A Life-Cycle Approach To Technology, Infrastructure, And Climate Policy Decision Making: Transitioning To Plug-In Hybrid Electric Vehicles And Low-Carbon Electricity

A Dissertation

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Abstract

In order to mitigate the most severe effects of climate change, large global reductions in the current levels of anthropogenic greenhouse gas (GHG) emissions are required in this century to stabilize atmospheric carbon dioxide (CO_2) concentrations at less than double pre-industrial levels. The Intergovernmental Panel on Climate Change (IPCC) fourth assessment report states that GHG emissions should be reduced to 50-80% of 2000 levels by 2050 to increase the likelihood of stabilizing atmospheric CO_2 concentrations. In order to achieve the large GHG reductions by 2050 recommended by the IPCC, a fundamental shift and evolution will be required in the energy system.

Because the electric power and transportation sectors represent the largest GHG emissions sources in the United States, a unique opportunity for coupling these systems via electrified transportation could achieve synergistic environmental (GHG emissions reductions) and energy security (petroleum displacement) benefits. Plug-in hybrid electric vehicles (PHEVs), which use electricity from the grid to power a portion of travel, could play a major role in reducing greenhouse gas emissions from the transport sector. However, this thesis finds that life cycle GHG emissions from PHEVs depend on the electricity source that is used to charge the battery, so meaningful GHG emissions reductions with PHEVs are conditional on low-carbon electricity sources. Power plants and their associated GHGs are long-lived, and this work argues that decisions made regarding new electricity supplies within the next ten years will affect the potential of PHEVs to play a role in a low-carbon future in the coming decades. This thesis investigates the life cycle engineering, economic, and policy decisions involved in transitioning to PHEVs and low-carbon electricity.

The government has a vast array of policy options to promote low-carbon technologies, some of which have proven to be more successful than others. This thesis uses life cycle assessment to evaluate options and opportunities for large GHG reductions from plug-in hybrids. After the options and uncertainties are framed, engineering economic analysis is used to evaluate the policy actions required for adoption of PHEVs at scale and the implications for low-carbon electricity investments. A logistic PHEV adoption model is constructed to parameterize implications for low-carbon electricity infrastructure investments and climate policy. This thesis concludes with an examination of what lessons can be learned for climate, innovation, and low-carbon energy policies from the evolution of wind power from an emerging alternative energy technology to a utility-scale power source. Policies to promote PHEVs and other emerging energy technologies can take lessons learned from the successes and challenges of wind power's development to optimize low-carbon energy policy and R&D programs going forward.

The need for integrated climate policy, energy policy, sustainability, and urban mobility solutions will accelerate in the next two decades as concerns regarding GHG emissions and petroleum resources continue to be environmental and economic priorities. To assist in informing the discussions on climate policy and low-carbon energy R&D, this research and its methods will provide stakeholders in government and industry with plug-in hybrid and energy policy choices based on life cycle assessment, engineering economics, and systems analysis.

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List of Abbreviations

AWEA	American Wind Energy Association
BBL	Barrel
BOS	Balance of Station or System
CAISO	California Independent System Operator
CCS	Carbon Capture and Sequestration
CO_2-eq	Carbon Dioxide Equivalent (100-year time scale)
CV	Conventional Vehicle
DOE	US Department of Energy
EIA	US Energy Information Administration
EIO	Economic Input-Output
EPA	US Environmental Protection Agency
EPRI	Electric Power Research Institute
ERCOT	Electric Reliability Council of Texas
EV	Electric vehicle
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
HOV	High Occupancy Vehicle
ICE	Internal Combustion Engine
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
ISO	Independent System Operator
kW	Kilowatt
LCA	Life Cycle Assessment
Li-ion	Lithium Ion
MISO	Midwest Independent System Operator
MJ	Megajoule
MPG	Miles per Gallon
MSA	Metropolitan Statistical Area
NiMH	Nickel-Metal Hydride
NPV	Net Present Value
PURPA	Public Utilities Regulatory Act of 1978
PHEV	Plug-in Hybrid Electric Vehicle
PPM	Parts Per Million
PTC	Production Tax Credit
PV	Photovoltaic
REPI	Renewable Energy Production Incentive
RTO	Regional Transmission Organization
R&D/RD&D	Research and Development (and Deployment)
RPS	Renewable Portfolio Standard
SOC	State of Charge
US	United States
USABC	United States Advanced Battery Consortium
V2G	Vehicle-to-Grid

Chapter 1: Introduction and Motivation

1.1 Problem Statement

Policymakers, researchers and the public are becoming increasingly concerned about climate change associated with anthropogenic emissions of greenhouse gases (GHGs) and the adverse impacts on ecosystems, economies, and populations. In order to mitigate the most severe effects of climate change, large global reductions in the current levels of GHG emissions are required in this century to stabilize atmospheric carbon dioxide (CO_2) concentrations at less than double pre-industrial levels (*1-5*). The Intergovernmental Panel on Climate Change fourth assessment report states that GHG emissions should be reduced to 50-80 percent of 2000 levels by 2050 to increase the likelihood of stabilizing atmospheric CO_2 concentrations (*1*).

In the United States (US), GHG emissions were about 7,050 million metric tons of CO_2-eq in 2006; 14.7 percent higher than U.S. emissions in 1990. CO_2 was the predominant GHG, representing about 85 percent of emissions in 2006 (see **Figure 1.1**) (*6*). Anthropogenic CO_2 is primarily emitted via the combustion of fossil fuels, which provide electricity, heat, propulsion and other services to decentralized constituencies throughout the economy. The electricity and transportation economic sectors represent the two largest sources of GHG emissions in the US, as shown in **Figure 1.2**. Burning fossil fuels in the electric power and transportation sectors accounted for 61 percent of GHG emissions in the US in 2006. Combustion emissions from US automobiles and light-duty trucks accounted for approximately 62 percent of US GHG emissions from the transport sector, or 18 percent of total US GHG emissions (*6*).

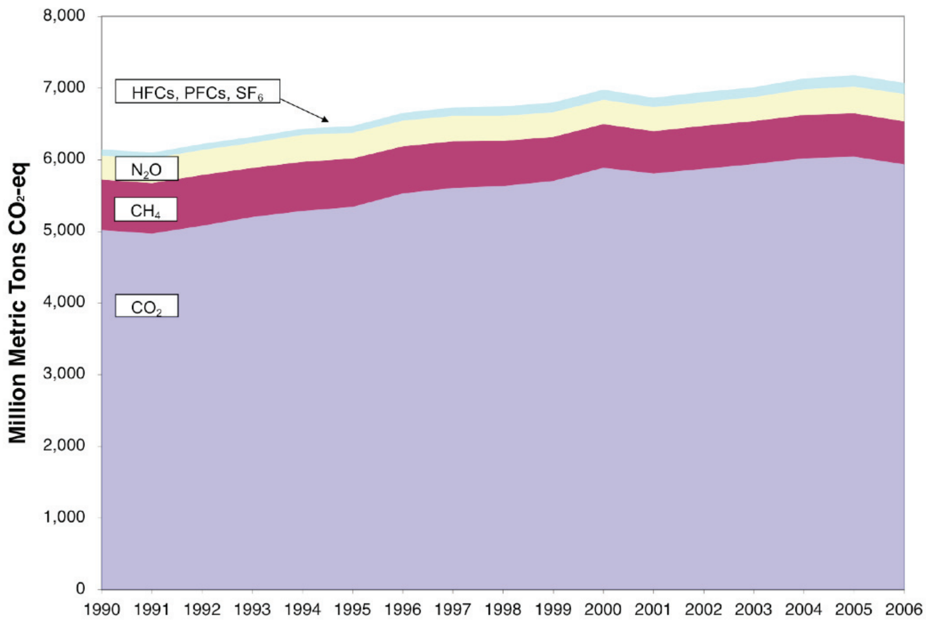

Figure 1.1. Share of CO_2, CH_4, N_2O, and other GHGs in the US from 1990-2006. Constructed with data from (*7*).

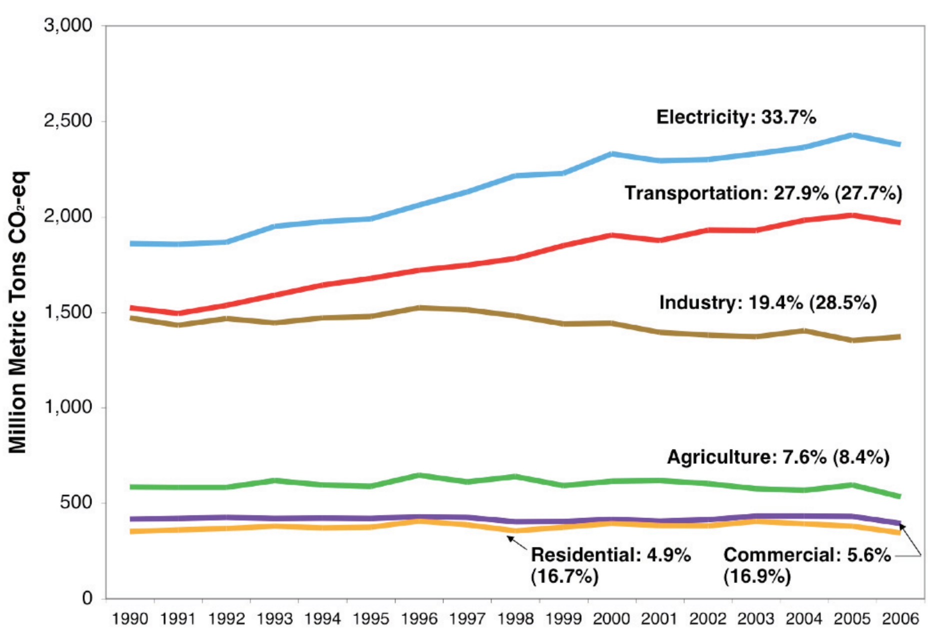

Figure 1.2. US GHGs by economic sector from 1990-2006. Numbers in parentheses represent percent of GHGs by end-use sectors. Constructed with data from (*6*)

In addition to concerns about climate change, dependence on imported oil supplies is seen as a threat to US national security (*8*). Petroleum provided about 96% of the energy to power the transportation sector in the US in 2006 (*9*). Passenger vehicle transportation, consisting of the light duty vehicle fleet (LDV), is overwhelmingly powered by gasoline. 8.9 million barrels of petroleum per day were supplied to US light duty vehicles in 2006, representing about 17 QBTU, or quads (17 EJ) of energy (*9*). Total US petroleum consumption was 20.73 million barrels per day in 2006, with net imports of crude oil and petroleum products representing about 10.1 and 3.5 million barrels per day, respectively. Hence, petroleum use in light duty vehicles represented about 65% of US petroleum imports in 2006. As shown in **Figure 1.3**, the transportation sector share of petroleum consumption has been rising, representing about 200 percent of domestic petroluem production in 2006 (*9*).

Because the transportation sector currently relies so heavily on petroleum for energy, oil price shocks have the potential to affect the wider economy. In the review by Jones, Leiby, and Paik (*10*), the authors report that most research has found US recessions following oil price shocks are largely attributable to the oil price and could not have been avoided through monetary policy. The authors also state empirical data shows that oil price shocks result in reallocation of labor in the economy. Real imported oil prices and U.S. recessionary periods are shown in **Figure 1.4**, and the effects of high oil prices on the U.S. economy remains a concern among policymakers.

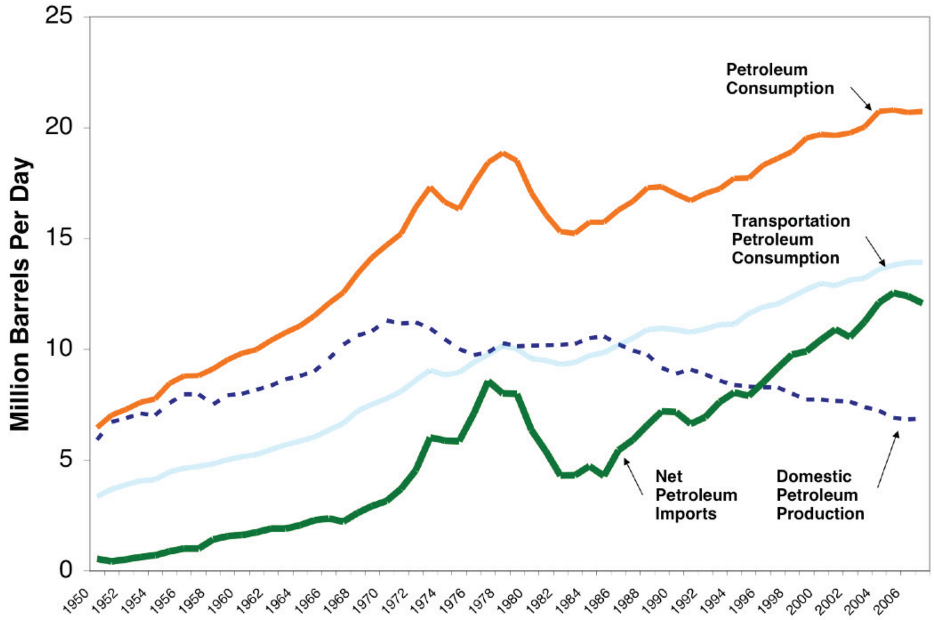

Figure 1.3. U.S. petroleum consumption, consumption from transportation, domestic production and imports. Constructed with data from (*9*).

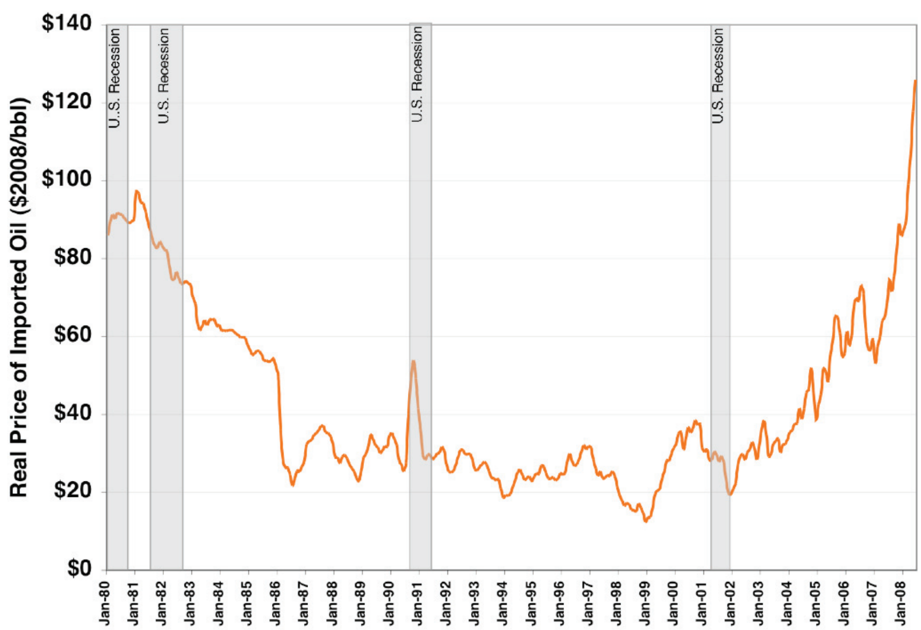

Figure 1.4. U.S. real price of imported oil and U.S. recessions. Constructed with data from (*11, 12*).

In the electric power sector, there were 3,970 billion kWhs and 2,400 million tonnes of CO_2 produced at power production facilities in 2004 (*13*). Thus, the average, direct CO_2 intensity electricity was 171 g CO_2 / MJ of electricity (615 g CO_2 / kWh). Pre-combustion upstream GHG emissions associated with producing and transporting energy carriers (primarily related to fuel extraction, processing and transportation) add substantial impacts to the direct emissions from combustion: e.g. 4-8% for coal and 13-20% for domestic natural gas (*14, 15*), contributing to an additional 5-25% for US electricity (*16*). The 2004 U.S. electricity portfolio is predominately powered by coal (51%), nuclear (20%) natural gas (18%), hydroelectric (7%), oil (3%) and renewables (1%) (*17*).

Policies for GHG mitigation face the challenge of reducing GHG intensity across multiple sectors in the economy. As shown in **Figure 1.5**, business as ususal forecasts depict continued growth of GHG emissions and similar energy and fuel sources through 2030. In order to achieve the 50-80% GHG reductions by 2050 recommended by the IPCC, a fundemental shift and evolution will be required in the energy system. Because the electric power and transportation sectors represent the largest GHG emissions sources, a unique opportunity for coupling these systems and achieving synergistic reductions exists in electrified transportation. Additionaly, by shifting energy demand from the transportation sector to the electricity sector, a large portion of petroleum use can be displaced, enhancing energy security.

