehicles. The total vehicle fleet size (consisting of both PHEVs and non-PHEVs) is taken from 2007 Ohio vehicle registration information reported by the U.S. Department of Transportation's Federal Highway Administration; in the year 2007 the light-duty vehicle fleet in Ohio was composed of about 6.5 millions of vehicles. The model is run with three different PHEV penetration levels: 1%, 3% and 5% of the total vehicle fleet. Vehicles driving patterns are based upon a household travel survey that was conducted in St. Louis, Missouri metropolitan area. The vehicle survey tracked second by second driving patterns of 227 vehicles over the course of a number of weekdays (30).

Figure 4.8 and Figure 4.9 show some statistical drivers information.

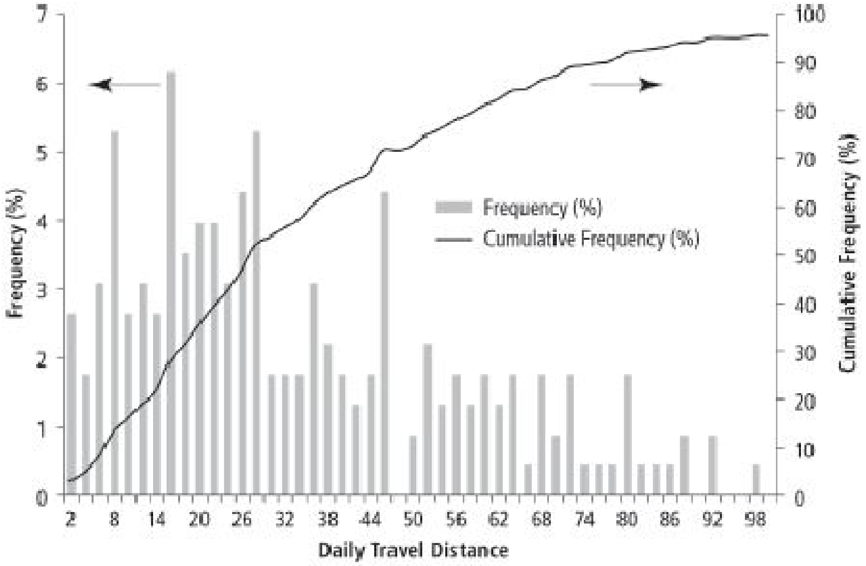

Figure 4.8: Distribution of driving distance for the 227 vehicles.

It was assumed that the PHEV fleet is evenly divided into the 227 driving profiles corresponding to the driving pattern data. All vehicles of each PHEV type are dispatched identically, thus were modeled 227 different 'PHEV types' corresponding to the driving profiles. The total contribution to the objective function and load balance constraints from each PHEV type is determined by multiplying the variables associated with each PHEV type by the number of PHEVs of that type.

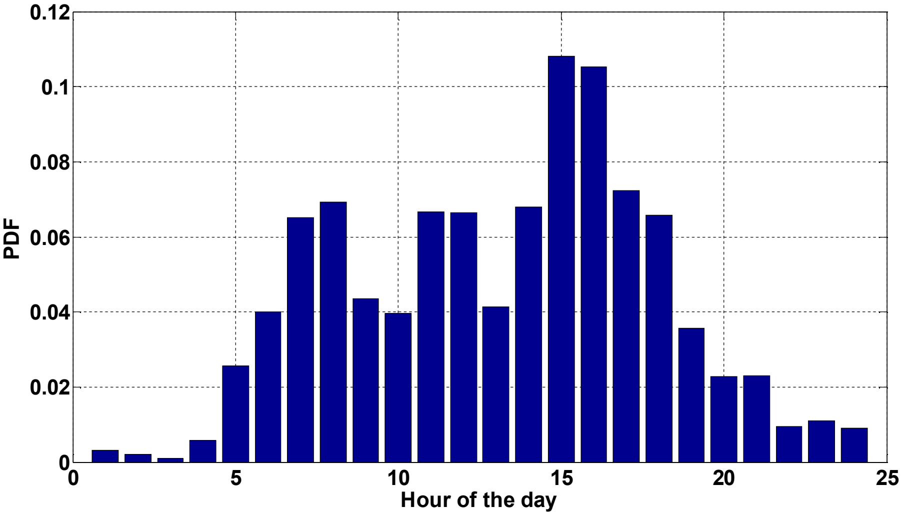

Figure 4.9: Average distribution of driving distance during the day.

The driving data was 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 be dispatched to charge their batteries. In doing so, it was supposed that a PHEV must not be driving for an entire hour for it to be considered 'grid-connected' in that hour. 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. Using the Advanced Vehicle Simulator (31), the driving pattern data was used to simulate the average gasoline and battery energy usage for each PHEV driving profile in both CD and CS modes. As is typically proposed in PHEV designs, it has been assumed that vehicles are driven in CD mode until the battery SOC reaches 30% of the battery's maximum storage capacity, at which point it is driven in CS mode and remains at 30% SOC unless recharged by grid-connecting. It was supposed that PHEVs have always sufficient gasoline to operate in either CS or CD mode. PHEV battery was assumed to have an energy storage capacity of 9.4kWh, which corresponds to an electric-only driving range of between 30 km and 60 km, depending on the vehicle class, and that the battery can only be discharged to a 30% SOC, all PHEV characteristics are reassumed in Table 4-3.

Characteristic	Value
Battery Capacity	9.4 kWh
Vehicle Mass	1488 kg
All-electric Range	60 km
Average Energy Use Over Drive Cycle	23 km/l and 59 Wh/km
CD-mode Electric Energy Use	0.183 kWh/km

Table 4-3: PHEV characteristics.

The plugs of the charging stations were supposed to have a power capacity of 1.875 kW (as a standard 120 V home circuit) with a charging efficiency of 90%.

Vehicle tailpipe emissions were estimated using emissions regulations and gasoline chemical composition. CO_2 emissions were estimated at 8.87 kg/gallon (about 2.35 kg/liter) of gasoline burned. For SO2 emissions, was assumed that emissions will exactly comply with EPA's Tier2 requirement of 0.17 g/gallon (about 0.045 g/liter) of gasoline burned. Tier2 also requires NOx emissions to be less than 0.07 g/mile (about 0.04 g/km). It was assumed that CVs and HEVs will be designed to exactly meet these requirements and PHEV emissions were estimated from HEV emissions based on proportional reduction in gasoline consumption.

5. Results

Effects of charging on the grid and on the energy dispatch

As shown in Figure 5.1, the annual load pattern shows two seasonal peaks: one in winter and the other and in the summer that are caused by heating and cooling loads, respectively. In 2007, these peaks occurred on February 6th and on August 8th, respectively. The bigger of these peaks is during the summer, as most building heating typically uses a fossil fueled furnace as opposed to electricity, whereas all building cooling is done using electricity. It is clear from the figure that Ohio's generation capacity is above the maximum annual load and that the state has a healthy reserve margin available. However this picture does not take into account the limits of transportation lines and the fact that could be not possible for the grid administrator to transport electricity from power plants to where loads are connected to the grid.