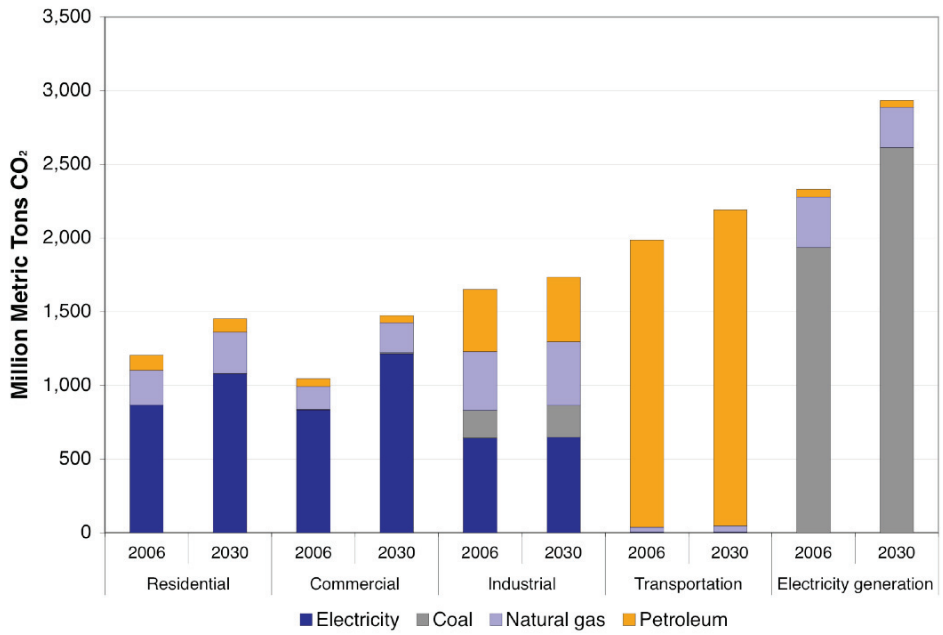

Figure 1.5. GHGs by economic sector and fuel source in the US in 2006 and reference case forecasts for 2030. Electricity generation is included in end-use sector impacts, and shown separately on the right of graph. Constructed with data from (*18*).

Substantially reducing GHG emissions from passenger transportation is challenging. Options include increasing vehicle fuel economy, reducing annual distances traveled, or diversifying to an energy source other than petroleum. Sustainable biofuels supplies appear to be limited in the near-term (*19*) and have large uncertainties regarding life cycle GHGs when land use is included (*20, 21*). The expense and efficiency of hydrogen fuel cells suggest they are more of a long-term technology goal rather than a transition technology away from petroleum (*22, 23*).

Electrified transportation via plug-in hybrid electric vehicles (PHEVs) carries the advantages of utilization of an existing infrastructure asset, the electricity grid, which preliminary studies suggest has sufficient available overnight system capacity for charging millions of PHEVs (*24, 25*).

While powering a portion of passenger transportation with electricity would reduce dependence on petroleum, whether or not it will result in the large GHG reductions necessary to mitigate climate change (*3, 26*) depends on policies and investments in the electricity sector. The scale of the US transport sector dictates that the GHG impacts from large PHEV adoption will materially affect US GHG emissions. Because life cycle GHG emissions from PHEVs depend on the electricity source that is used to charge the battery (*27*), and power plants and their associated GHGs are long-lived (*28, 29*), decisions made regarding new electricity supplies within this decade will affect the potential of plug-ins to play a role in a low-carbon future in the coming decades.

Achieving large GHG reductions from plug-ins will require considerable investment in low-carbon electricity infrastructure. In contrast to the infrastructure requirements for other low-carbon transportation fuels (e.g., hydrogen, ethanol), the development of a low-carbon electricity system as part of a plug-in hybrid infrastructure serves a valuable purpose itself and survives the technology if plug-ins are not adopted over the long-term. That is, infrastructure decisions for low-carbon fuels can be viewed as investment options whose value depend on the adoption of the technology it supports. In order to compare potential strategies to reduce US national GHG emissions, the life cycle economic and environmental impacts of alternative options and associated infrastructure must be contrasted.

The government has a vast array of policy options to promote low-carbon technologies, some of which have proven to be more successful than others. This analysis uses a combination of input-output and process model-based life cycle assessment (*30-32*) to evaluate options and opportunities for large GHG reductions from plug-in hybrids. After the options are framed, this thesis uses engineering economic analysis to determine the policy actions required for large plug-in hybdrid adoption and low-carbon energy infrastructure. If PHEVs are to be powered with electricity generated from sources that do not involve the emission of carbon dioxide, many have argued that wind – that blows both night and day – is an obvious option. We explore how the cost of wind became competitive, paying particular attention to the relative contributions made by government research, transfers of technology from other domains, and government policies to promote deployment. By examining what policies and investments would increase the likelihood of meeting emissions targets under economic and engineering constraints, a framework is developed to assist in low-carbon policy decision-making in the near and mid-term.

1.2 Organization of Thesis and Research Questions

This thesis is divided into four chapters, each written as a stand-alone research paper. References cited will appear at the end of each chapter. While reading the chapters in numerical order will help the reader to build the broader narrative in transitioning to plug-in hybrid vehicles and low-carbon electricity, readers should also be able to skip to the topic of interest without substantial difficulty.

The research questions investigated, with insight into the approach and context listed as sub-bullets, in this thesis are:

1) What are the life cycle GHG emissions and energy use of plug-in hybrid electric vehicles compared to traditional vehicles and hybrids?

    a) What variables are subject to uncertainty and how could they change the original answer? The effects of different GHG intensities of electricity, low-carbon liquid fuel, virgin or recycled battery feedstocks, and vehicle characteristics are examined.

2) What are the economic factors, demand-side infrastructure conditions, and uncertainties comprising the decision space in scalable adoption of PHEVs?

    a) What are the demand side needs and infrastructure required for PHEV adoption at scale?

    b) When are PHEVs economically competitive and what factors influence the estimation? What policies could encourage PHEV adoption and what are the ranges of expected costs?

3) What are the electricity requirements and charging profiles of various levels of PHEV adoption?

    a) How much low-carbon generation is potentially needed to serve various levels of PHEV adoption and what is the role for public policy?

4) How did federal R&D, technical change, and public policies affect the installation of wind energy in the US from 1970-2006?

    a) What lessons can be learned for climate, innovation, and low-carbon energy policies from the evolution of wind power from an emerging alternative energy technology to a utility-scale power source?

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Chapter 2: Life Cycle Assessment of Plug-in Hybrid Electric Vehicles and Implications for Climate and Energy Policy

2.1 Introduction

Reducing greenhouse gas (GHG) emissions from motor vehicles is a major challenge for climate policy. Modest increases in vehicle efficiency have been offset by increased total travel, and transportation has accounted for about 40% of the growth in carbon dioxide (CO_2) emissions from all energy-using sectors since 1990 (*1*). One approach to reduce GHGs from vehicles is improving fuel economy, e.g., the hybrid electric vehicle (HEV) (*2*). A second approach is a low-carbon fuel, such as cellulosic ethanol (*3*-*5*). A third approach is a plug-in hybrid (PHEV), which substitutes electricity for a portion of the petroleum used to power the vehicle. We estimate and compare life cycle GHG emissions from PHEVs, an HEV, and a conventional gasoline vehicle (CV). Since emissions from PHEVs largely depend on the sources of electricity used, we consider various electricity generation options with varying carbon intensities as well as the effects of using cellulosic ethanol liquid fuel.

A transition to plug-in hybrids would begin to couple the transportation and electric power generation sectors. Combustion emissions from United States (US) automobiles and light-duty trucks accounted for approximately 62% of GHG emissions from the US transport sector, or 18% of total US GHG emissions (*6*). Powering transport with electricity would shift GHG emissions and criteria pollutants from distributed vehicle tailpipes to largely centralized power plants. Collectively, burning fossil fuels in the transport and power sectors accounted for about 61% of GHG emissions in the US in

Note: This chapter is based on: Samaras, C.; Meisterling, K., Life Cycle Assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles: Implications for Policy. *Environ. Sci. Technol.* 2008, **42** (9), 3170-3176

2006 (*6*). The scale of the US transport sector dictates that the GHG impacts from widespread PHEV adoption will materially affect US GHG emissions.

A plug-in hybrid in a parallel configuration can use an on-board battery to travel on electricity from the grid, and it can operate as a traditional HEV, burning liquid fuel (*7, 8*). PHEVs provide electric-powered travel, but have ranges comparable with conventional vehicles because they can operate as HEVs. The vehicle's battery can be recharged at typical electrical outlets, hence PHEVs substitute electricity for gasoline to supply a portion of the power needed for travel. Vehicles that travel fewer than 50 kilometers (km) per day are responsible for more than 60% of daily passenger vehicle km traveled in the US (*9*). Thus, plug-in hybrids may be able to power a substantial portion of daily travel with electricity, and could displace a large fraction of gasoline use. In addition to concerns about climate change, dependence on imported oil supplies is seen as a threat to US national security (*10*) and a passenger transport system partially powered by electricity could reduce oil dependence.

The life cycle GHG emissions benefits of PHEVs depend on the vehicle and battery characteristics, and on the GHG intensity of the electricity and liquid fuel used to power the vehicle. A review of PHEV design considerations and environmental assessments has been completed by Bradley and Frank (*8*). Previous studies investigating GHG impacts from PHEVs focus solely on the impacts of electricity and gasoline for PHEV propulsion. The Electric Power Research Institute (EPRI) has conducted a series of PHEV analyses. Their preliminary reports (*11, 12*) analyzed PHEVs charged with electricity produced from natural gas combined cycle power plants. Other studies have shown larger regional GHG reductions in areas with less GHG-intensive generation portfolios (*13, 14*). Citing available overnight spare generation capacity, Kintner-Meyer *et al*. (*13*) found that 73% of the existing light-duty vehicle fleet could be supported as PHEVs from the existing power supply infrastructure. Kempton *et al.* estimated potential large GHG reductions using offshore wind to power plug-in vehicles (*15*). A recent EPRI analysis (*16*) modeled the electricity system and PHEV adoption scenarios and found GHG reductions compared to CVs and HEVs. The electricity charging PHEVs in that analysis was 33-84% less carbon intensive than the current US generation portfolio.

This analysis contributes to the PHEV literature by including several aspects omitted by previous work. First, energy use and GHG emissions from battery production are included. Sensitivity analyses are provided to determine how changes in the electricity mix, vehicle efficiencies, battery characteristics, and biofuel use affect the life cycle GHGs from PHEVs. Finally, this analysis highlights how low-carbon electricity decisions and investments are coupled to vehicle and transport sector investments if plug-in hybrids are to reduce life cycle GHGs compared to high efficiency gasoline-powered vehicles.

2.2 Method

Life cycle assessment (LCA) quantifies the environmental impacts of a product's manufacture, use, and end-of-life (see **Figure 2.1**). LCA traditionally utilizes either a process-based methodology or an economic input-output (EIO) methodology (*17-19*). A process-based methodology examines and quantifies resource inputs and environmental outputs associated with each stage of a product's life cycle. An EIO methodology can reduce the potentially sizable truncation error of omitted upstream impacts and the extensive data requirements of a process model by aggregating activities and impacts up to the economic sectoral level (*18, 20*). The Economic Input-Output Life Cycle Assessment model (EIO-LCA) is a linear input-output model that uses published input-output economic accounts of all the 491 sectors of the US economy and determines environmental discharges associated with a dollar value of economic activity in each sector (*21*). In order to reduce uncertainty associated with both process and EIO–based methods, the field of life cycle assessment is increasingly combining elements from both approaches, in what is termed a hybrid life cycle assessment (*22-25*).

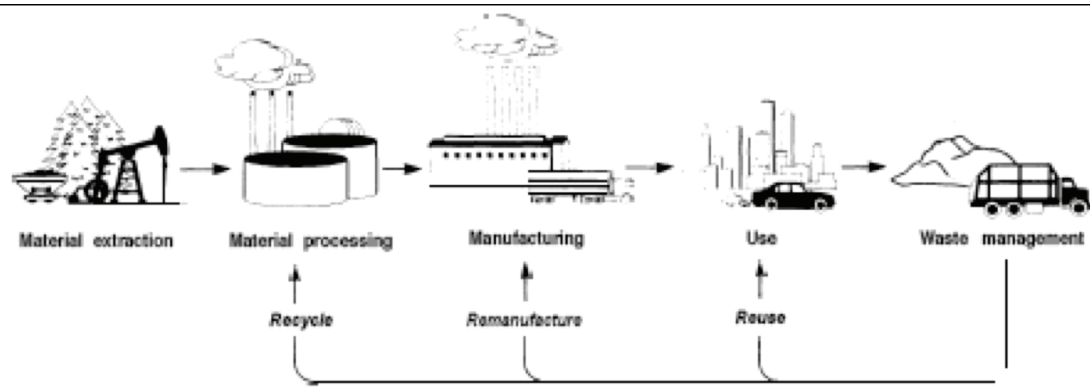

Figure 2.1. Stages of the product life cycle **(*26*)**

We use data from previous process LCAs, the Economic Input-Output Life Cycle Assessment model (EIO-LCA) (*21*), and the literature to provide a hybrid (*23, 25*) estimation of the life cycle GHG emissions of PHEVs. We compare life cycle energy use and global warming potential (GWP) of PHEVs with CVs and HEVs. GWP is measured in grams of CO_2 equivalent (CO_2-eq) with a time horizon of 100 years using the values recommended by the Intergovernmental Panel on Climate Change (*27*). This report includes GHG emissions associated with energy use and fuel production, along with vehicle and storage battery production.

The system boundary in **Figure 2.2** illustrates the processes and inputs that are considered in the analysis. The emission factors for fuels and electricity are shown in **Table 2.1**. All values in this analysis are higher heating values (HHV).

Table 2.1. GHG emissions factors used for fuel and electricity

	Carbon intensity of energy source (g CO_2-eq / MJ HHV)	**Source**
Electricity		
Current US direct emissions (at power plant from fuel combustion)	171 (615 g / kWh)	(*28*)
Upstream emissions	15 (54 g / kWh)	(*28, 29*)
US average (life cycle)	186 (670 g / kWh)	
Low-carbon portfolio (life cycle)	56 (200 g / kWh)	See **Table 2.5**
Carbon-intensive portfolio (life cycle)	250 (950 g / kWh)	Adapted from (*30, 31*)
Diesel		
Site emissions (fuel combustion)	69	(*1, 32*)
Upstream emissions	18	(*32*)
Gasoline		
Site emissions (fuel combustion)	67	(*1, 32*)
Upstream emissions	19	(*32*)
Ethanol		
Site emissions (fuel combustion)	0	
Upstream emissions (corn-based)	73	(*3*)
Upstream emissions (low-input biomass)	5	(*5*)

Notes: CO_2-eq = carbon dioxide equivalents; direct and upstream emissions numbers may not match total due to rounding.

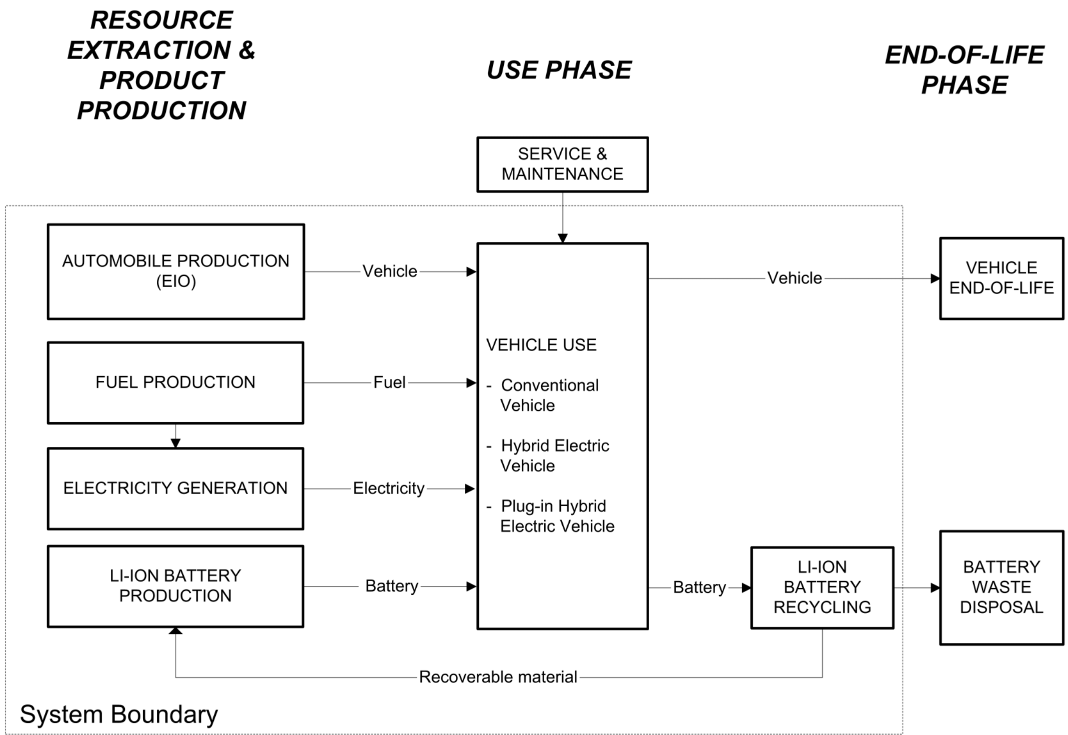

Figure 2.2. System boundary. Where noted, the Economic Input-Output Life Cycle Assessment (EIO-LCA) model was used.

The systems considered are as follows: a conventional internal-combustion (IC) sedan-type vehicle such as the Toyota Corolla (CV), a hybrid electric sedan-type vehicle (HEV), such as the Toyota Prius, and three plug-in HEVs, powered with liquid fuel and electricity from the grid. The PHEVs considered have electric ranges of 30 km (PHEV30), 60 km (PHEV60) and 90 km (PHEV90). The useful life of all vehicles is assumed to be 240,000 km (about 150,000 miles) (*11, 12, 33*). The functional unit of analysis is 1 km of vehicle travel in the US.