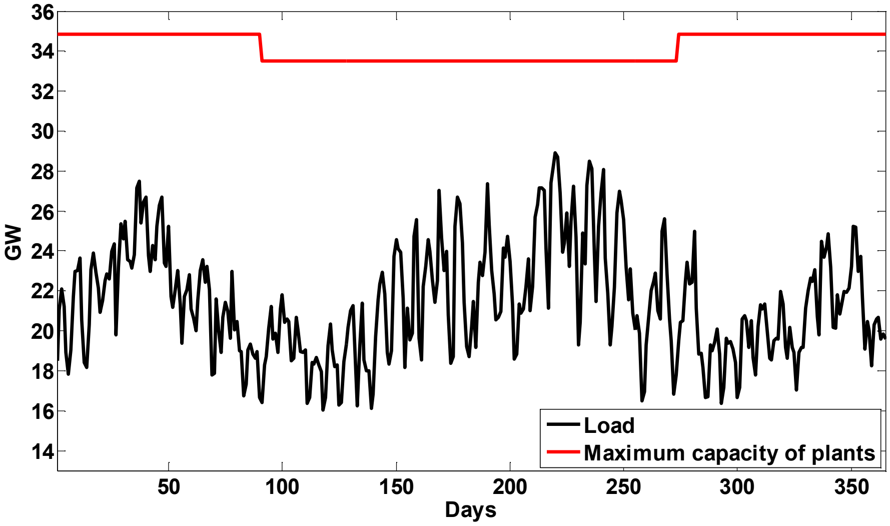

Figure 5.1: Maximum daily load and generating capacity in Ohio during the year 2007 without PHEVs.

Figure 5.2 and Figure 5.3 show the diurnal load profit on two sample days, one in the winter and the other in the summer.

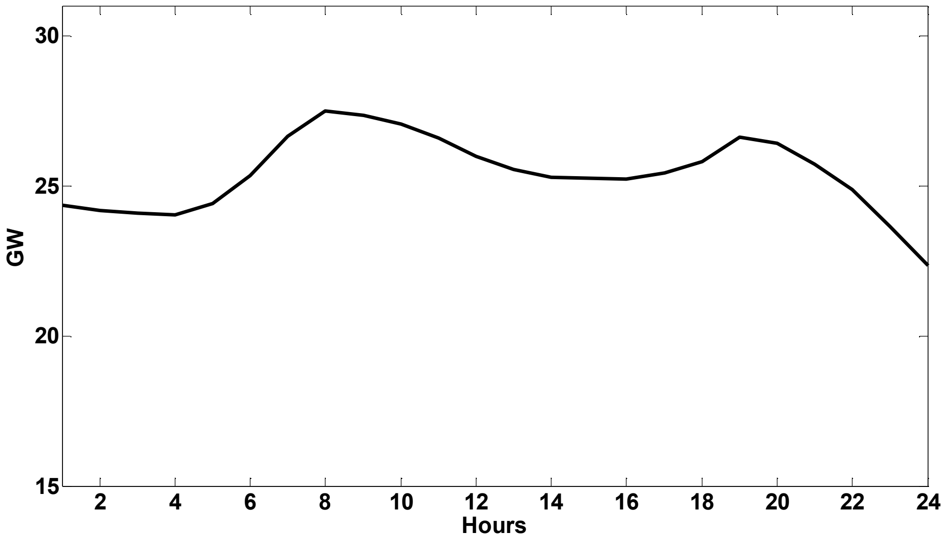

Figure 5.2: Total load on the grid on February 6th.

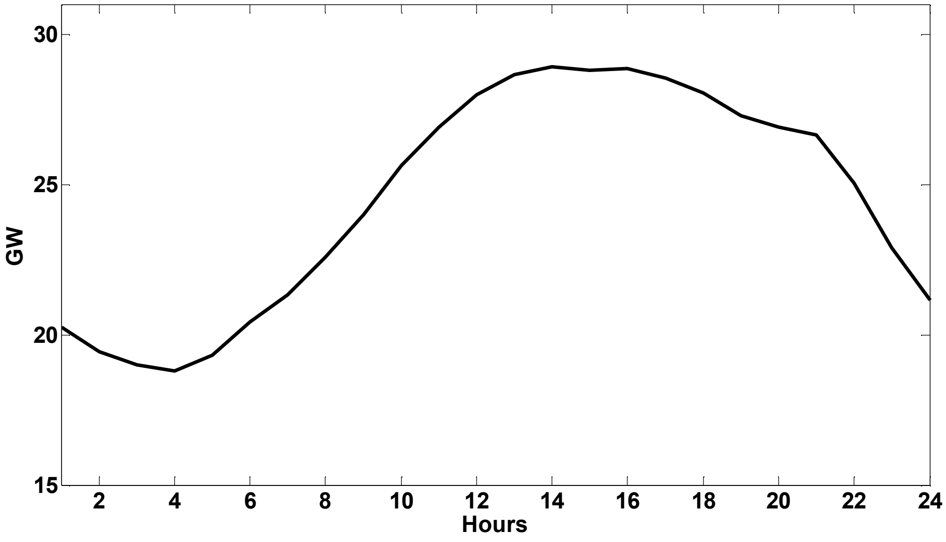

Figure 5.3: Total load on the grid on August 8th.

Figure 5.2 shows that the typically diurnal load profile in the winter has two peaks, with the highest load around 10 AM with a power demand of 27.5 GW; Figure 5.3 shows that during the summer load profile has one single higher peak around 3 PM, with a power demand of 29 GW. On the summer day the maximum load appears in the afternoon around 3 PM with the load reaching 29 GW, which happens to be the maximum annual load on the grid.

The PHEV charging scenario will influence the power demand on the grid and the dispatch of generators during the day. 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. Figure 5.4 shows how a controlled strategy charging will affect the load profile on the grid the summer peak day.