Building on the relationship given in Facanha and Hovarth (*34*), life cycle GHG emissions for vehicles are calculated using the following equation:

$$GHG = \sum_{i=1}^{n} \frac{I_i}{L} * E_i \qquad (1)$$

Where

GHG = Life cycle GHG emissions [g CO_2 equivalent (100 yr) per km traveled]

n = Total number of inputs

I_i = Input (energy, gallons, $US)

E_i = GHG intensity of each input (g CO_2-eq / I_i units)

L = Lifetime of vehicle (km)

For example, consider the battery in a conventional HEV. We estimate the HEV has a lithium ion (Li-ion) battery with 1.3 kWh of energy storage capacity. Using the emissions factors in **Table 2.1** and **Table 2.3**, 120 kg CO_2-eq are emitted to produce one kWh of Li-ion battery storage capacity. The battery is assumed to last the lifetime of the vehicle, 240,000 km (about 150,000 mi). Thus, life cycle GHG emissions of the battery input = $(1.3) * (120*10^3) / 240{,}000 = 1$ g CO_2-eq / km (see **Table 2.1** for GHG emissions associated with each input).

2.2.1 Vehicle Production

The PHEVs considered in this analysis are assumed to be similar to an existing HEV, a Toyota Prius, with additional battery capacity to enable plug-in capabilities in a parallel configuration. There have been several aftermarket conversions of Prius HEVs to PHEVs and it is assumed that the introduction of a sedan PHEV will build upon an HEV design. In an alternative PHEV series configuration not considered in this analysis, propulsion is solely powered by electricity and liquid fuel combustion is used to maintain the battery's charge (*7*). PHEVs in a series configuration may require a larger battery and a smaller combustion engine than a parallel configuration (*7*). Following the work of Lave and MacLean (*33*), this study used the Toyota Corolla for the baseline conventional vehicle (CV). The Corolla has similar characteristics, dimensions, and curb weight to the Toyota Prius (*35*).

Automobile manufacturing for all vehicles considered was assumed to be identical, except for the addition of the storage batteries for HEVs and PHEVs. While HEVs have smaller IC engines than a comparable conventional vehicle, we assume HEV electric motors and control equipment account for any differences in impacts. To estimate GHG emissions from vehicle manufacturing (not including the PHEV battery), we use EIO-LCA (*21*). GHG emissions from vehicle end-of-life have been found to be small as compared to the use phase (*36*) and are therefore omitted.

An EIO methodology relies on benchmark accounts of economic activity from defined economic sectors from the US Department of Commerce, and hence uses producer prices (as opposed to retail prices) as inputs. The EIO-LCA model reports economic and emissions data in five-year increments, and data from 1997 were the latest available. In the automobile manufacturing sector, producer price is approximately 80% of the retail price (*37*), and producer price indices are 141.7 and 133.7 for 1997 and 2006 respectively (*38*). Thus, we estimate that the Toyota Corolla, which retails in 2006 for $16,100 (*39*), has a producer price of about $13,500 in 1997. The EIO-LCA model reports that 102,000 MJ of primary energy are consumed and 8.5 tonnes of CO_2-eq are emitted during the manufacturing of this Toyota Corolla-type vehicle.

We have augmented the EIO-LCA data to estimate GHGs from vehicle manufacturing under the different scenarios of GHG intensities of electricity considered in this analysis. To produce the Corolla-like vehicle, EIO-LCA reports that about 6,100 kWh of electricity are purchased in the economy. Assuming life cycle GHG emissions are 670 g CO_2-eq per kWh of electricity in 1997 (**Table 2.1**), GHG emissions from the electricity life cycle account for about half of the total emissions from vehicle manufacturing. The augmented emissions are calculated by first subtracting GHG emissions due to electricity (at 670 g CO_2-eq per kWh) from total GHG emissions from vehicle manufacturing. GHG emissions due to electricity are added back on, according to the carbon intensity of interest.

The price premium for HEVs and PHEVs over a conventional vehicle such as a Toyota Corolla will be predominately comprised of the additional battery, and to a lesser extent motor controls and electronics (*40*). Also represented in this premium may be intrinsic research, design, and manufacturing costs of a novel automobile as compared to the established complementary assets for a Corolla. Hence, aside from the batteries, the price and impacts of a Corolla were used in the baseline analysis of manufacturing impacts for all vehicles. **Table 2.2** summarizes energy and GHG emissions associated with vehicle production. These results are consistent with previous vehicle production emissions estimates (*4, 36, 41-43*).

2.2.2 Battery Production

Successful deployment of a US PHEV fleet will be heavily influenced by battery technology, which has seen recent technological improvements. Most current HEVs and electric vehicles (EVs) utilize Nickel-Metal Hydride (NiMH) batteries. NiMH batteries have displayed good performance characteristics after several years in use in retail EVs and HEVs (*44*). Since NiMH batteries have relatively low energy density (35 to 55 Watt-hour/kg), they would add considerable mass and volume to the vehicle. An alternative battery chemistry for use in PHEVs is Lithium-ion (Li-ion). Li-ion batteries have the advantage of higher energy densities (80 to 120 Wh/kg), which can facilitate PHEV operation (*44-46*). On the other hand, Li-ion batteries currently face challenges related to aging, cycle life, and relatively high cost. Technological improvements have positioned Li-ion as a likely candidate for use in future plug-in hybrids (*46*) and it is the electricity storage device considered in this analysis for both HEVs and PHEVs.

The HEV in our analysis uses a Li-ion battery weighing 16 kg, and the PHEVs use Li-ion batteries weighing 75-250 kg, depending on electric range considered. Data on primary energy use for battery production, resource extraction and processing, and recycling come from Rydh and Sandén’s cradle-to-gate analysis (*45*). They considered a SAFT Li-ion VL50E cell with a metal oxide-based cathode (Co, Mn, Al). They report 1,200

Megajoules (MJ) of primary energy are required during the manufacture of 1 kilowatt-hour (kWh) of Li-ion battery storage capacity. In addition to the energy used in manufacturing, between 310-670 MJ of primary energy are required to produce the materials for 1 kWh of Li-ion battery energy storage capacity. This range depends on whether the input materials are recycled or virgin. We use an approximate mid value of 500 MJ / kWh of battery capacity for material production, yielding a total of 1,700 MJ of primary energy to produce one kWh of Li-ion battery capacity. Impacts from non-recoverable battery waste disposal are omitted.

In our study, we assume battery production occurs in the US, and no impacts from battery transport have been included. The GHG intensity of battery production will depend on the fuels used in the primary energy demand, and the fraction of primary energy that is electricity. We apply the GHG emission factors from **Table 2.1** to the energy carriers from Rydh and Sandén; they report 75% of total energy required for battery production is primary fuel for electricity, and conversion efficiency of primary fuel to electricity is 35% (*45*). We assume the remaining energy is from diesel for mining operations. If natural gas instead represents a large fraction of energy inputs to the battery life cycle, impacts would decrease slightly. The focus on materials production and battery manufacture in the Rydh and Sandén study omits other supply chain impacts from battery manufacturing, which could increase life cycle impacts from batteries. Additionally, if the batteries are produced in Asia, battery impacts would be affected by the carbon intensity of the electricity used in production and to a lesser extent, the increased impacts from ocean freight.

Table 2.2, **Table 2.3**, and **Table 2.4** present energy and GHG emissions associated with Li-ion battery production and the sensitivity of GHG impacts to virgin or recycled material use.

Table 2.2. Energy and GHG emissions associated with vehicle and Li-ion battery production. Rydh and Sandén (2005) report that 75% of the energy used in Li-ion is primary fuel for electricity generation; we assume the remainder (non-electricity) is from diesel.

	Unit		Source
Vehicle production			
Energy use	MJ / vehicle	102,000	(*21*)
GHG emission	kg CO_2-eq / vehicle	8,500	(*21*)
Battery production			
Energy density	kWh / kg battery	0.1	(*44-46*)
Energy required for materials and manufacturing	MJ / kWh battery capacity	1,700	(*45*)
GHG emissions	kg CO_2-eq / kWh battery capacity	120	Energy used is 75% electricity, 25% diesel (*45*); GHG intensity from Table S1

The impacts of battery production for each vehicle configuration are shown in **Table 2.3** Estimated impacts from NiMH battery production, adapted from Rydh and Sandén (*45*), are approximately double those of Li-ion and are shown in **Table 2.3**. As discussed, improvements in battery technologies and manufacturing could potentially reduce the GHG impacts. Alternatively, one or more battery replacements during the vehicle useful life will increase total life cycle impacts. If the battery is deep-cycled (battery is consistently discharged to 80% Depth of Discharge, or DOD), it may last about 2,500 cycles (*47*) (about 10 years if the battery is cycled 5 times per week, however, aging is a concern for Li-ion battery technology). In addition, the source of materials for the batteries affects impacts of manufacturing. Sensitivities of manufacturing impacts in relation to the amount of recycled material inputs utilized are presented in **Table 2.4**.

Table 2.3. Energy and GHGs from Li-ion storage battery production for HEVs and PHEVs. Total battery capacity is 20% greater than energy required for PHEV propulsion to allow for sufficient capacity to operate as a HEV at 80% DOD. The table also shows impacts from NiMH battery production, which is more energy intensive per kWh of battery capacity than Li-ion.

	Unit	**CV**	**HEV**	**PHEV 30**	**PHEV 60**	**PHEV 90**
Electric range of battery	km	-	0	30	60	90
Energy required (from battery) for PHEV range	kWh	-	0	5.4	10.7	16.1
		-				
Total battery capacity to enable 80% DOD	kWh	-	1.3	6.7	13.4	20.1
		-				
Li-ion						
Battery mass	kg	-	16	84	168	252
		-				
Production	MJ / battery	-	2,210	11,400	22,800	34,200
	kg CO_2-eq / battery		160	810	1,610	2,420
	MJ / km	-	0.01	0.05	0.09	0.14
	g CO_2-eq / km	-	1	3	7	10
NiMH						
Battery mass	kg	-	36	190	370	560
		-				
Production	MJ / battery	-	4,200	22,000	43,000	64,000
	kg CO_2-eq / battery		300	1,600	3,100	4,600
	MJ / km	-	0.02	0.09	0.18	0.27
	g CO_2-eq / km	-	1	6	13	19

Table 2.4. Li-ion battery impacts over the vehicle life cycle when battery is produced with recycled or virgin materials, using ranges reported by Rydh and Sandén (*45*).

	Unit	HEV	PHEV 30	PHEV 60	PHEV 90
Battery impacts: as assumed (1700 MJ/kWh$_e$ capacity)	g CO_2-eq / km	1	3	7	10
Battery impacts: all recycled material inputs (1510 MJ/kWh$_e$ capacity)	g CO_2-eq / km	1	3	6	9
Battery impacts: all virgin material inputs (1870 MJ/kWh$_e$ capacity)	g CO_2-eq / km	1	4	7	11

Rydh and Sandén completed their analysis for a SAFT Li-ion VL50E cell with a metal oxide-based cathode (Co, Mn, Al) (*45*). As cathode and anode materials in Li-ion batteries evolve, energy requirements for battery production may change. Rydh and Sandén report that the energy intensity of NiMH battery production is nearly double that of Li-ion per kWh of capacity, largely due to differences in energy densities. Thus the adoption of NiMH as the dominant PHEV battery would increase the life cycle impacts from PHEVs. To compare similar products, we assume that the same battery chemistry will be employed in both HEVs and PHEVs.

The GREET 2.7 model estimates vehicle cycle impacts, while the GREET 1.7 model (*32*) is a separate tool that estimates fuel cycle impacts. GREET 2.7 also estimates impacts from battery manufacturing (*48*). If this model is employed, impacts from battery manufacturing are lower. However, the lithium-ion battery background data in the

GREET 2.7 model is still under development and the model developers have identified this part of the model as requiring additional information. Given the data limitations with the GREET 2.7 model regarding lithium-ion batteries, we use impacts as reported by Rydh and Sandén in our assessment.

The lifetime of a Li-ion battery depends on how the battery is used, so the vehicle use phase will influence upstream impacts from battery manufacturing. The lifetime of Li-ion batteries decreases as depth-of-discharge (DOD) of each cycle increases. It is assumed that the batteries in HEVs and PHEVs last the lifetime of the vehicle and will be discharged to a maximum of 80% DOD. If the battery requires a replacement during the life of the vehicle, impacts from battery manufacturing would approximately double. Alternatively, less carbon intensive battery manufacturing or improvements in battery energy density would reduce GHG impacts. Since it is very difficult to predict technological developments of electricity storage devices, our results show impacts due to current battery production in order to indicate the potential to reduce impacts from battery manufacture.

2.2.3 Use Phase

The majority of vehicle life cycle energy use and GHG emissions result from powering the vehicle with liquid fuel or electricity (*4*). The use phase includes energy and emissions from vehicle operations as well as from vehicle service, fixed costs such as insurance and other services, and upstream impacts from fuel production (*49*). In comparing the CV, HEV, and PHEVs, this analysis omits impacts from vehicle service, maintenance, and other fixed costs, assuming these to be similar across vehicle technologies, or that differences have negligible impact in comparison with the use phase (*4*). HEVs and PHEVs may require fewer oil changes (and other services) for the IC motor as it endures fewer operating hours, but the differences in GHG impacts are likely to be small compared to the overall life cycle.

2.2.4 Liquid Fuel

When one liter of gasoline is burned, about 2.3 kg of CO_2 are released (67 g CO_2 / MJ of fuel) (*1*). In addition to combustion, life cycle GHG emissions from gasoline include crude oil extraction and transportation, refining, and fuel distribution. These upstream GHG emissions were estimated to be about 0.67 kg of CO_2-eq per liter of fuel (19 g CO_2-eq / MJ) using the GREET 1.7 model (*32*). For the base case, corn-based ethanol comprises 3% of liquid fuel (volume basis). Other cases consider cellulosic ethanol with reduced life cycle GHG emissions compared to corn ethanol. Diesel fuel represents a negligible fraction of US automobile and light truck fuel use and was omitted.

The life cycle GHG emissions of corn and cellulosic ethanol used are 73 and 5 g CO_2-eq / MJ (HHV), respectively (*3, 5*). Schmer *et al.* include carbon abatement through soil carbon storage in their estimate. Tilman *et al.* have also recently shown that carbon negative fuels can be produced from a diverse mix of plants grown on degraded soil (*50*). Farrell *et al.* estimate cellulosic ethanol production emits 10 g / MJ (converted to HHV), but do not include soil carbon storage, which depends on past and future management practices. Spatari *et al.* (*51*) performed a life cycle assessment of cellulosic ethanol from switchgrass, and estimated life cycle emissions at 20 g / MJ ethanol (converted to HHV), and did not include soil carbon storage. As emerging research on GHGs from land use change and biofuels continues (*52, 53*), different ranges of GHGs from cellulosic ethanol can be used.

2.2.5 Electricity Used to Power PHEVs

While electricity consumption does not emit CO_2 at the point of use, determining the GHG intensity (g CO_2-eq / kWh) of electricity used to charge PHEVs is a key parameter in estimating the life cycle GHG impact. In the electric power sector, there were 3,970 billion kWh and 2,400 million tonnes of CO_2 produced at power facilities in 2004 (*54*). Thus, the average direct CO_2 intensity of electricity was 171 g CO_2 / MJ of electricity (615 g CO_2 / kWh). If PHEVs are considered marginal load, the GHG intensity of power plants ramped up, dispatched, and ultimately constructed to meet this additional demand should be used to calculate PHEV impacts. If, on the other hand, PHEVs are considered part of the total load, the GHG intensity of the generation mix serving the load should be used. We adopt three scenarios to represent the GHG intensity of electricity, and show sensitivity of the results to changes in electricity GHG intensity. This method allows straightforward comparisons between the vehicle types, regardless of whether the PHEV load is considered marginal.

Pre-combustion upstream GHG emissions associated with the extraction, processing and transportation of fuels for power generation add substantial impacts to direct emissions from combustion: 8-14% for coal and 13-20% for domestic natural gas (*31, 55*). Kim and

Dale (*29*) report electricity life cycle GHG emissions to be 193 g CO_2 equivalents per MJ electricity (MJe) generated in the US in 2000 (695 g CO_2-eq / kWh). The Energy Information Administration's (EIA) Annual Energy Review for the year 2000 reports direct (combustion exhaust only) CO_2 intensity of electricity production was 178 g CO_2 / MJe (640 g / kWh) (*54*). Using the figures from Kim and Dale, and EIA, we calculate upstream emissions of 15 g CO_2-eq / MJe (55 g / kWh), adding an additional 9% of the direct emissions. This calculation is performed with year 2000 data, since Kim and Dale performed their life cycle assessment for the year 2000. To estimate life cycle emissions in the year 2004, we assume the upstream emissions were also 9% of the direct emissions. EIA reports direct emissions were 171 g CO_2 / MJe (615 g CO_2 / kWh) in 2004. Thus, for the US average scenario, we estimate upstream emissions of 15 g CO_2-eq / MJe (54 g / kWh) produced, and total life cycle emissions of 186 g CO_2-eq / MJ (670 g / kWh) of electricity produced. Direct and upstream impacts are included in the electricity scenarios.

This analysis considers three scenarios for life cycle GHG intensities of electricity – a system that is similar to the current US average, a low-carbon scenario, and a carbon-intensive scenario. For the base-case scenario, electricity used to charge PHEVs has a life cycle CO_2 intensity similar to the average intensity of the current US power portfolio, or 670 g CO_2 per kWh of electricity (*29, 54*). The *carbon-intensive* scenario represents a case where coal (the most carbon-intensive fuel) is the predominant fuel for electricity generation, and emits 950 g CO_2-eq / kWh. This figure could represent the combustion and upstream impacts of a mix of existing less efficient subcritical coal plants and additions of more efficient supercritical coal plants (*30, 31*). If solely less efficient, existing coal plants are used to charge PHEVs, the carbon-intensive electricity scenario would have higher GHG intensity. The *low-carbon* scenario describes an electricity system where renewables, nuclear, or coal with carbon capture and sequestration account for a large share of the generation, thus making the total life cycle GHG intensity of electricity low, at 200 g CO_2-eq / kWh. The GHG impacts from electricity generation infrastructure are generally negligible compared to combustion emissions, with the exception of low-carbon generation (which have little or no combustion emissions) (*56*). **Table 2.5** outlines a representative electricity mix for the *low-carbon* scenario and contains direct and upstream impacts of electricity generation, including generation infrastructure. The life cycle GHG emissions of our electricity scenarios do not include transmission and distribution infrastructure.

Table 2.5. A hypothetical electricity mix to represent the low-carbon portfolio considered. An electricity mix with life cycle emissions of 200 g CO_2-eq / kWh could be constructed with many different combinations, including some sources not considered below (e.g. solar thermal, tidal, and geothermal). This low-carbon portfolio is used to illustrate a potential generation mix with life cycle emissions of 200 g CO_2-eq / kWh. We are not arguing that the future electricity mix will match this scenario, but the portfolio presented may be one possibility. CCS = Carbon capture and storage; PV = photovoltaic (direct conversion of sunlight to electricity). Coal and natural gas carbon content from EPA (*57*); Efficiency of fossil fuel generation and CCS emissions from IECM (*30*); Upstream emissions from coal and natural gas from Jaramillo et al. (*31*); Nuclear, hydro, wind, and PV from Weisser (*58*).

Fuel (source)	**Direct (g CO_2 / kWh)**	**Upstream (g CO_2-eq / kWh)**	**Total life cycle emissions (g CO_2-eq / kWh)**	**% of electricity generated**
Coal	800	50	850	10%
Coal w/ CCS	100	50	150	25%
Natural gas	400	75	475	15%
Nuclear	0	10	10	25%
Hydro	0	8	8	5%
Wind	0	15	15	15%
PV	0	60	60	5%
GHG intensity of mix			**200**	

The actual GHG intensity of the electricity used to recharge PHEV batteries will depend on the mix of generation types dispatched, which varies by region, season, and time of day. In this analysis, we calculate life cycle emissions assuming various electricity GHG intensities. Thus, we demonstrate the effects of various generation fuels and fuel mixes charging PHEVs. As population densities change regionally in the future, electricity demands (including potential PHEV demands) will be correlated.

2.2.6 Vehicle Efficiency

Conventional vehicle gasoline consumption is 0.08 liter / km (30 mpg, or 2.5 MJ / km), and hybrids (both HEV and PHEV) consume 0.05 liter of gasoline / km (45 mpg, or 1.7 MJ / km), for liquid fuel-powered transport (*33, 59, 60*). In addition, 0.20 kWh of electricity (at the power plant) is required for one km of electric grid-powered travel (*11*). To calculate plant-to-wheel electricity required, we use the 0.18 kWh/km requirement for a compact sedan (includes regenerative braking benefits and efficiency losses in the battery and charger) from the Electric Power Research Institute (*11*). We also use 9% losses in electricity transmission and distribution from the EIA (*54*). These result in 0.20 kWh of electricity from the power plant required for a PHEV to travel one km using electricity as the energy source. **Table 2.6** reviews assumptions for fuel and electricity consumption during travel. Both liquid fuel and electricity consumption per km will vary with different types of vehicles, characteristics, and driving styles.

Increased weights of battery packs may affect both liquid fuel and electricity propulsion requirements for PHEVs. Preliminary estimates of how weight affects HEV fuel economy have been made by Reynolds and Kandlikar (*61*). Zervas and Lazarou (*62*) detail how reductions in vehicle weight affect CO_2 emissions from transport in the context of European Union policy. In the regression presented by Reynolds and Kandlikar, increasing vehicle weight by 100 kg increases fuel consumption by 0.72 liters per 100 km for an HEV. When engine power (kW) is added as a predictor variable in that study, the HEV result is not statistically significant. To be consistent with previous studies (*16*), effective fuel consumption remains the same as PHEV battery capacity increases in this study and changes in fuel economy are explored in the sensitivity analysis.

Table 2.6. Parameters for liquid fuel and electricity consumption during travel.

	Unit	Value	Source
Liquid-fuel powered travel			
Conventional vehicle	MJ / km	2.5	
	l gasoline / km (mi / gal)	0.08 (30)	(*59*)
HEV and PHEV	MJ / km	1.7	
	l gasoline / km (mi / gal)	0.05 (45)	(*59, 60*)
Electricity-powered travel and electric drive system (plant-to-wheel)			
Electricity consumption during electric powered travel, including charging/discharging losses	kWh / km (kWh / mi)	0.18 (0.29)	(*11*)
Transmission and distribution efficiency	(Plant-to-plug)	0.91	*(28)*
Electricity required to power travel (plant-to-wheel)	kWh / km	0.20	
Battery depth-of-discharge (DOD)		0.8	(*46*)

2.2.7 Driving Patterns

Driving behaviors are a key component for assessing the impact of PHEVs. These patterns will determine the fraction of total vehicle travel that is powered by gasoline or by electricity from the grid. Furthermore, driving patterns might also dictate how often a PHEV can be charged. For example, if a car is parked at a workplace regularly, it might be possible to charge the PHEV twice in one day (once at home, once at work). We assume that PHEVs are charged once per day. GHG emissions per km of vehicle travel were calculated for each vehicle using the following relationship:

$$\frac{GHG}{km} = (\alpha)\left[\frac{kWh}{km} * \left(\frac{GHG_{powerplant+upstream}}{kWh}\right)\right] + (1-\alpha)\left[\frac{l_{fuel}}{km} * \left(\frac{GHG_{fuel+upstream}}{l_{fuel}}\right)\right] \quad (2)$$

where α represents the fraction of travel that is powered by electricity, and (1-α) represents the fraction of travel powered by liquid fuel. The term multiplied by α represents the combustion and upstream impacts of electricity, while the term multiplied by (1-α) represents the combustion and upstream liquid fuel emissions.

To determine alpha (the fraction of vehicle travel powered by electricity) a cumulative distribution of daily vehicle kilometers traveled has been constructed (**Figure 2.3**) from the US Department of Transportation National Household Travel Survey (*9*). This distribution reports the percentage of total daily vehicle kilometers from vehicles traveling less than a given distance per day. National Household Travel Survey Data is available at http://nhts.ornl.gov. To determine the number of kilometers traveled by each unique passenger vehicles per day, we used the NHTS DAYPUB database with national weights. When all daily travel could be powered by electricity, alpha takes the value of 1 (the PHEV travels fewer km than its electric range); when daily travel is entirely liquid fuel powered (CV and HEV), alpha is 0. Alpha is a fraction between 0 and 1 when PHEV daily travel is farther than its electric range (the PHEV uses electricity from the grid and liquid fuel). With the PHEV configurations considered in this analysis, electricity from the grid powers between 47% and 76% of vehicle travel (**Table 2.7**). It is possible that PHEV ownership will be concentrated in users that travel fewer miles per day than the national average, such as those with fixed and known short commuting distances. In this case, electricity would power a larger percentage of the distances traveled by PHEVs.

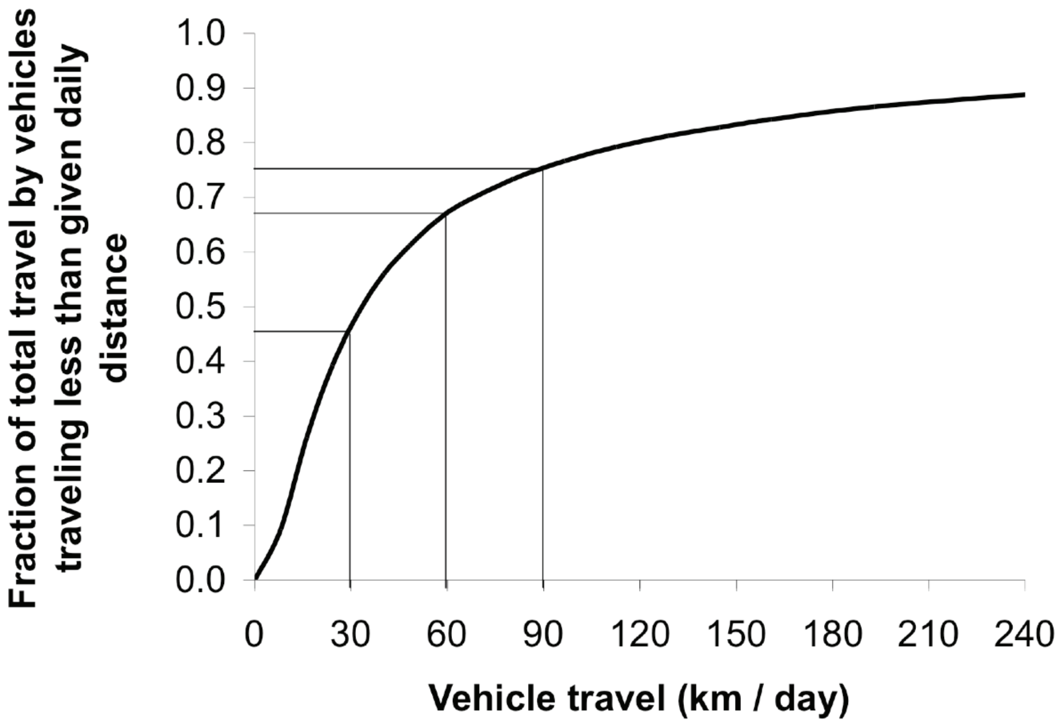

Figure 2.3. Cumulative distribution of daily passenger vehicle travel (km / day). By estimating the kilometers traveled by each vehicle per day, the percent of travel that could potentially be powered with electricity with the various PHEV configurations can be obtained. The distribution was constructed with data from the National Household Travel Survey (*63*).

Table 2.7. Fraction of total vehicle kilometers powered by electricity (α) and gasoline (1-α). Most likely results from the distributions are shown in this table.

	CV	**HEV**	**PHEV30**	**PHEV60**	**PHEV90**
α	0	0	0.47	0.68	0.76
1-α	1	1	0.53	0.32	0.24

This study did not consider two-way power flows between the vehicle and the grid (V2G), in which the vehicle battery could provide ancillary services or other power to the grid in exchange for revenue (*64*). A V2G system could also potentially provide storage and dispatch capabilities for intermittent renewable energy sources (*65*), and Kempton *et al.* calculated that large offshore wind resources off the Eastern US coast matched the power demand for end uses in East coast states (*15*). The net GHG benefits of a V2G system would depend on the GHG intensity of electricity used for charging and the GHG intensity of the electricity displaced by two-way power flows, and is an interesting topic for future research.

2.3 Results

Under the 2004 US average GHG intensity of electricity, PHEVs were found to reduce use phase GHG emissions by 38-41% compared to CVs, and by 7-12% compared to

HEVs. These use-phase impacts omit battery manufacturing, and can assist in framing impacts if battery manufacturing impacts decrease. The lifetime and performance of the battery is an important parameter for the economic and environmental success of PHEVs. As shown in **Figure 2.4**, the additional GHG emissions from Li-ion battery manufacturing (*45*) yield life cycle impacts from PHEVs that are slightly lower than HEVs, assuming the original battery lasts the lifetime of the vehicle. Life cycle energy use and GHG emissions are described in **Table 2.8**.

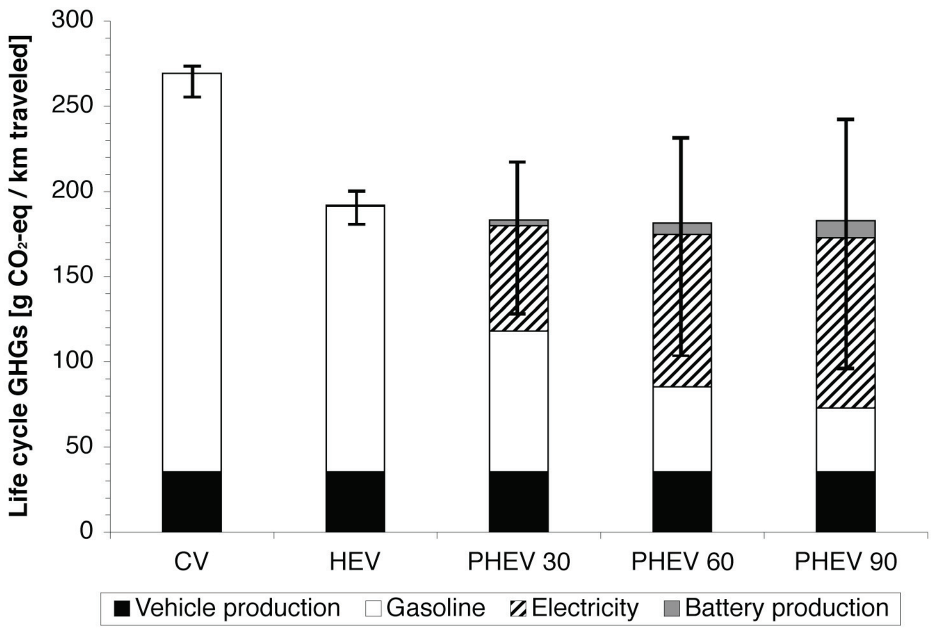

Figure 2.4. Life cycle GHG emissions (g CO_2-eq / km) of conventional vehicles (CV), hybrid electric vehicles (HEV) and plug-in hybrids (PHEV) with all-electric ranges of 30, 60, or 90 km. Life cycle CO2 intensity of electricity is 670 g CO_2-eq / kWh (186 g / MJ; US Average scenario). Uncertainty bars represent changes in total emissions under the carbon-intensive (950 g CO_2-eq / kWh) or low-carbon (200 g CO_2-eq / kWh) electricity scenarios.

Table 2.8. Life cycle energy use and GHG emissions from conventional vehicles, hybrids, and plug-in hybrids using current US Average GHG intensity of electricity.

		Units	CV	HEV	PHEV 30	PHEV 60	PHEV 90
Production phase	Vehicle	MJ / km	0.4	0.4	0.4	0.4	0.4
		g CO_2-eq / km	35	35	35	35	35
	Battery	MJ / km	-	0.01	0.05	0.09	0.14
		g CO_2-eq / km	-	1	3	7	10
Use phase	Gasoline: site	MJ / km	2.6	1.8	0.9	0.6	0.4
		g CO_2-eq / km	177	118	63	38	28
	Gasoline: upstream	MJ / km	0.6	0.4	0.2	0.1	0.1
		g CO_2-eq / km	57	38	20	12	9
	Electricity: site	MJ / km	-	-	0.7	1.0	1.2
		g CO_2-eq / km	-	-	57	82	92
	Electricity: upstream	MJ / km	-	-	0.1	0.1	0.1
		g CO_2-eq / km	-	-	5	7	8
Total impact	Energy Use	MJ / km	3.6	2.6	2.3	2.2	2.2
	GHG emissions	g CO_2-eq / km	269	192	183	181	183

The potential for PHEVs to achieve large-scale GHG emission reductions is highly dependent on the energy sources of electricity production. We use the US average case to provide baseline comparative impacts and use low and high-carbon scenarios to illustrate GHG emissions under varying sources of electricity production. PHEVs reduce life cycle GHG emissions by 32% compared to CVs, but have small reductions compared to HEVs, under the current US average electricity GHG intensity. Under the *carbon-intensive* scenario, life cycle PHEV impacts are 9-18% higher than HEVs. Without appropriate policies, widespread PHEV adoption could migrate toward this scenario, given the abundance of US coal reserves and planned coal power plant additions (*66*). Under the *low-carbon* scenario, large life cycle GHG reductions (51-63% and 30-47% reductions compared to CVs and HEVs, respectively) are possible with PHEVs. Thus, if large life cycle GHG reductions are desired from PHEVs, a strategy to match charging with low-carbon electricity is necessary.

PHEV charging is likely to occur in the evening and overnight as commuters return home from work. Since the GHG intensity of electricity changes with time of day, season, and service territory, it is important to show how changes in GHG intensity of the electricity charging PHEVs affect the comparative life cycle impacts. **Figure 2.5** can be used to evaluate the benefit of PHEVs as compared to CVs and HEVs, based upon the GHG intensity of electricity generation associated with the place and time of interest.