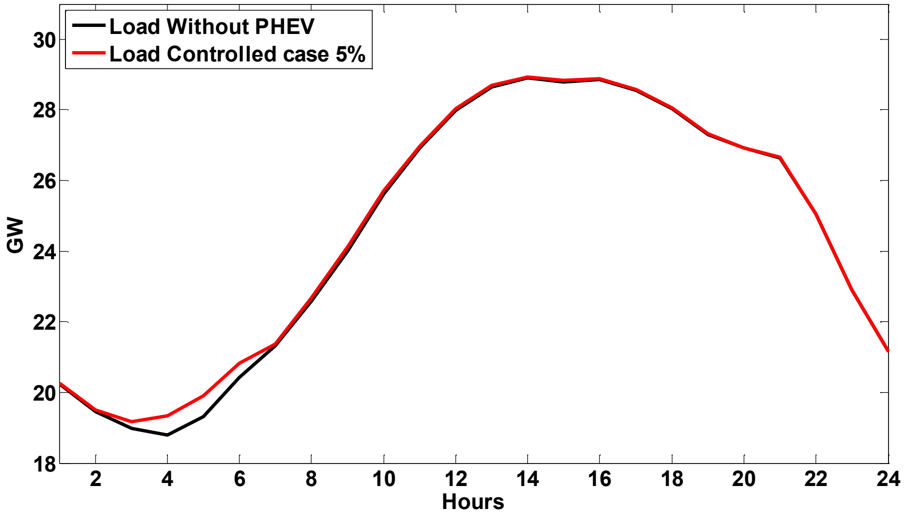

Figure 5.4: Effect of a controlled charging on the load profile.

Figure 5.5 represents the charging load profile on the power grid due to PHEVs use for the summer peak load, it is possible to see how there is a concentrate load in the morning that reach a peak of 600 MW while minimal load is added on the grid during the afternoon. Looking at the charging load profile for the winter peak instead, is clear how part of the vehicles charging is done also during the afternoon because the load on the grid is not too high to avoid it. In this way PHEVs owners could save more gasoline when driving back home after work.

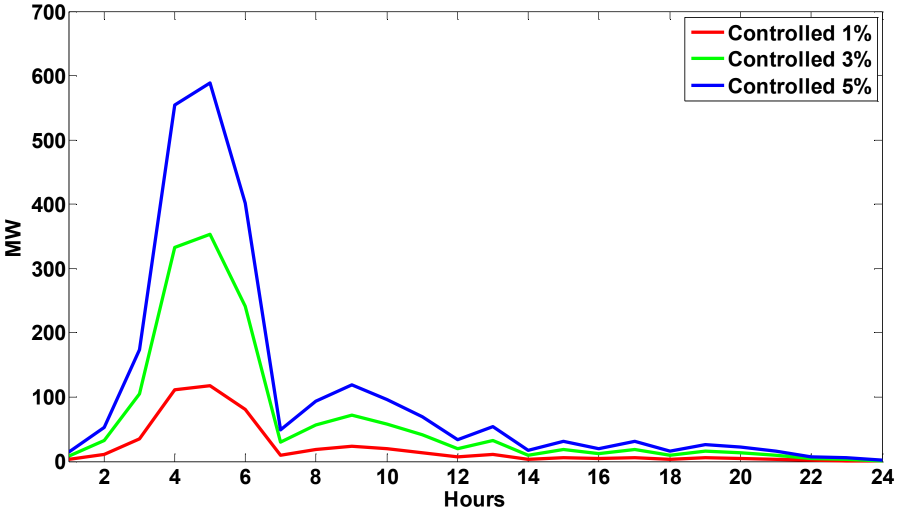

Figure 5.5: Controlled charging load profile for August 8th.

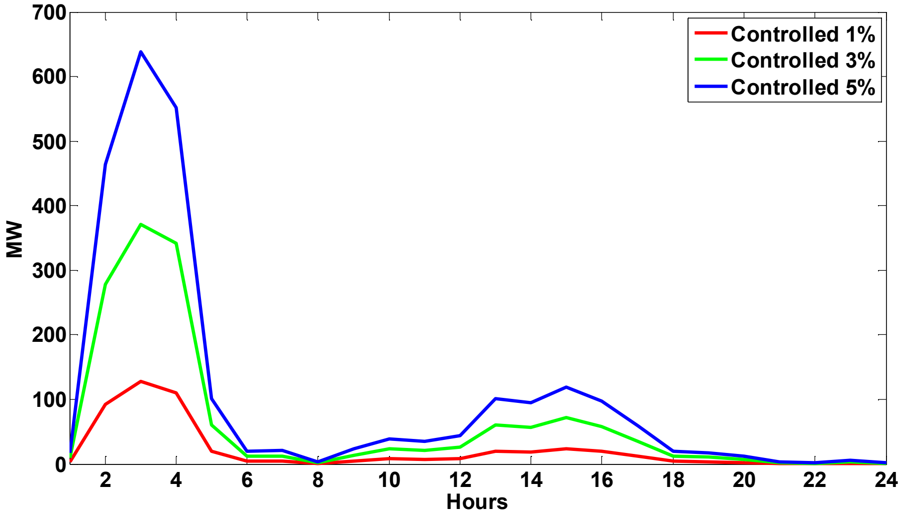

Figure 5.6: Controlled charging load profile for February 6th.

With an uncontrolled strategy charging load is no more optimized by the grid administrator and vehicles are recharged whenever are parked for at least one hour without any regards to the power grid. Figure 5.7 represent the charging load profile with an uncontrolled strategy, depending only on driver's statistical information charging load is constant all the days of the year in the simulation.

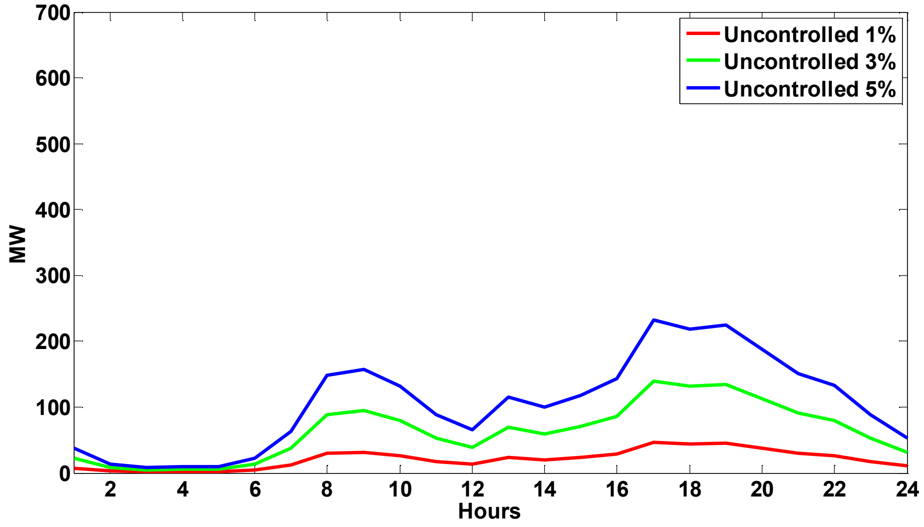

Figure 5.7: Uncontrolled charging load profile.