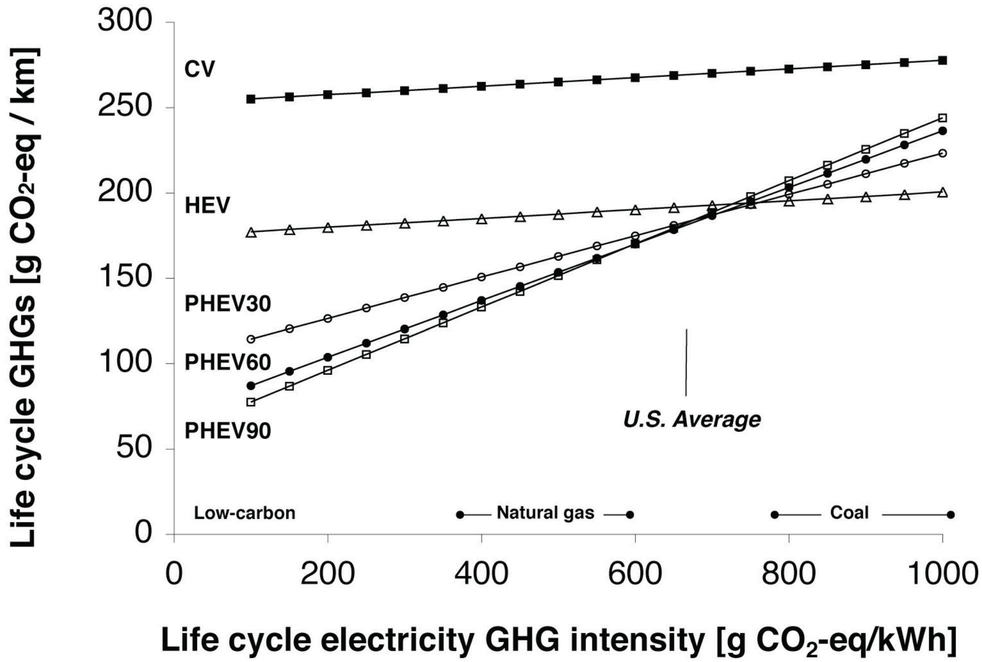

Figure 2.5. Life cycle GHG emissions from vehicles shown as a function of the life cycle GHG intensity of electricity generation. Electricity is used during production of the vehicles, and the slight slope of the CV and HEV lines reflect GHG intensity of electricity used during production. The chart indicates which generation options correspond to various GHG intensities to provide some insight into generation mixes. The low carbon portfolio could be comprised of nuclear, wind, coal with carbon capture and sequestration, and other low carbon electricity generation technologies (see **Table 2.5**). The vertical line at 670 g CO_2-eq / kWh indicates the US Average life cycle GHG intensity.

Figure 2.6 expands on the above scenarios by comparing cellulosic ethanol and gasoline use in each of the vehicles. With an 85% cellulosic ethanol blend (E85) and the current US average electricity, fuel-efficient vehicles that do not use electricity, such as HEVs or other CVs with high fuel economy, will minimize GHGs. In contrast, with a low-carbon electricity portfolio, plug-in hybrids utilizing primarily electricity for propulsion will have lower GHGs in a system where petroleum remains the dominant liquid fuel. **Table 2.9** shows the sensitivity of the life cycle GHG results to changes in GHG intensity of electricity, vehicle efficiencies, and E85 cellulosic ethanol use. As with CVs and HEVs, emissions from PHEVs are sensitive to changes in fuel economy. If kWh/km requirements for PHEVs improve by 20% while holding liquid fuel economy constant for all vehicles, life cycle GHGs from PHEVs are 10-13% lower than HEVs. Conversely, a 20% improvement in liquid fuel economy across the vehicle technologies results in HEVs having 4-13% lower life cycle GHGs than plug-in hybrids. Finally, the adoption rate of biofuels and flex-fuel vehicles, changes in the electricity mix, and changes in driving patterns will also influence the potential benefits of a plug-in hybrid automobile fleet.

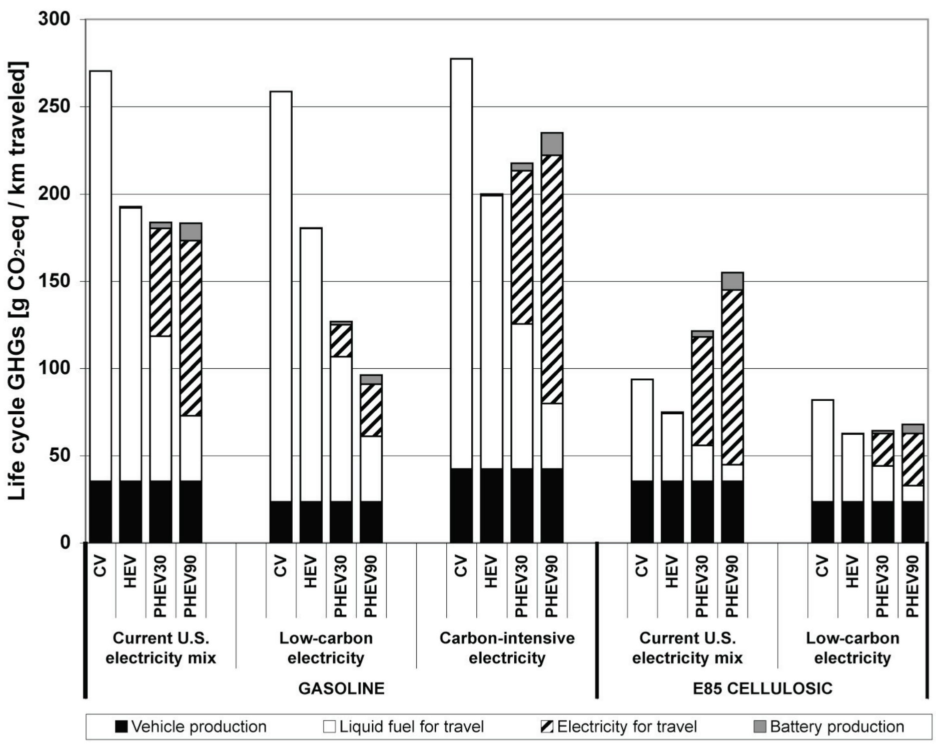

Figure 2.6. Life cycle GHG emissions sensitivity of CVs, HEVs and PHEVs with 30 or 90 all-electric km ranges under fuel and electricity carbon intensities. Life cycle carbon intensity of electricity assumed to be 670, 200, and 950 g CO_2-eq / kWh for US average, low-carbon, and carbon-intensive scenarios, respectively. “E85” is a liquid fuel with 85% cellulosic ethanol (volume basis), and the remainder gasoline.

Table 2.9. Sensitivity of results to changes in GHG intensity of electricity, vehicle efficiencies, and E85 cellulosic ethanol use.

Scenario	Parameter varied	Life cycle GHG emissions [g CO_2-eq / km]				
		CV	HEV	PHEV 30	PHEV 60	PHEV 90
Baseline results (gasoline)		269	192	183	181	183
Carbon-intensive scenario	electricity GHG intensity	276	199	217	228	235
Low-carbon scenario	electricity GHG intensity	257	180	126	104	96
High kWh/km required (10% degradation)	0.22 kWh/km	269	192	190	192	195
Low kWh/km required (20% improvement)	0.16 kWh/km	269	192	170	162	161
Low fuel economy (20% degradation)	10 km/l (CV), 15 km/l (HEV and PHEV)	328	231	204	194	192
High fuel economy (20% improvement)	15 km/l (CV), 23 km/l (HEV and PHEV)	230	166	169	173	177
E85 Cellulosic liquid fuel		94	75	121	144	155
Carbon-intensive scenario	electricity GHG intensity	101	82	155	191	207
Low-carbon scenario	electricity GHG intensity	82	63	64	66	68

Under widespread PHEV market penetrations, the reduced demand for liquid fuel could have important implications for the feasibility of biofuel use in the transport sector. Cellulosic biofuels offer potential GHG reductions from transport, however the resource base is limited (*50, 67*). Gasoline use in light duty vehicles is about 17 EJ / year (*54*). To supply 25% of this current demand with ethanol from cellulosic crops, between 50 and

100 million hectares (ha) of land would be required (180 million ha are currently used each year for growing crops (*68*)). This is based on a 40% conversion efficiency from energy in plant matter to energy in ethanol (*69*), and between 6 and 12 Mg of biomass yield per ha (dry basis) annually (*5*). Thus, between 45 and 90 GJ of liquid fuel would be produced per hectare.

Tilman *et al.* report that biofuels grown on degraded land could provide about 13% of current global petroleum use in transport, and 19% of current global electricity consumption, which would reduce global GHG emissions by 15% (*50*). Furthermore, biomass processing systems that produce both protein for animal feed and carbohydrates for liquid fuel and electricity production could ameliorate the tension between energy and feed crops (*70*). Since it is unlikely that biofuels alone will provide necessary GHG emission reductions, PHEVs could provide a platform to efficiently leverage these low-carbon energy streams. Under the configurations and driving patterns used in this analysis, an all PHEV fleet would reduce current gasoline use from 17 EJ / year to between 4-9 EJ / year. 10 million ha of land could supply one EJ of liquid fuel, assuming a yield of 90 GJ of ethanol per hectare. Non plant-based feedstocks, such as municipal solid waste (MSW), can also be used to produce low-carbon liquid fuel. However all of the MSW produced in the US could produce less than one EJ of ethanol per year (*71*).

2.4 Discussion

For large GHG reductions with plug-in hybrids, public policies that complement PHEV adoption should focus on encouraging charging with low-carbon electricity. Policies could include adjusting renewable portfolio standards to account for potential off-peak charging. If PHEVs supply a sizeable portion of passenger travel, charging intelligence will likely be incorporated to maximize utilization of available resources and low-cost electricity, facilitate user billing and replacement of motor fuel taxes for infrastructure funding, as well as potentially enable two-way power flows between vehicles and the grid (*64*). Public policies could utilize charging intelligence to minimize the carbon intensity of electricity used, either by prices or credits.

While it is evident that GHG intensity of the electricity used to charge PHEVs greatly affects their ability to reduce GHG emissions from transport, a policy discussion regarding electricity supply decisions and PHEVs deserves wider attention and dialogue. US power generation facilities, especially aging coal power plants, are generally nearing the end of their useful lives and will have to be replaced or overhauled within the next two decades. Because power plants typically are in service for 30 years or more, technology decisions regarding new generation capacity will have profound and long-lasting GHG impacts (*72, 73*). The Department of Energy reports plans to build 50 GW of coal power plants in the next 5 years and a total of 154 GW within the next 24 years (*66*), and the US Energy Information Administration reference case forecasts a 2030 electricity mix with higher carbon intensity than today's mix (*74*). If new coal plants are untenable, increasing demand for natural gas, even in the absence of potential PHEV adoption, will likely require large increases in liquefied natural gas (LNG) imports. The life cycle GHG impacts of LNG for electricity are higher than for domestic natural gas (*31*). Hence large reliance on LNG to power PHEVs could increase emissions relative to using domestic natural gas, and introduce additional energy security risks. Large reductions in the GHG intensity of the electricity sector within the next 30 years will only be realized by sustained replacement of retired carbon-intensive capital with low-carbon generation.

Long-term planning horizons in the automotive sector are much shorter than the power sector, with an automotive fleet cycle of 12-15 years. If PHEVs have high adoption in two or three fleet cycles from now, the electricity supply technology decisions made within the next ten years will affect the GHG intensity of the electricity system encountered by those vehicles. A commitment to developing a low-carbon electricity portfolio becomes even more important if large GHG reductions from PHEVs are desired within the current cycle of electricity capital turnover.

Concerns regarding climate change and national GHG emissions demand that a shift to PHEVs be analyzed, and so GHGs are the focus of this study. However, with a potential transition from a primarily petroleum-based passenger transport sector to one powered with electricity, climate change is one consideration, while the impacts on criteria air pollutants (*75*), reduced oil dependence, and toxic releases are others. A thorough life cycle impact assessment of PHEVs would potentially estimate acidification, eutrophication, photochemical smog, terrestrial and aquatic toxicity, human health impacts, resource depletion, land and water use, and perhaps additional impact categories (*76*). Future research could identify the environmental tradeoffs among these impacts categories from a PHEV fleet. While the environmental fate and transport of current battery technology materials are not similar to lead-acid batteries (*77*), potential toxicity during materials procurement and battery manufacturing, and a strategy to deal with the recovery, recycling, and disposal of vehicle batteries should be part of the dialogue in a transition to large-scale adoption of storage batteries in vehicles.

When charging PHEVs with electricity that has a GHG intensity equal to or greater than our current system, our results indicate that PHEVs would considerably reduce gasoline consumption but only marginally reduce life cycle GHGs when compared with gasoline-electric hybrids or other fuel efficient engine technologies. With a low-carbon electricity system however, plug-in hybrids could substantially reduce GHGs as well as oil dependence.

The effect of PHEVs on GHG emissions from the transportation sector will depend on the rate of consumer adoption. Our focus on low, current, and high GHG-intensive electricity scenarios allows decision makers to think about what an electricity system should look like, over various adoption scenarios, if PHEVs are pursued as a source of large GHG emissions reductions. With the slow rate of capital turnover in the electricity sector, a low-carbon system may require many years to materialize. Considerable reductions in greenhouse gas emissions using plug-in hybrids in the coming decades will likely require decisions within the next ten years to develop a robust low-carbon electricity supply.

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Chapter 3: Economics, infrastructure and policies of emerging energy technologies: Plug-in hybrid vehicles

3.1 Introduction

Substantially reducing global greenhouse gas (GHG) emissions from passenger transportation is challenging. With petroleum currently providing more than 96 percent of the United States (US) transportation energy supply (*1*), options include increasing vehicle fuel economy, reducing annual distances traveled, or diversifying to an energy source other than petroleum. Sustainable biofuels supplies appear to be limited in the near-term (*2*) and the expense and efficiency of hydrogen fuel cells suggest they are more of a long-term technology goal rather than a transition technology away from petroleum (*3, 4*). Electrified transportation carries the advantages of utilization of an existing infrastructure asset, the electricity grid, which preliminary studies suggest has sufficient available overnight system capacity for millions of plug-in hybrids (PHEVs) (*5, 6*).

Economic competitiveness of PHEVs will be required for large-scale consumer adoption. In the decision to invest additional initial capital in a high fuel economy (e.g. hybrid) vehicle, gasoline prices greatly affect the decision (*7, 8*). Lave and MacLean argued in 2002 that gasoline prices had to be \$3.55-\$5.10/gallon to economically justify a hybrid premium (*8*). Gasoline prices are similarly a strong incentive for PHEV purchases, however additional factors including battery cost, household infrastructure requirements, electricity price, and vehicle use enter into the decision space. Lemoine et al. state that current gasoline prices would require PHEV battery prices to be below \$650/kWh, rather than the \$1,000-\$2,000/kWh they are currently for a PHEV to be economically competitive (*6*). Hence, if large consumer adoption of PHEVs is desired, appropriate policies must improve the cost differential between owning a PHEV and owning a comparable internal combustion (ICE) engine vehicle.

This chapter will answer three questions: 1) What are the demand-side needs and infrastructure required for PHEV adoption at scale? 2) What are the economic factors and uncertainties comprising the decision space in scalable adoption of PHEVs? 3) What policies could encourage PHEV adoption and what are the ranges of expected costs? This research takes an approach to inform the set of decisions that bound a future desired outcome – large scale adoption of PHEVs and the transition to electricity supplying a major portion of US transportation energy demand. Following a technical analysis, recommendations on the implications of the study's findings on climate change policy will be presented.

3.2 Method

3.2.1 Scalability of plug-in hybrids and demand-side infrastructure assessment

Before rigorous technical and policy analysis is undertaken for an emerging energy technology, a screening estimation of the scalability and critical infrastructure needs is warranted. Supply-side infrastructure will consist of available power generation capacity for a transition to electrified transportation; preliminary work has suggested that existing overnight electricity supplies have adequate capacity to power up to 73% of the current light duty vehicle fleet as PHEVs (*5*). Lemoine et al. estimated that off-peak charging in the California Independent System Operator (CAISO) territory could enable up to 5 million PHEVs, and that CAISO could adequately respond to aggressive PHEV adoption

(*6*). While transmission constraints may present an issue in existing locally congested areas, transmission issues need to be addressed on a corridor-by-corridor basis on both the transmission and distribution systems, which we leave for future work. The demand-side infrastructure screening undertaken in this work takes a bounding approach to estimate access and costs to plug-in a passenger transportation vehicle in the US

The primary demand-side infrastructure need for PHEVs is an electrical outlet to recharge the vehicle. Several different types of charging connections, both inductive and conductive emerged in the 1990s to charge electric vehicles (*9*). Because a vehicle was only able to be charged with a certain connection type (similar to the situation with many mobile phones), this limited public charging to only compatible stations and required the user to have specialized charging equipment for home use. While it is unclear if a standard charging protocol will emerge with the commercialization of PHEVs, we assume here that PHEV charging will be conductive charging using standard, prevalent and familiar home outlets.

US home outlets can be rated 120V (with 15 or 20A) or 240V (generally with 30 or 40A for vehicle charging). 120V outlets, the standard outlet used for most applications, usually do not require electrical service upgrades, but deliver less energy to the vehicle as a function of time and hence increase charge times. 240V outlets, used for high demand applications such as clothes dryers and ovens, would have the benefit of lower charging times, but generally higher installation costs if service upgrades are necessary. Automakers could include vehicle connections that were adaptable to both lower and higher power flows, however charging at higher power flows would be limited to households with capable infrastructure in place.

If off-peak overnight charging is desired to reduce the strain on the electrical grid, then it is necessary for PHEVs to have access to an outlet where they are parked overnight, or near residences. So, first adopters of PHEVs will likely be those with access to a charging outlet where they park their vehicles overnight.

The US Census estimates that about 62% of US households consist of single unit, detached structures (*10*) as shown in **Figure 3.1**. About 29% of US households are within central cities, 47% in suburbs, and the remaining 24% outside of Metropolitan Statistical Areas (MSAs) (**Figure 3.2**). Spatial distribution between urban and rural areas will influence driving and commute patterns, and the viability of PHEVs.