The charging load is less intensive respect to the controlled scenario but is distributed during the morning and the afternoon, and especially during the summer will increase afternoon peak loads on the grid. In Figure 5.8 it is possible to see that with an uncontrolled charging strategy the peak load on the grid increases.

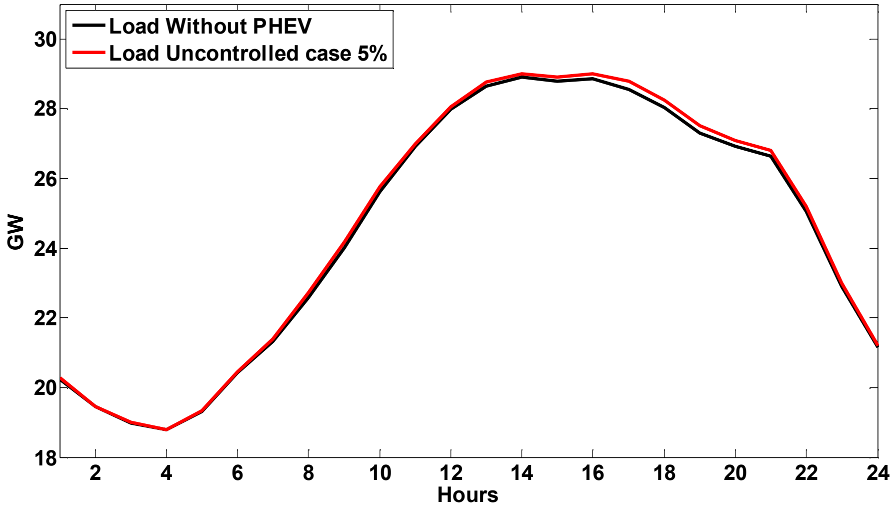

Figure 5.8: Effect of the uncontrolled charging on the load profile.

With 5% of PHEV penetration in the market the peak load is not increased considerably; but in the future with larger PHEV market penetration charging load could start creating considerable problems for the grid reliability. National Research Council has proposed in a recent study that PHEV market penetration could reach 30% of light-duty fleet by the year 2050. Being uncontrolled charging load fixed by driver's behaviors in the model, taking the 5% penetration load and multiplying it six times, the charging load profile of a hypothetical case with 30% PHEV penetration can be calculated. Than adding it at the already existing load present on the grid it is possible to make a first estimation on how load profile could change on the grid in this scenario. Results are shown in Figure 5.9; summer peak load is increased by 3.4% reaching 30 GW and shifted later in the afternoon. Also, if generating capacity available in Ohio is greater than that value, the effects of such a load on the transportation lines should be analyzed. This analysis requires more detailed information on the grid scheme and where exactly generators and load are located. Such considerations are beyond the scope of this work and will not be considered in this analysis.

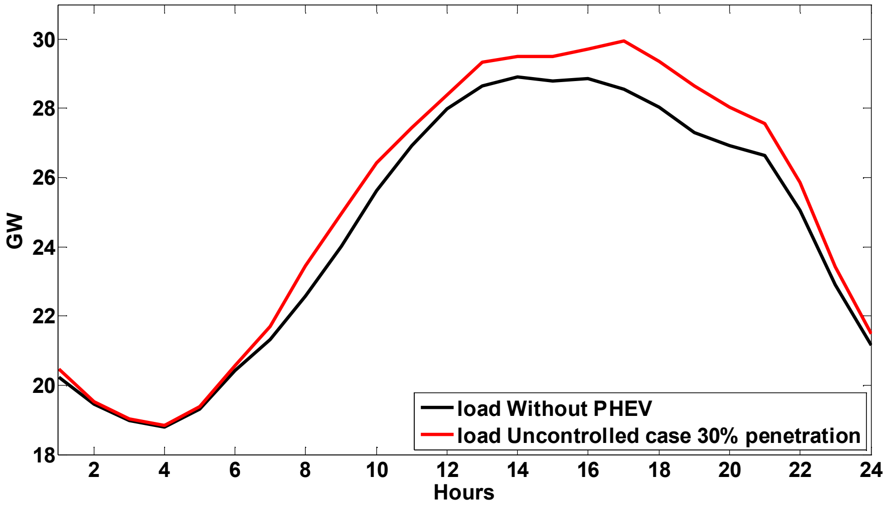

Figure 5.9: Summer peak load on the grid with a 30% PHEV penetration in the market.

Emissions Impacts of PHEV charging scenarios

PHEVs are supposed to reduce pollutants by using electricity instead of gasoline as a transportation energy source. Their net emissions impact will be strictly related to the generation mix in the power system in question, and the mix of generating technologies used to serve the vehicle charging load. In a system with a high penetration of renewable or nuclear power plants, the net emissions associated with PHEVs can be very low, as opposed to a system with predominantly coal which would yield higher PHEV emissions. In some systems the charging scenario will also be an important factor, since different generating fuels can be marginal at different times of day, which would result in very different generator emissions depending on when PHEVs are charged.

In Ohio, for instance, a controlled charge will give charging in periods with low loads and most of the generation will be supplied by base-load units that usually are nuclear or coal plants. Uncontrolled charging, on the other hand, is done during the afternoon and is covered with peak-load plants such as gas turbines.

In the case of Ohio the high penetration of coal plants results in an increase of total SO2 emissions, a decrease of total CO2 emissions, and minimal variation of NOx emissions, as shown in Table 5-1,Table 5-2 and Table 5-3.

	Without PHEV	Controlled 5%	Uncontrolled 5%
Generators	130,04	130,01	129,84
Cars	30,34	30,31	31,45
Total	160,38	160,32	161,29
Difference		-0.56%	-0.60%

Table 5-1: Total annual CO2 emissions (megatons) with 5% PHEV penetration.

	Without PHEV	Controlled 5%	Uncontrolled 5%
Generators	130,54	130,49	130,05
Cars	6,15	6,14	6,33
Total	136,69	136,63	136,38
Difference		+0.001%	-0.04%

Table 5-2: Total annual NOx emissions (kilotons) with 5% PHEV penetration.

	Without PHEV	Controlled 5%	Uncontrolled 5%
Generators	984.97	984,59	983,52
Cars	0,56	0,56	0,58
Total	985,53	985,148	984,1
Difference		+0.14%	+0.10%

Table 5-3: Total annual SO2 emissions (kilotons) with 5% PHEV penetration.

Figure 5.10 shows that the emissions impacts on a per-vehicle basis, showing that PHEV use can yield some CO_2 emissions of around 1.1 tons on an annual basis in an uncontrolled charging case, which corresponds to a 24% emissions reduction. With a controlled strategy, on the other hand, the CO_2 emissions reductions are minimal.

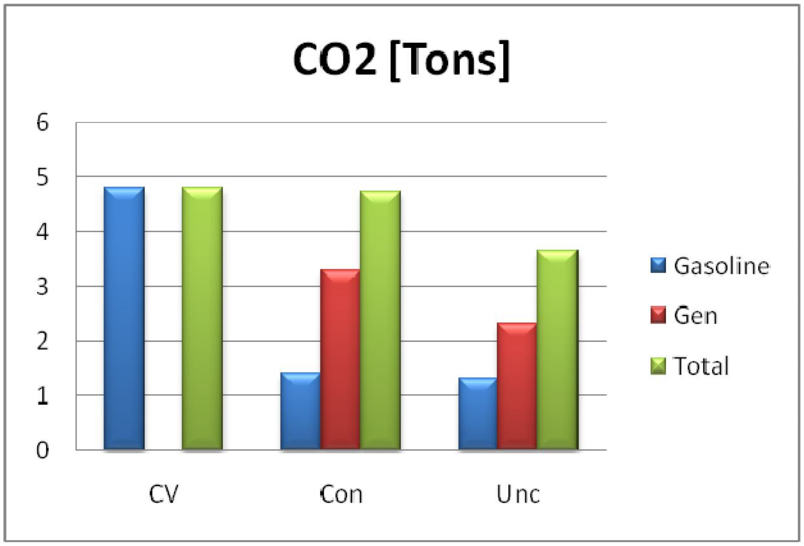

Figure 5.10: Annual per-vehicle CO2 emissions (tons).

Annual NOx 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; Figure 5.11 shows annual per-vehicle

NOx emissions. Due to the high penetrations of coal and heavy oil as generation fuels, annual per-vehicle SO2 emissions will increase by between 10 and 12 kg with PHEV use, as shown in Figure 5.12.

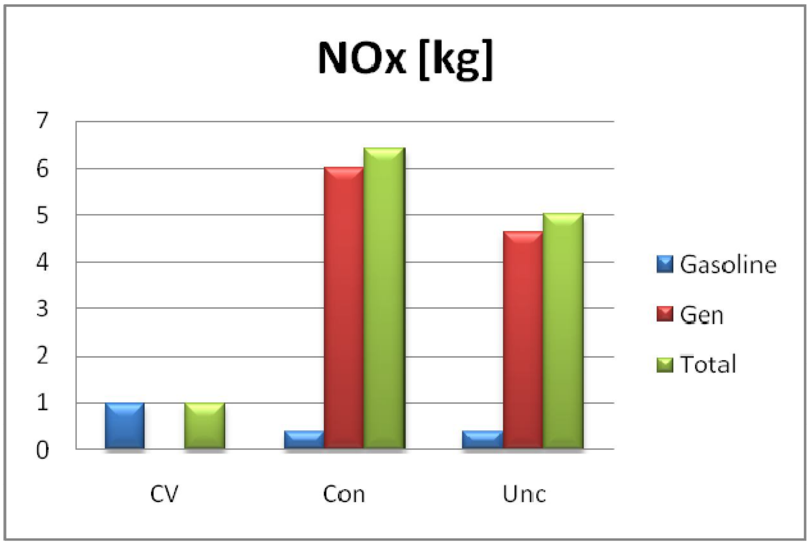

Figure 5.11: Annual per-vehicle NOx emissions (kg).

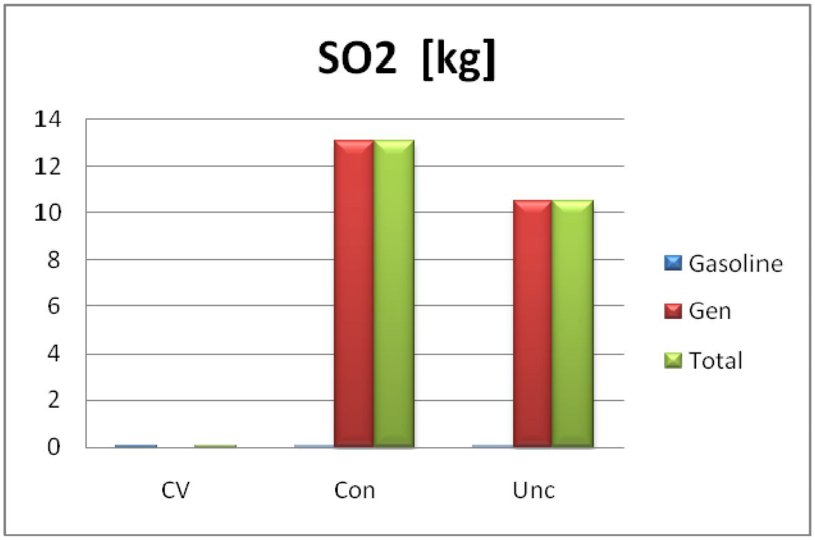

Figure 5.12: Annual per-vehicle SO2 emissions (kg).

Looking at the results summarized in Figure 5.13, it is clear that if the primary goal of PHEV use is reducing emissions, the uncontrolled charging scenario would be preferred since CO_2 and SO_2 emissions are lower with a negligible difference in NOx emissions.

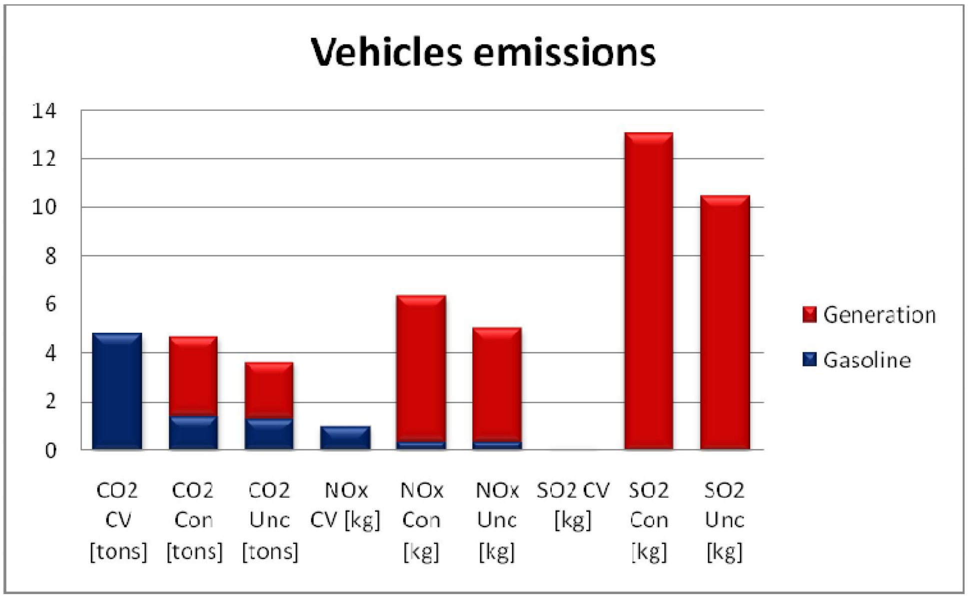

Figure 5.13: Resume of annual per-vehicle emissions.