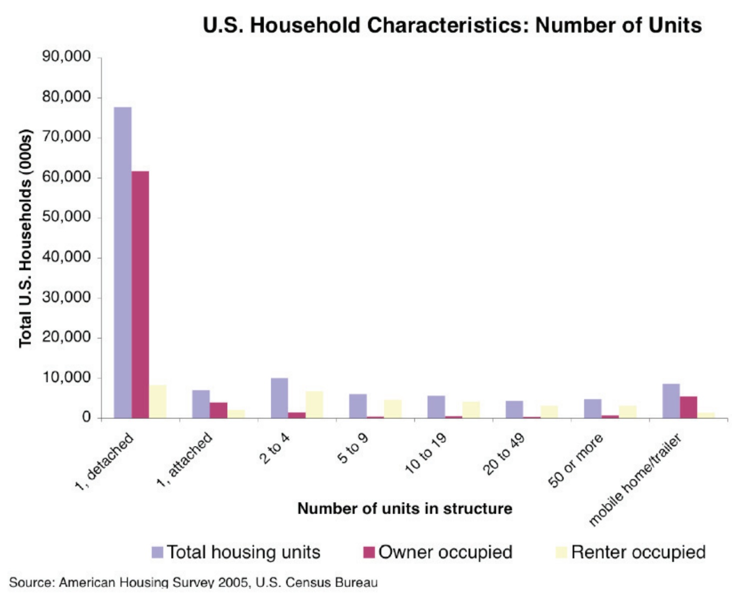

Figure 3.1. Distribution of the number of housing units in a structure among US households. The majority of households consist of single-unit detached structures, facilitating PHEV charging. Constructed using data from (*10*).

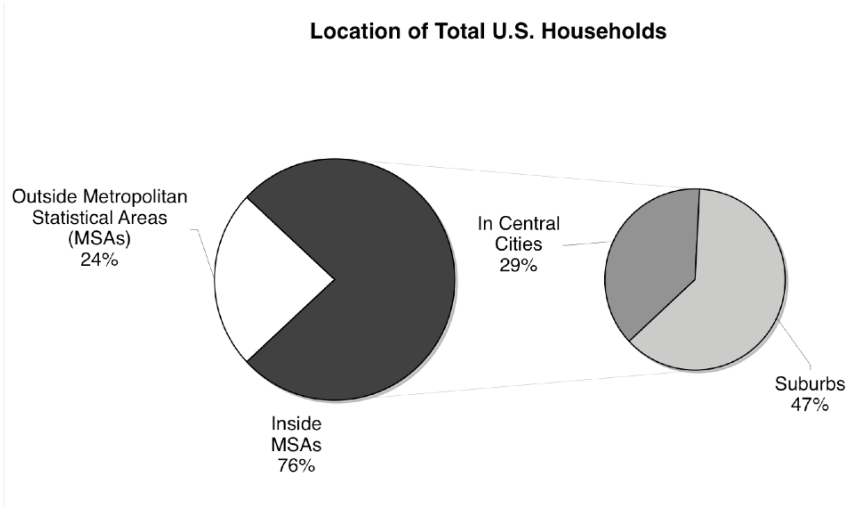

Figure 3.2. Location among US households. The majority of households exist within MSAs. Constructed using data from (*10*).

Households with existing garages that have an existing electrical outlet will require no or minimal infrastructure investment and will be ideal charging locations for first adopters of PHEVs. Approximately 63% of US households have a garage or carport, although there is a wide disparity between owner-occupied households and renter-occupied households (**Figure 3.3**). If an existing garage requires the installation of an additional outlet, installation costs would range between \$200-\$500. If an existing carport did not have electrical capabilities, installation of an outdoor electrical line and outlet are assumed to be between \$500-\$1000 depending on conditions. Costs could increase if a dedicated 30 amp circuit is required and/or if an electrical service panel upgrade is required. Because of the additional utility revenue streams possible with PHEVs, utilities may choose to partially or fully reimburse the homeowner for the costs of electrical upgrades and/or inspections.

Households without existing garages, but with access to off-street parking comprise the next largest subset, or 31% of total occupied households. Since the access to off-street parking category is not further divided into subcategories by the US Census Bureau, this category could include household access to driveways, surface parking lots, indoor parking garages, or other spaces. Infrastructure costs would vary from installing an outdoor electrical outlet in a driveway to retrofitting existing or including outlets in new surface lots or garages. The costs of installing an outdoor outlet for a driveway is assumed to be similar of that of a carport, or \$500-\$1000. Costs of retrofitting or installing outlets in surface lots or garages would likely be borne by businesses, apartment managers, fleet managers, and municipalities considering providing capabilities for electric vehicle charging. While the cost borne by third parties may eventually be passed on to consumer, this analysis examines household costs, and leaves the costs of public charging for future work.

The final category of household parking availability, those without access to either a garage or off-street parking, comprises about 6% of total occupied households. This trend varies by region, from 17% of Northeastern households to 3% of Western households. Additionally, the number of households without access to dedicated parking is far larger in dense metropolitan areas, with about 48% of New York City MSA households without access to household parking (**Figure 3.4**). This trend is somewhat buffered by mass transportation usage reducing potential relative demand for PHEVs in the Northeast and from households in dense urban centers (**Figure 3.5**). Households in the Northeast use mass transportation as the primary mode of travel to work at 3 times the national average, and 39% of households in the New York City MSA use mass transportation to travel to work - nearly 10 times the national average.

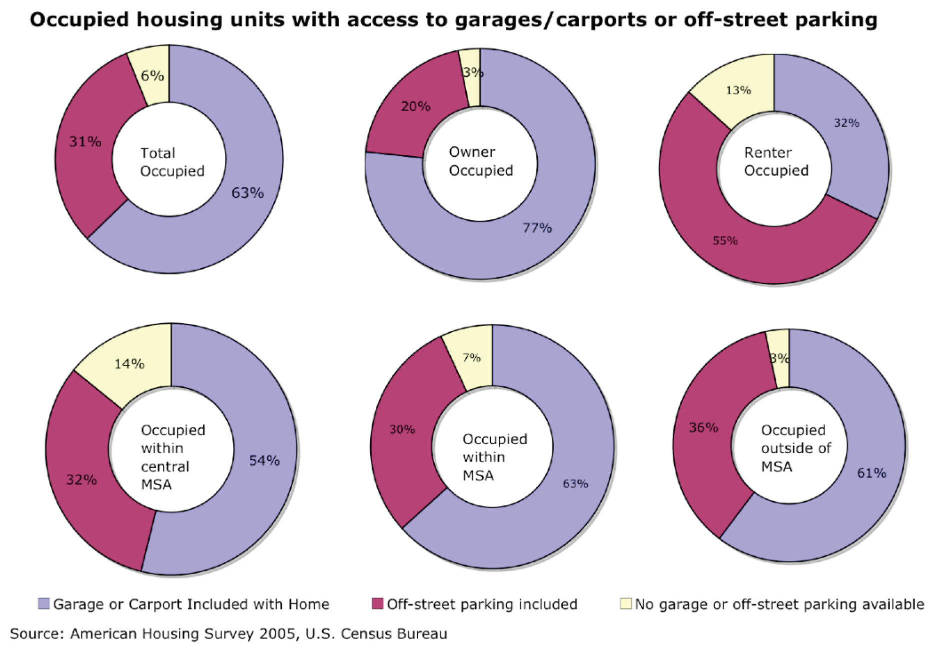

Figure 3.3. Percentage of US occupied households with access to a garage or carport, access off-street parking, or no access to a garage or off-street parking. Constructed using data from (*10*).

Renters comprise a larger proportion of those without dedicated parking access than owners, and may face higher demand-side infrastructure costs of PHEV ownership than homeowners. This introduces additional equity issues in the discussion of PHEV infrastructure and is an opportunity for additional detailed policy analysis in future work.

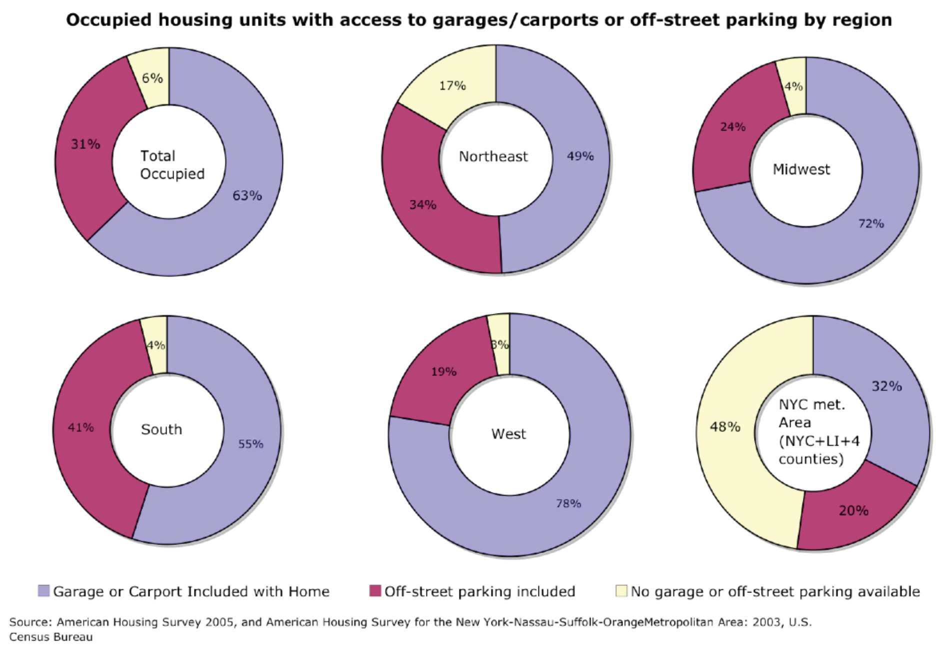

Figure 3.4. Percentage of US occupied households with access to a garage or carport, access off-street parking, or no access to a garage or off-street parking by region. Conditions in a dense Metropolitan Statistical Area are illustrated with the New York-Nassau-Suffolk-Orange data, which also includes Rockland, Putnam, and Westchester counties. Constructed using data from (*10*).

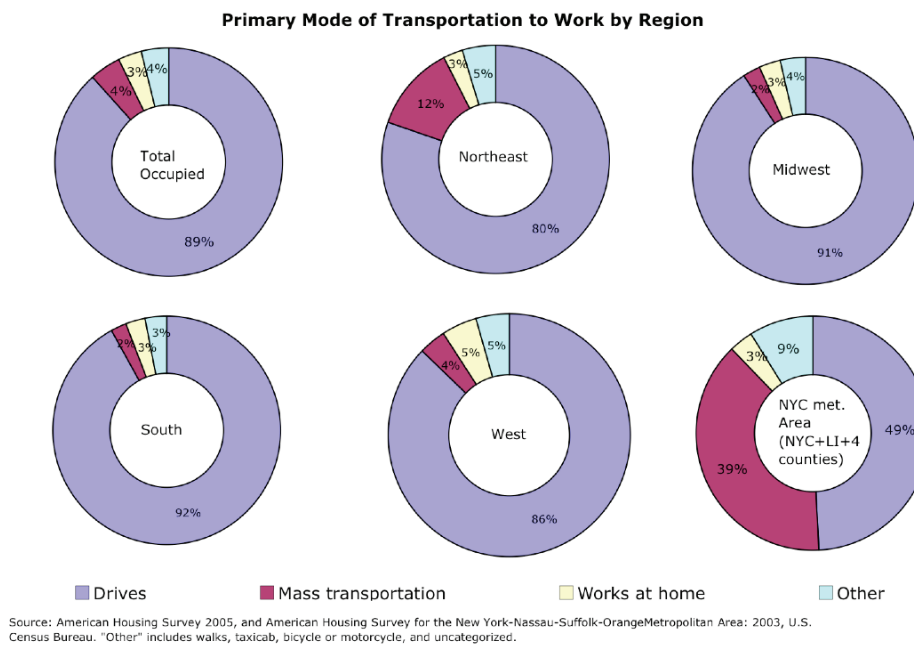

Figure 3.5. Primary mode of transportation to work of US occupied households by region. Conditions in a dense Metropolitan Statistical Area are illustrated with the New York-Nassau-Suffolk-Orange data, which also includes Rockland, Putnam, and Westchester counties. Constructed using data from (*10*).

3.2.2 Economic Comparisons

Large-scale consumer adoption of alternative energy and automotive technologies will depend on the economic competitiveness of the new technology compared to other available options. For large-scale adoption of PHEVs, consumers must realize a greater economic benefit on the cost of owning and operating a PHEV than the cost of owning and operating a CV. The amount of miles that a user travels on electricity (influencing operating costs per mile), any additional capital vehicle premiums, and any additional demand-side infrastructure costs will affect the decision and policy space for PHEVs.

Operating costs in this analysis consist of solely fuel and electricity purchases. As in (*11*), differences in vehicle service and maintenance costs are assumed to be negligible. To compare similar vehicles, we use light duty passenger sedans similar to a Toyota Prius and a Toyota Corolla. We assume PHEV electrical efficiency of 318 Wh/mile at the wall outlet (*12*), PHEVs operating in HEV mode and traditional HEVs both achieve 44 mpg, and CVs achieve 30 mpg (*13, 14*). As detailed below, we assume installed battery prices represent the entire retail premium between a PHEV and CV, so our comparison can be made with any vehicle that achieves 30 mpg, not solely the Corolla.

The primary economic benefit derived from PHEV operation versus traditional HEV operation is the price differential for traveling solely on electricity versus traveling on gasoline. The US average residential retail electricity rate for 2007 varied from \$0.064-\$0.241 per kWh between states, with an average of about \$0.11/kWh (*15*). Retail costs of US motor gasoline averaged \$2.81/gallon in 2007 and averaged about \$4.00/gallon in June of 2008 (*16*). As shown in **Figure 3.6** the economic equivalent price of gasoline for PHEV operation based on the electricity price in 49 US states ranges from about \$1.00-\$2.50/gallon. In Hawaii, where electricity is expensive, the equivalent fuel price is about \$3.40/gallon. Gasoline prices in Hawaii are generally also higher than US average prices, with the Hawaii and US average retail prices (excluding taxes) about \$3.43 and \$3.29, respectively in May 2008 (*16*). Thus, when only operational prices are included, electric-powered PHEV travel generally has an economic advantage in all US states. Since some territories offer reduced electricity prices for off-peak use (but not off-peak gasoline purchases), the economic advantage of electric-powered travel would be enhanced in these areas. Additionally, if residential consumers face real time or time of use prices, these prices would have to be above \$0.25/kWh before the economic equivalent gasoline price was about \$3.50/gallon. The most expensive generation typically is only dispatched over a limited period of the year. Spees and Lave argued that 20% of the generation capacity in the PJM territory was dispatched for fewer than 202 hours of the year (*17*). While consumers may be economically discouraged from charging during the few times of the year with extremely high priced electricity, the economics of electric-powered travel would likely not become less favorable under real-time or time of use prices.

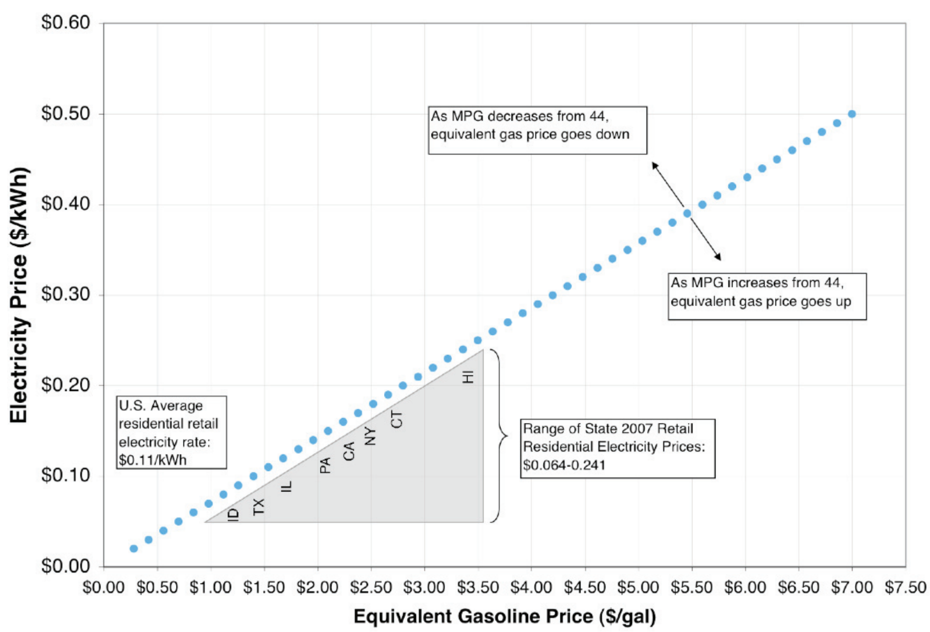

Figure 3.6. Economic equivalent prices of retail gasoline and residential retail electricity for PHEV operation. Operating a PHEV using the range of 2007 state electricity prices are equivalent to paying approximately \$1.00-\$3.40/gallon for gasoline. These are per mile operating costs only (excluding vehicle capital costs), and assume PHEVs require 318 Wh/mile and achieve 44 mpg. Constructed using data from (*15*).

The economic advantages of driving on electricity versus driving on gasoline do not change if there is a price on CO_2. If the cost of CO_2 is accounted for, either via a carbon tax, cap-and-trade allowances, or the implied shadow price of carbon dioxide, per mile operation costs remain lower for PHEVs to operate on electricity rather than on gasoline. To bound the analysis, **Table 3.1** shows the per mile of operating a PHEV, a HEV, and a CV under a CO_2 price of $0, $30, and $60 per tonne. This range is consistent with the values of cap-and-trade allowances in the US Lieberman-Warner Climate Security Act (*18*), as well as a recent estimation of the shadow price of CO_2 to meet a 550 ppm stabilization target (*19*).

Table 3.1. Per mile operating costs (excluding vehicle capital costs) of a PHEV driving on electricity (318 Wh/mile), a PHEV/HEV driving on gasoline (44mpg) and a CV (30mpg) given various prices of electricity, gasoline, and CO_2. The range of electricity prices under a carbon tax show conditions when electricity has zero (or very low) g CO_2-eq/kWh and 950 g CO_2-eq/kWh (similar to a coal plant). The gasoline price under a carbon tax assume both combustion and upstream impacts are included, leading to 11.34 kg CO_2-eq/gallon (*20, 21*). Both electricity and gasoline prices under a carbon tax conservatively assume a 100% tax incidence on the consumer, used as an upper bound.

Cost of electricity	Cost of driving on electricity ($/mi)	Cost of gasoline ($/gal)	Cost of driving on gasoline ($/mi at 44mpg)	Cost of driving on gasoline ($/mi at 30mpg)
$0.11/kWh	$0.03	$3	$0.07	$0.10
$0.15/kWh	$0.05	$5	$0.11	$0.17
$0.30/kWh	$0.10	$7	$0.16	$0.23
Including a $30/tonne CO_2 tax				
$0.11-$0.14/kWh	$0.03-$0.04	$3.34	$0.08	$0.11
$0.15-$0.18/kWh	$0.05-$0.06	$5.34	$0.12	$0.18
$0.30-$0.33/kWh	$0.10-$0.11	$7.34	$0.17	$0.24
Including a $60/tonne CO2 tax				
$0.11-$0.17/kWh	$0.03-$0.05	$3.68	$0.08	$0.12
$0.15-$0.21/kWh	$0.05-$0.07	$5.68	$0.13	$0.19
$0.30-$0.36/kWh	$0.10-$0.12	$7.68	$0.17	$0.26

While the operating cost spread between PHEVs and ICEs is favorable, the primary reason PHEVs are not currently economically competitive is the additional capital cost of the battery (and infrastructure) required and the uncertainty if the battery will last the life of the vehicle under PHEV conditions. The additional initial investment in PHEVs will likely be only made at scale if consumers perceive the value of the stream of fuel costs savings (and any additional bundled value services) as being greater than the initial capital outlay. We explore the inputs to this decision, and model variables and their uncertainty are given in **Table 3.2**.

Table 3.2. Model parameters for the decision to purchase a CV or PHEV

Parameter	Description	Best Estimate	Low Estimate	High Estimate	Source
α_e	Percentage of annual PHEV miles traveled on electricity	61%	26%	73%	(*11, 22*)
C_b	Capacity of PHEV battery, kWh	11.9	4.0	19.9	Assumed
D	Annual vehicle miles traveled	12,000	9,000	16,000	(*23*)
F_{CV}	CV efficiency, gallons per mile	30	25	35	(*12, 13*)
F_{HEV}	HEV/PHEV efficiency, gallons per mile	44	37.9	50	(*12, 13*)
F_{PHEV}	PHEV efficiency, kWh/mile	0.318	0.20	0.35	(*12, 24*)
K_I	Cost of home PHEV infrastructure	\$500	\$200	\$1,000	Assumed
P_b	Price of battery, \$/kWh	\$1,000	\$250	\$2,000	(*6, 25, 26*)
P_e	Price of electricity, \$/kWh	\$0.15	\$0.08	\$0.30	(*15*)
P_f	Price of fuel, \$/gal	\$4	\$2	\$8	(*16*)
r	Discount rate for consumer preference	6%	0%	16%	(*8, 27*)
T	Vehicle lifetime, years	12	10	15	Assumed

While a range of both gasoline and electricity prices are investigated, they are assumed to be both fixed and certain over the life of the vehicle for each comparison made. That is, in a scenario with an \$8/gallon gasoline parameter, that price remains at \$8 for the entire net present value analysis. A sensitivity and Monte Carlo analyses are presented below. The present value of CV operation, PV_{CV}, is determined by the annual operating costs represented by the annuity:

$$PV_{CV} = \left(P_f \cdot D \cdot F_{CV}\right)\left[\frac{1 - \frac{1}{(1+r)^T}}{r}\right]$$

Depending on battery capacity, PHEVs are powered by electricity (α) and by gasoline ($1-\alpha$) for a portion of daily travel. Values of α for different battery capacities, which is the percentage of daily travel powered by electricity, are listed in **Table 3.2**, and estimated from (*11, 22*). Since it is possible that individual consumers will have varying values of α, we decouple these values from battery size during the sensitivity analysis below.

The additional capital costs for a PHEV include the present value of household infrastructure upgrades, K_I, as discussed above, and the present value cost of the battery, K_b, using PHEV battery capacities. K_b is given by the product of battery unit price per kWh, P_b, and battery capacity, C_b. Battery costs are extremely important to the economic viability of PHEVs and the costs used in this analysis represent the total price to the consumer for battery and components (\$/kWh available). Current aftermarket PHEVs conversions have an installed retail cost of about \$2,000/kWh (*25*). As estimated in (*6*), we assume that battery costs consumers would face from vehicle manufacturers would be \$1,000 kWh, while the US Advanced Battery Consortium has near-term and long-term cost goals of \$300 and \$200/kWh, respectively (*26, 28*). The capacity of the battery is determined by assuming an 80% depth of discharge, a lithium-ion battery energy density of 0.1 kWh/kg (*29*) and 0.318 Wh/mile at the wall outlet required for PHEV travel (*12*).

The battery sizes listed correspond to a PHEV with capacities of 10, 30, and 50 miles of electric ranges (PHEV10, PHEV30, and PHEV50, respectively). We assume net additional battery costs represent the entire retail premium between a PHEV and HEV or CV (*6, 11*), and that battery costs are paid in full at the time of vehicle purchase. A full initial capital outlay for the battery and infrastructure upgrades would also be equivalent to the present value of annualized costs using the same discount rate and lifetime used to analyze future fuel costs.

The present value cost of PHEV operation, PV_{PHEV}, is given by:

$$PV_{PHEV} = K_b + K_I + \left[\left(\alpha_e \cdot P_e \cdot D \cdot F_{PHEV}\right) + \left[\left(1-\alpha_e\right)\left(P_f \cdot D \cdot F_{HEV}\right)\right]\right]\left[\frac{1-\dfrac{1}{(1+r)^T}}{r}\right]$$

3.3 Results

Figure 3.7 shows the decision space bounding the choice to purchase a CV versus a PHEV30, using the best estimate parameters listed in **Table 3.2**. Battery costs and gasoline prices are the most sensitive variables in the model and the figure shows that PHEV30s are not economically competitive using current estimated battery prices ($1,000/kWh) unless gasoline prices are about $7/gallon. If the US Advanced Battery

Consortium (USABC) goal of $300/kWh is achieved (*26*), PHEVs would be competitive at around $3/gallon.

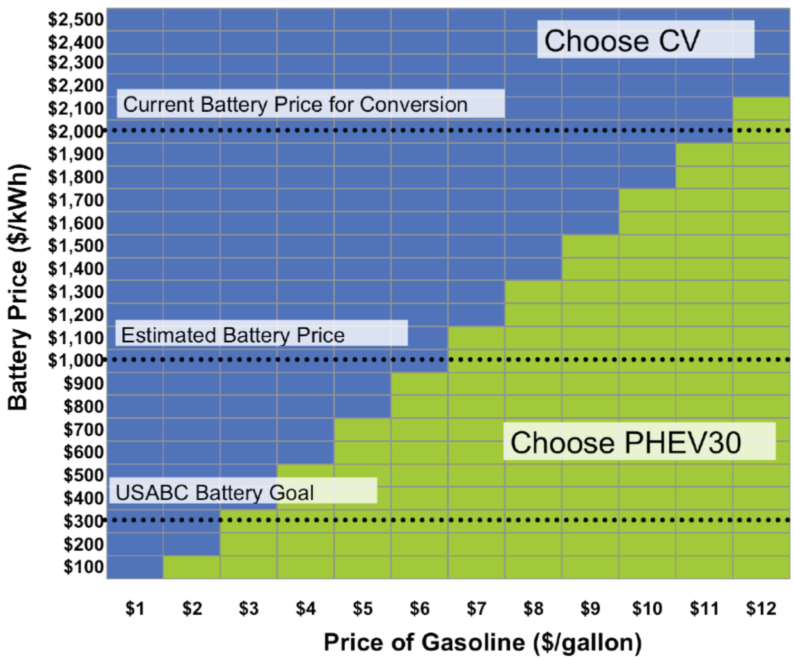

Figure 3.7. Economic decision space in the choice between a CV and a PHEV30 under various battery and gasoline prices. The upper left of the space represents expensive batteries and inexpensive fuel, leading the consumer to choose a CV. The bottom right of the space represents inexpensive batteries and expensive fuel, leading the consumer to choose PHEVs. Present value of capital and operating costs under the best estimate assumptions in **Table 3.2**.

As shown in **Figure 3.6**, vehicles with higher gasoline efficiencies increase the economic equivalent price of gasoline versus driving on electricity. Hence the economic decision space for choosing a highly efficiency vehicle (such as a HEV with 44 mpg) over a PHEV30 would shift. Choosing a PHEV30 over an HEV when battery costs were $1,000/kWh would require a gasoline price of about $11/gallon. The public policies and priorities established surrounding these decisions will guide market directions toward more efficient CVs or PHEVs.

Because the economic viability of PHEVs increases with the price of gasoline, PHEVs may have initial success in markets with comparatively higher fuel prices. As shown in **Figure 3.8**, gasoline prices including taxes for several European nations are considerably higher than the U.S (*30*). Electricity rates are also typically higher in some nations with high fuel costs (*31*), so policymakers could develop incentives that offer low-cost, (and potentially low-carbon) electricity prices to PHEV customers, increasing the financial viability of PHEVs.

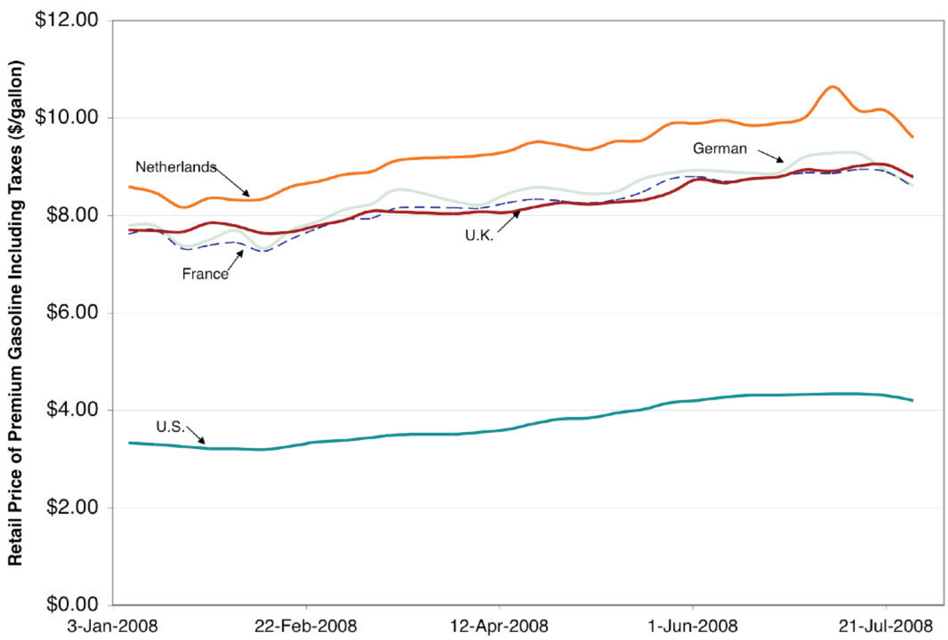

Figure 3.8. Retail Premium Gasoline Prices ($/gallon) in 2008 for selected countries.

3.3.1 Sensitivity Analysis

While battery price and fuel costs are important parameters in the economic decision between a PHEV and CV, a sensitivity analysis is conducted to identify any other parameters with the ability to change the answer. Uncertainties in other variables, such as changes in vehicle efficiencies due to increased battery weights (*32*), also require sensitivity analysis to determine the potential impact on results. As shown in **Figure 3.9** and **Table 3.3**, battery size is the only other single parameter where changes in assumptions greatly affect the estimation. This result shows that a consumer purchasing a PHEV10 (4 kWh battery) would realize a small positive net present value by choosing a PHEV over a CV. When consumers discount savings from future fuel costs at 16 percent as estimated by (*27*), then the net present value from a PHEV10 is negative.

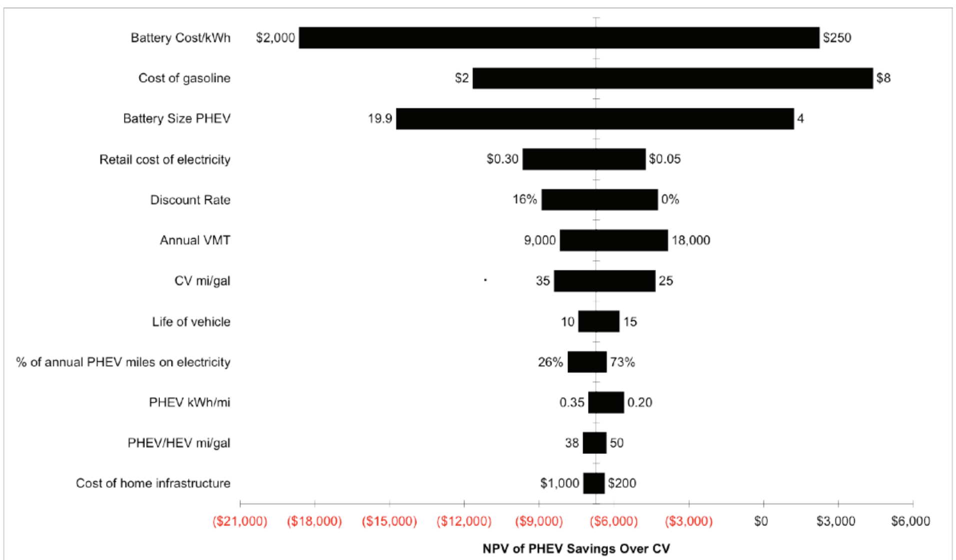

Figure 3.9. Sensitivity analysis of parameter variation on the net present value estimation between a PHEV and a CV. Parameters listed in **Table 3.2**.

Table 3.3. Sensitivity of nominal and net present value savings of various PHEVs over a CV, assuming $4.00/gallon gasoline, 6% interest rate, 12 year life, $0.15/kWh, battery sizes of 4, 11.9, and 19.9 kWh, battery costs of $1,000/kWh, and α values corresponding to the estimated percent of annual travel on electricity (*11, 22*)

	PHEV10	**PHEV30**	**PHEV50**	**CV**
Annual Electricity Used (kWh)	992	2328	2786	
Annual Electricity Cost	$149	$349	$418	
Annual Gasoline Used (Gallons)	202	106	74	400
Annual Gasoline Cost	$807	$425	$295	$1,600
Total Annual Fuel Savings	$644	$825	$888	
Total Lifetime Nominal Fuel Savings	$7,727	$9,905	$10,651	
Total Lifetime Real Fuel Savings	$5,398	$6,920	$7,442	
Battery and Infrastructure Costs	$4,500	$12,400	$20,400	
Net Nominal Value	$3,227	($2,495)	($9,749)	
Net Present Value	$898	($5,480)	($12,958)	

As shown in (*32*), small PHEVs that charge frequently generally have greater economic and environmental benefits compared to larger PHEVs and HEVs. If the consumer is able to purchase a small PHEV (e.g. a PHEV10) and drive predominately on electricity (via short trips and frequent charging), then the consumer is gaining the gasoline and cost savings of a larger PHEV without the additional capital cost required for a larger battery. These results highlight the potential for increased economic and environmental competitiveness of small PHEVs with frequent charging, which would allow a greater percentage of a user's daily travel to be on electricity. This gives policymakers another tool to increase the competitiveness of PHEVs – support for public, workplace, and retail charging opportunities. However, as shown in (*6*) peak charging could be problematic for the grid and so policies must balance private costs to the consumer versus social costs of additional grid instability, peak power usage, or additional power plants required. Also, if charged once per day, a PHEV10 would enable about 26 percent of users to travel solely on electricity during daily travel. This would result in considerably less oil use reduction than a PHEV20, PHEV30, or PHEV50 (about 48%, 61%, and 73% of vehicles in use travel less than 20, 30, or 50 miles per day) (*22*). So a tradeoff exists between battery size and potential gasoline displacement.

The sensitivity analysis above estimates how the original model changes when one of the parameters in the model varies. However, it is possible that one or more of the parameters will be different for various scenarios, technology development, or user behavior. To address the uncertainty of the parameters in the model, a Monte Carlo analysis is conducted. Using a triangular distribution between the low estimate, best estimate, and high estimate values from **Table 3.2** and 1000 trials, the results show that PHEVs are economically competitive with CVs in about 20% of the randomized trials as shown in **Figure 3.10**. The mean present value subsidy required for PHEVs to have economic parity with CVs under the Monte Carlo analysis is about $5,100. This strongly supports the need for government action if large adoption of PHEVs is desired.