This result is not, however, universally true and the emissions impacts will be highly sensitive to the generation mix. For example, in countries like France or Switzerland where hydroelectricity and nuclear is more abundant, controlled charging may be preferred since more hydroelectricity and nuclear may be used for vehicle charging. For this reason, using PHEVs in these countries may be more beneficial from a net emissions standpoint than countries such as the United States and Germany, which have a large mix of coal-fired generation. Figure 5.14 compares the generation mix of these countries, which can help to deduce the differences in emissions impacts of PHEV use.

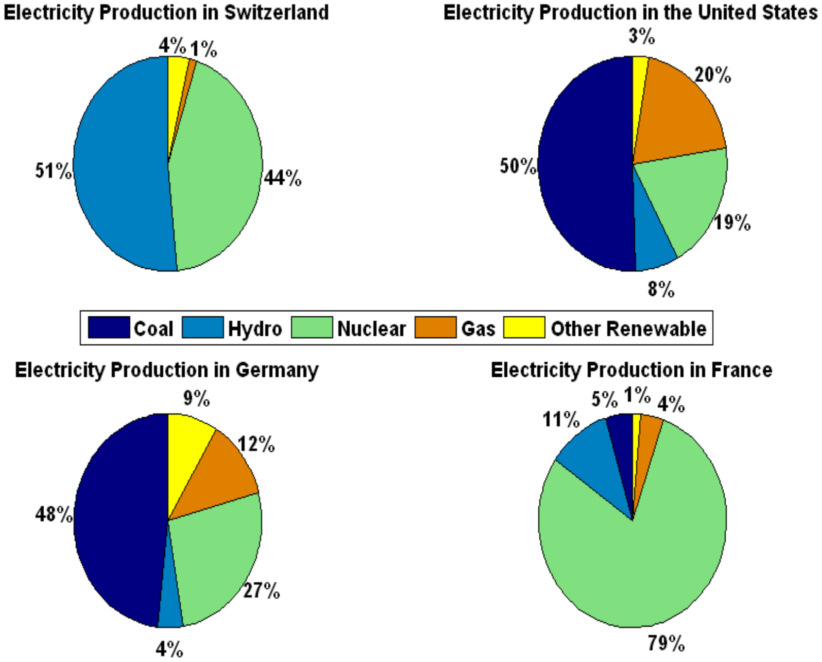

Figure 5.14: Electricity generation mix of different countries in 2007.

PHEV ownership cost

This analysis has thus far focused on how PHEVs affect emissions, showing that PHEVs could be useful in reducing emissions. Now it turns to the question of the ownership cost of PHEVs and whether PHEV purchases would be economically sustainable for potential buyers. This analysis assumes a future scenario in which the requisite charging and control infrastructures needed for control charging, such as charging stations that can exchange information with and be controlled by the grid operator, are in place.

Vehicle purchasing cost

The architecture of a PHEV is different from 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, PHEVs use 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.

Today, to buy a conventional vehicle a customer has to spend around 21,000$, and this price is not expected to vary significantly in the future. To buy a PHEV40, instead, he needs around 51,000$ currently, while for the future a cost reduction is estimated leading prices about 27,000$. With these cost reductions, PHEVs are expected to have a price premium of approximately 6000$ (relative to conventional vehicles) (32).

Vehicle operating cost

Analysis of vehicle operating costs focuses on the cost of fuels, gasoline and electricity, for PHEVs and compares it to the driving costs of CVs. The average daily trip of drivers considered in the model is about 60 kilometers and the PHEVs considered have an all-electric range of approximately 35 kilometers.

Figure 5.15 shows that gasoline savings can reach more than 70% and one single PHEV will reduce annual gasoline consumption by an average of around 1500 liters compared to a CV.

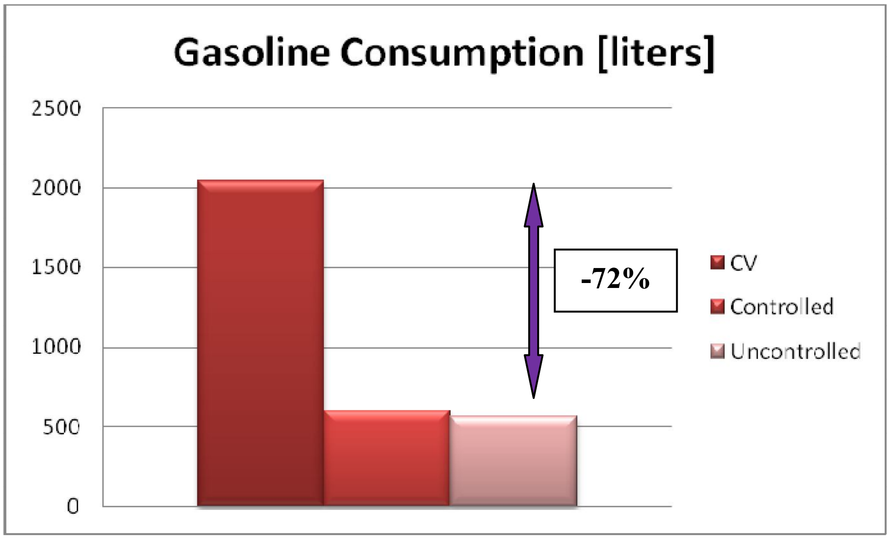

Figure 5.15: Average annual per-vehicle gasoline consumption (liters).

		Annual Gasoline Savings	
	Total Annual Gasoline Used (liters)	liters	%
Conventional vehicles	13,143,860,403		
5% penetration of PHEVs with controlled charging	12,681,519,134	462,341,268	3.5%
5% penetration of PHEVs with uncontrolled charging	12,668,496,002	475,364,400	3.6%

Table 5-4: Annual liters of gasoline burned by all light-duty vehicles (PHEVs and CVs) in Ohio in 2007.

Table 5-4 summarizes total gasoline consumption by the entire light-duty vehicle fleet (including non-PHEVs) and shows that a 5% penetration of PHEV in Ohio will decrease total vehicle fleet gasoline consumption by about 3.5%. Although fuel consumption is reduced through use of PHEVs, there will be an increase in electricity demand.

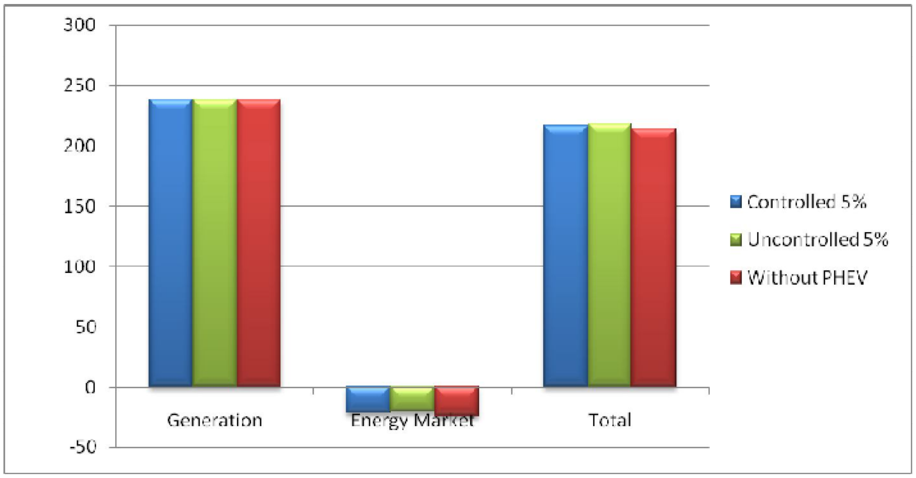

Figure 5.16: Annual generation cost for Ohio in 2007 ($ million).

Figure 5.16 shows total annual generation costs, broken down by the cost of in-state generation and net purchases from the rest of the market, with and without the PHEV fleet, showing that the net impact on generation costs will be a mere 0.1% increase. The cost of this electricity to PHEV owners is difficult to determine, because it is not clear what retail rates will be charged to PHEV owners. Retail residential electricity rates were averaged about 0.111 $/kWh in Ohio in 2007 (33), based on values reported by the EIA. 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. This simulations show that adding the PHEV charging loads increase 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, utility 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 that PHEV owners do not pay due to reduced gasoline consumption. For this reason, this cost analysis is done by parameterizing the cost of electricity.

Similarly, although the average retail price of gasoline in Ohio in 2007 was 2.27 $/gallon (around 8.6 $/Liter) (34), 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. Thus, also the price of gasoline is parameterized in the analysis. Furthermore, this cost analysis focused on the uncontrolled charging scenario, since this is the most likely scenario when PHEVs first enter the vehicle fleet. Figure 5.17 shows annual PHEV and CV operating costs based on 2007 electricity and gasoline prices, showing that PHEVs will spend on average 46% less than CVs on transportation fuel.

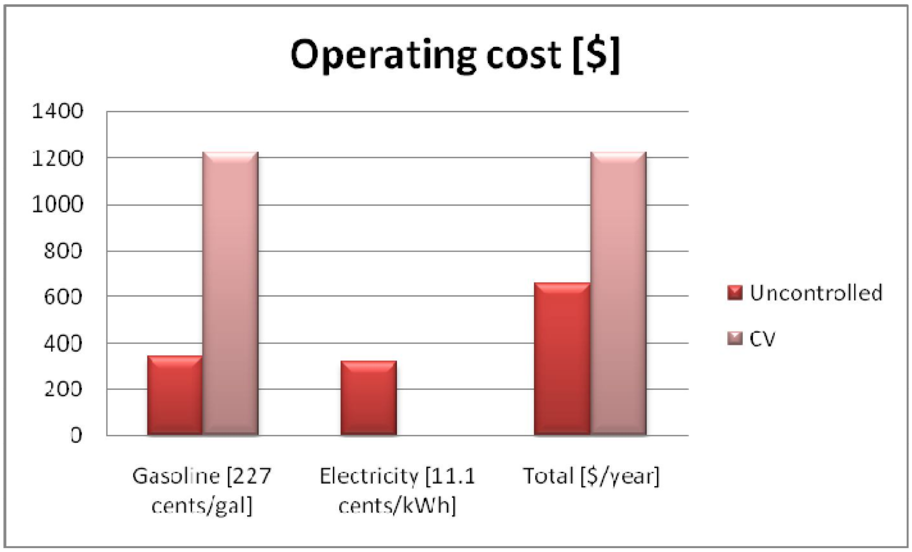

Figure 5.17: Average annual vehicle operating cost.

Figure 5.18 summarizes the effect of gasoline and electricity prices on the relative operating cost savings of PHEVs over CVs.

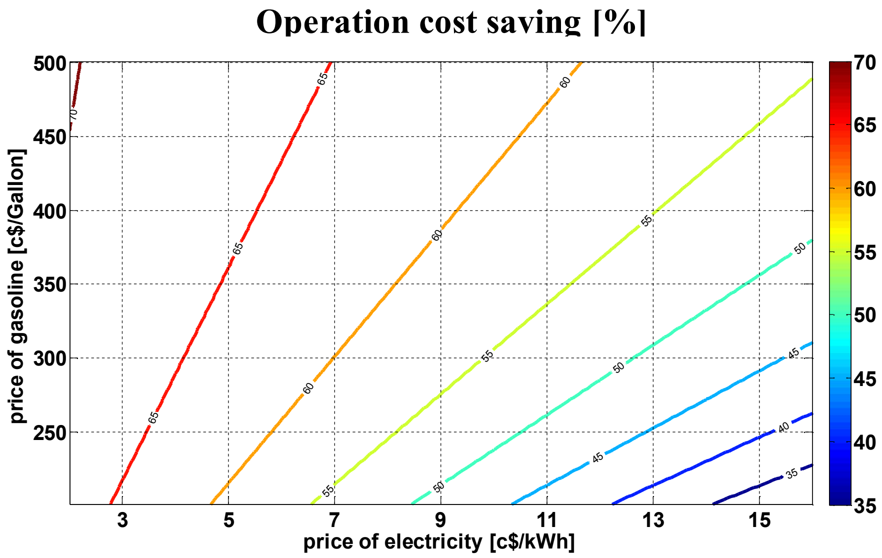

Figure 5.18: Fuel cost saving of a PHEV relative to a CV, as a percentage of CV fuel cost.

Payback time of PHEVs

Payback time is an important factor in determining whether future consumer will decide to buy a PHEV. The basic tradeoff facing the consumer is the higher upfront capital cost of a PHEV relative to the stream of driving cost savings due to reduced gasoline costs. Figure 5.19 and Figure 5.20 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) drive the price difference between a PHEV and CV to these levels.

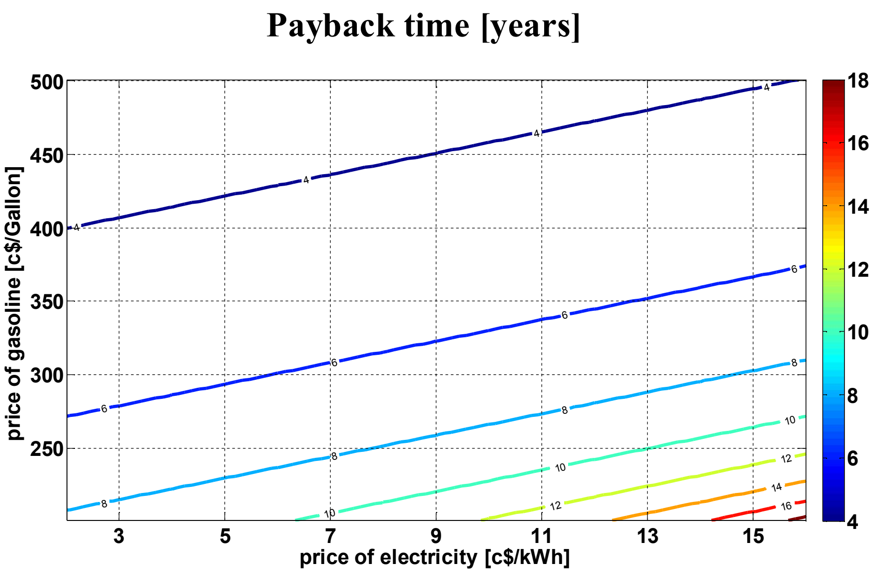

Figure 5.19: Payback time of a PHEV as a function of gasoline and electricity prices with an additional investment cost of 6,000$.

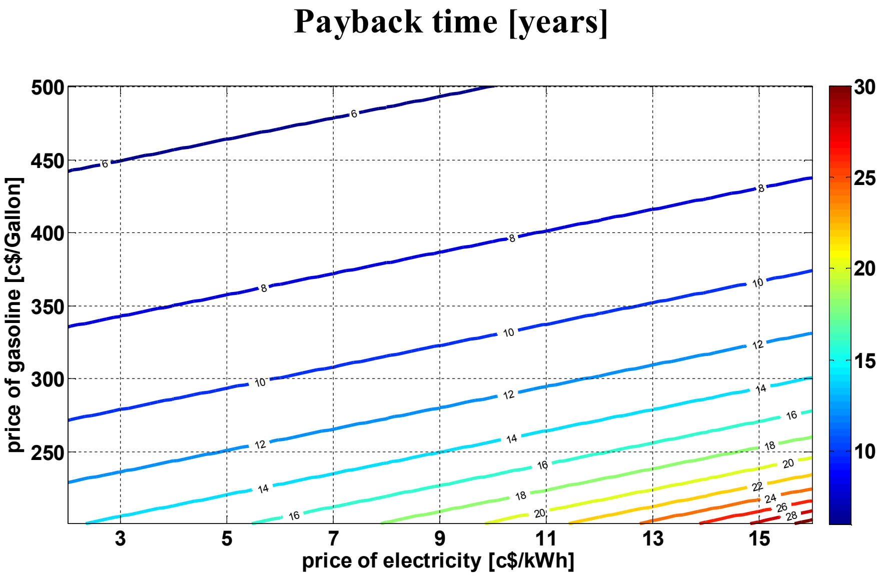

Figure 5.20: Payback time of a PHEV as a function of gasoline and electricity prices with an additional investment cost of 10,000$.

6. Conclusions

This work is a summary of the research activities conducted at the Centre for Automotive Research on modeling the interaction between PHEVs and the power grid. The effects of PHEVs on the electric power grid, their owners and the global environmental aspect were analyzed for the State of Ohio. The analysis is based upon a unit commitment model of the Ohio electric power system formulated using AMPL and solved with the cut and branch algorithm of cplex 12.1; the model simulates the commitment and dispatch of conventional generators as well as the dispatch of PHEVs to charge when not being driven. Generation data were estimated based on historical CEMS data from the EPA. Two different charging scenarios, controlled and uncontrolled, have shown that the strategy used to recharge PHEVs batteries will have a big impact on their emissions.

Analysis results show that with such a high coal penetration in the generation mix, the best strategy (from an environmental point of view) would be the uncontrolled charging. This strategy leads to an annual decrease of about 1 ton of CO2 emitted by a single vehicle (around 24%) while SO2 and NOx will be increased due to high use of coal for power generation; better results could be obtained using cleaner sources of energy to generate electricity.

However it has to be considered that with an uncontrolled strategy, PHEVs charging will increase peak load on the grid because vehicles will be plugged-in during the afternoon when load on the grid is already high. Considering a future scenario with a PHEV penetration in the market of 30% it was estimated that the highest peak load on the grid, the summer peak load, is going to increase more than 3%. An increased peak load could need more generating capacity to be installed; furthermore it has to be considered if electricity could be transported from power plants to where vehicles are plugged-in without exceeding transportation limits of the grid.

Another important benefit is that PHEVs have the potential to reduce oil consumption, in this way they can decrease dependence from importations avoiding problems due to oil price instability: results show that a single PHEV can save more than 70% in terms of gasoline with respect to a conventional vehicle in Ohio. Since electricity is a cheaper transportation fuel than gasoline there will be a great reduction in vehicle operation costs, with payback time for customers between 8 and 12 years (depending on the PHEV capital cost premium) with a gasoline price of 3 \$/gal and an electricity price of 0.11 \$/kWh.

Future studies could analyze which influence an increase of electricity demand, due to PHEVs market penetration, could have on electricity price; than analysis could evaluate if specific policies will be necessary to help PHEV entering the market and how states should act on this topic. Another important aspect that has not been covered by this analysis is V2G services and how they could change the market of energy and costs for PHEVs owners, future studies could also focus on a smaller-scale system analyzing power flows on single lines of the grid to verify if charging loads could create problems for grid reliability.

Another important area of research that has to be explored yet is the use of PHEVs batteries as distributed energy storage devices; in this way they can help renewable power sources spread in the electric market reducing their unpredictability.

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Publications

This work has been submitted in different forms to two conferences and to a journal:

- *Cost and Emissions Impacts of Plug-In Hybrid Vehicles on Ohio Power Grid.* **R. Fagiani, V.Marano, R.Sioshansi.** Energy Engineering, Economics and Policy: EEEP 2010, June 29th - July 2nd, 2010 – Orlando, Florida, USA. (Draft paper submitted).
- *Cost and Emissions Impacts of Plug-In Hybrid Vehicles (PHEVs) and their Interaction with the Electric Power System.* **R. Fagiani, V.Marano, R.Sioshansi.** International Conference on Sustainable Energy & Environmental Protection: SEEP 2010, June 29th - July 2nd, 2010 – Politecnico di Bari, Bari, Italy. (Abstract accepted).
- *Cost and Emissions Impacts of Plug-In Hybrid Vehicles on the Ohio Power System.* **R.Sioshansi, R.Fagiani, V.Marano.** Energy policy, 2010. (Draft paper submitted).