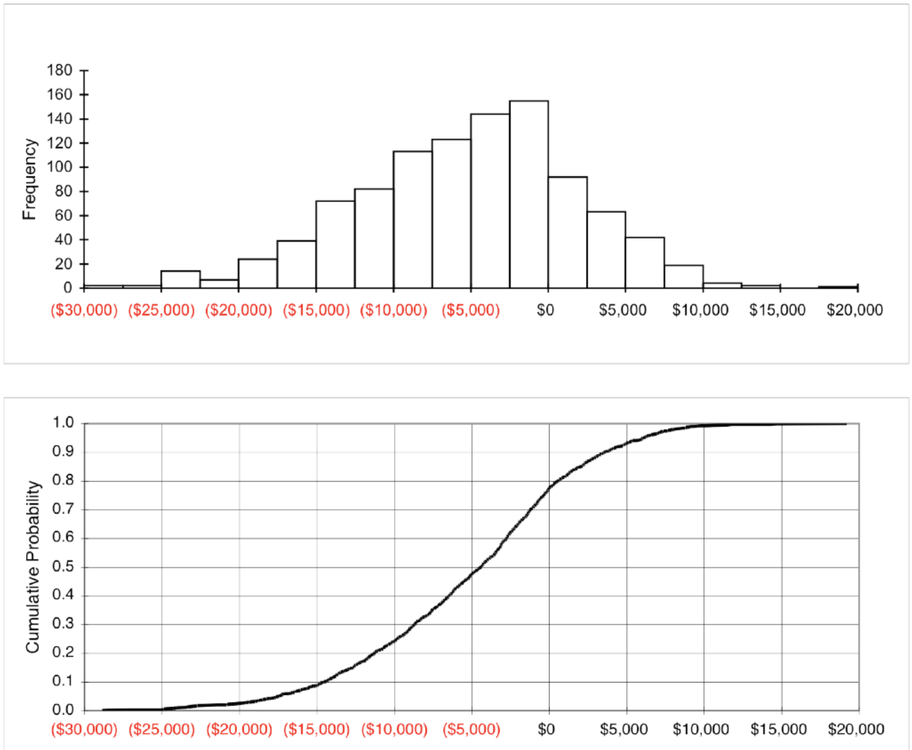

Figure 3.10. Monte Carlo analysis of the net present value economic decision space in the choice between a owning and operating a PHEV and a CV under all model parameters. Triangular distributions between the low estimate, best estimate, and high estimate model parameters were used.

3.3.2 Potential Policy Actions for Adoption

The NPV analysis has shown at current battery prices, a consumer purchasing a PHEV30 or a CV must receive, and value, an additional $5,500 in compensation to choose a PHEV for solely economic benefit. As with current HEVs, there will be first adopters who purchase PHEVs for technological or environmental (*7, 33*) reasons. HEV sales were about 9,300 units in the first year of availability (2000) and grew to more than 250,000 by 2006 (*7, 34*). Still, hybrid sales represented only about 1.5 percent of LDV sales in 2006 (*35*). If large scale PHEV adoption is desired, policymakers can examine and take lessons learned from the policies used to promote traditional hybrids. The work on the effectiveness and influences of tax policy on existing hybrid vehicle sales is still emerging, with the preliminary work finding that gasoline prices as well as government tax incentives are significant predictors of HEV sales (*7, 34, 36*).

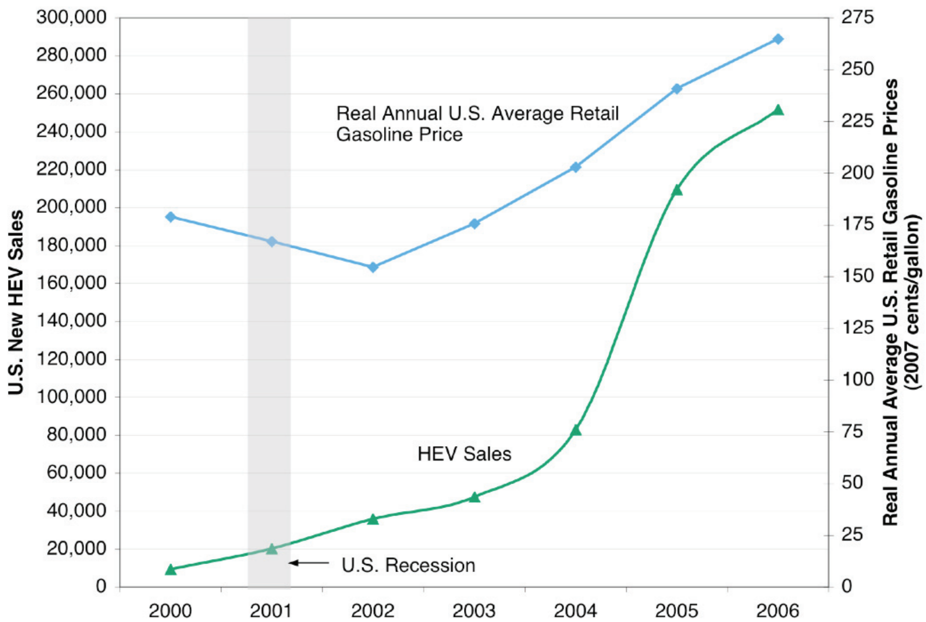

Figure 3.11. US hybrid vehicles sales and real annual average retail gasoline prices, 2000-2006. Constructed with data from (*34, 37*)

From 2000-2006, government incentives were effectively used to promote the adoption of traditional hybrids (*7*). A federal tax deduction for hybrid vehicles of $2,000 was in place beginning in model year 2000. The Energy Policy Act of 2005 converted this $2,000 deduction to a tax credit that varied by vehicle model, beginning in 2006. The relative benefit of a tax deduction depends on the consumer's federal tax bracket, whereas the benefit of tax credit is the same for all taxpayers up to the total tax liability for a consumer (if a consumer owes no taxes, then they cannot claim a HEV tax credit).

Beginning in 2006, the Toyota Prius qualified for a $3,150 federal tax credit before the high sales volume of this model resulted in the expiration of the credit (*7*). Sallee found that consumers (rather than automakers via higher prices) retained a large portion of the credit, largely because Toyota viewed price increases as detrimental to future sales (*36*).

In addition to federal tax incentives, various states offered policy actions including income tax incentives, state vehicle sales tax exemptions, access to High Occupancy Vehicle (HOV) lanes as a single occupant, and parking fee reductions or exemptions. State income tax credits and state sales tax exemptions for HEVs, averaged about $2,000 and $1,040, respectively from 2000-2006 in the thirteen states that offered benefits (*7*). The regression analysis in (*7*) estimated that a sales tax exemption had a much larger effect on HEV adoption than a state income tax credit, even though sales tax exemptions had lower values on average. For a benefit equivalent to 5 percent of the retail price of the vehicle, a sales tax benefit is associated with a 26 percent increase in HEV sales, while an equivalent income tax benefit is only associated with a 7 percent increase in HEV sales (*7*). Access to HOV lanes was only significantly associated with HEV adoption in congested Northern Virginia (*7*), hence HOV access may be important in areas where commuters who travel to work via a congested expressway. Policy options to encourage PHEV adoption could be enacted on multiple levels, as with HEVs, however the data presented in (*7*) shows the choice of state policy can determine the magnitude of the effect.

If policymakers extend the approximately $3,000 tax credit available that was available for a HEV in 2006 to a PHEV, the breakeven cost of gasoline would fall from $7/gallon to $6/gallon, as shown in **Figure 3.12**.

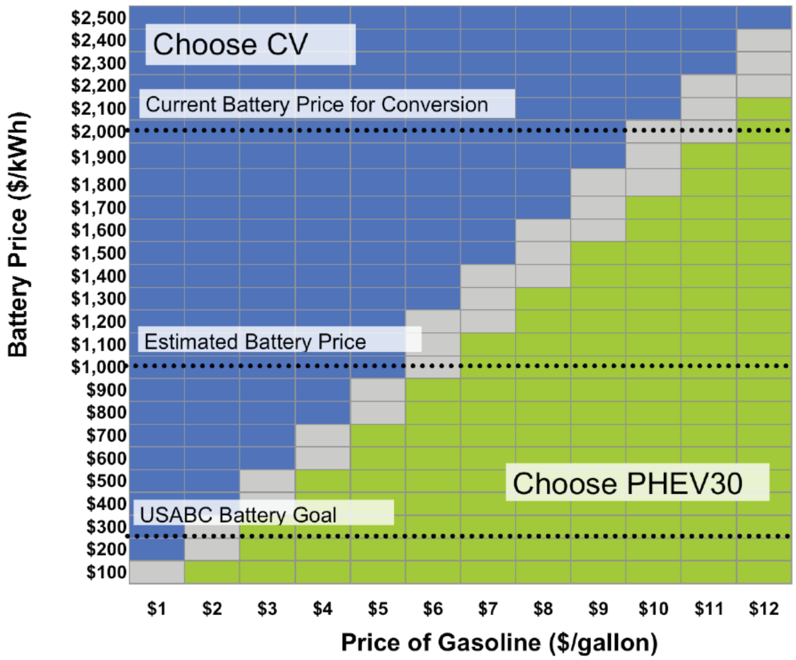

Figure 3.12. Effect of including a $3,000 PHEV tax credit on the decision to purchase a PHEV30 under the best estimate parameters in **Table 3.2**. With the effect of the $3,000 subsidy included, showed as the grayed area, PHEVs would be competitive at about $6/gallon assuming a battery price of $1,000/kWh.

The negative NPVs listed in **Table 3.3** represent the subsidy required to economically justify a PHEV purchase. A $3,000 federal tax credit alone would not fully offset the negative NPV for a PHEV30. Under this level of subsidy, it is likely that PHEV adoption similar to the initial HEV experience and be limited to first adopters unless consumers face fuel prices of $6/gallon or battery prices fall by half. **Figure 3.13** shows that a present value subsidy of approximately $5,500 would be required to make PHEV30s competitive at $4/gallon.

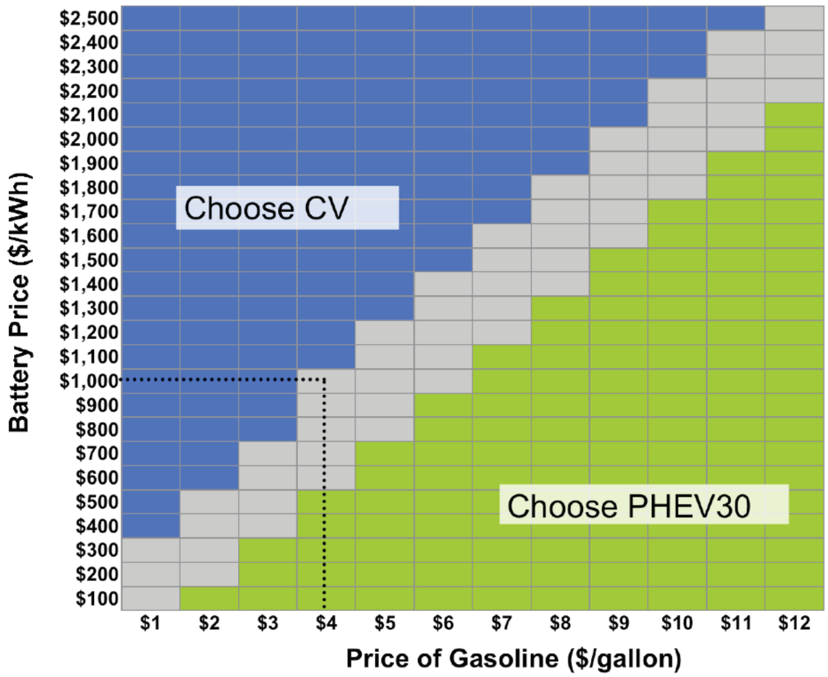

Figure 3.13. Effect of including a $5,500 PHEV tax credit on the decision to purchase a PHEV30 under the best estimate parameters in **Table 3.2**. With the effect of the $5,500 subsidy included, shown as the grayed area, PHEVs would be competitive at about $4/gallon assuming a battery price of $1,000/kWh.

Regardless of the specific policy designs, it is evident from the HEV experience that the level of government incentives available did not encourage widespread HEV adoption, although expensive gasoline (in 2005 and 2006) and additional tax incentives (in 2006) resulted in large increases in HEV sales. In 2002, Lave and MacLean estimated that the fuel savings of a HEV over a CV would be nominally about half of the premium required for an HEV (or about a third of the premium if the fuel savings were discounted at 6 percent over the life of the vehicle (*8*)). A similar situation appears to exist with PHEVs under the assumptions in this analysis.

If widespread adoption of PHEVs is desired, then considerable government support is required up to, and perhaps beyond, the net present value differences between consumer battery investment and estimated lifetime fuel savings. This could be achieved with a bundle of value offered by federal tax incentives or rebates, state tax incentives and sales tax/fee exemptions. Additional revenue through vehicle-to-grid (V2G) payments (*38*) would also reduce the amount of subsidy required, as long as the consumer was not concerned that V2G operations would result in premature battery failure.

We have treated PHEVs and CVs as complete substitute goods in this analysis, in that a consumer would be indifferent in choosing between them but for price. In reality, many consumers may be hesitant to adopt PHEVs until they have proven reliable or unless they are bundled with sufficient warranties or other mechanisms to reduce the investment risk of batteries (e.g. battery leasing). Additionally, if battery prices at scale remain closer to the $2,000/kWh rather than the $1,000 used in this analysis, then considerably higher levels of support will be required, and the economics become more unfavorable. Future work can frame the decision space between supply-push polices (increasing federal battery R&D with a goal of cost reductions) and demand-pull policies (consumer tax credits or rebates).

3.4 Discussion

This work has estimated demand-side PHEV charging infrastructure costs and feasibility, compared economic costs of PHEVs, and provided policy perspectives on potential PHEV adoption efforts. The primary demand-side infrastructure need is access to an electrical outlet where the vehicle is parked overnight. About 94% of US households have access to either a garage, carport, or off-street parking at their residence, although this varies by region and between homeowners and renters (*10*). Home infrastructure upgrades, if required, would vary between about $200 and $1,000 per household and need to be considered in the engineering economic analyses and public policies regarding PHEVs.

Based on PHEV size, the net present value terms to be economically competitive for PHEVs would range between no subsidy (PHEV10), a subsidy of about $5,500 (PHEV30) and a subsidy of about $13,000 (PHEV50). The results are highly sensitive to the battery cost, the price of gasoline, and the battery size.

No subsidy is required to create a positive NPV for a PHEV10 because the small battery results in low additional capital costs and efficiency (both in electric and gasoline modes) provides considerable fuel savings over a conventional vehicle (as does a HEV). However, as discussed, a PHEV10 might not satisfy oil displacement goals or environmental goals desired with PHEVs, and the trend toward more efficient ICEs and HEVs may achieve similar results to the PHEV10 and at lower cost. **Table 3.4** shows the CO_2 abatement and oil displacement costs of various PHEVs. It appears that the supply curves for both GHG and oil displacement become steep quickly as PHEV battery capacity (and hence premium) are increased. This analysis only includes private costs to the user, and future work can include net social costs. These could include climate change, air pollution, health effects, government expenditures and additional social costs of transportation (see, for example (*39-42*)) and fossil fuel combustion (*19, 43, 44*).

Table 3.4. GHG abatement and barrels of oil displacement costs for various PHEVs compared to a CV that gets 30 mpg. GHG and oil displacement costs are estimated by individually dividing the net present value premium that a consumer would have to pay for the various PHEVs (see **Table 3.3**) by the tonnes of GHG or barrels of oil respectively over a 12 year life. GHG from electricity is estimated using the life cycle US average (0.67 kg/kWh) and gasoline GHG (11.34 kg/gal) includes both combustion and upstream fuel cycles (*11, 20, 21*). GHG values in the table are shown in tonnes.

	PHEV10	**PHEV30**	**PHEV50**
Annual CO_2-eq from Electricity	0.7	1.6	1.9
Annual CO_2-eq from Fuel	2.3	1.2	0.8
Total Annual CO_2-eq	3.0	2.8	2.7
Total Annual CO_2-eq Savings	1.6	1.8	1.8
Total Lifetime CO_2-eq Savings	19.0	21.2	22.0
GHG Abatement Cost ($/tonne)	**-$47**	**$258**	**$588**
Total Gasoline Savings (gallons)	2,378	3,524	3,916
Total Barrels of Oil Savings (at 19.6 gallons gasoline produced/bbl)	121	180	200
Oil Displacement Cost/barrel	**-$7**	**$30**	**$65**

However, PHEVs represent a technological pathway to reduced oil dependence and lower GHG emissions in the transportation sector, while utilizing existing infrastructure systems. Policymakers seeking to maximize PHEV subsidy effectiveness can base subsidies on the installed battery capacity, with an optimum range between a PHEV10 and a PHEV30.

Government policies to support PHEVs should aim to provide a bundle of value to PHEV consumers to compensate for the technology risk and premium, if widespread adoption is desired. Consumers respond more positively to immediate savings such as rebates or sales tax exemptions, rather than income tax credits received after filing taxes, even if the income tax credits are more generous than the sales tax exemptions (*7*). This suggests that consumers place a higher discount rate on hybrid vehicle incentives, and that effective PHEV subsidy policies should seek to provide immediate benefits via sales tax exemptions, registration exemptions, and potentially rebates to maximize the effectiveness of the subsidy per dollar of government tax expense or expenditure. Additional mechanisms, such as free public charging/parking, HOV lane access, V2G, vouchers for home electrical upgrades or for a portion of home electricity usage could provide alternatives or additions to federal and state tax incentives.

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Chapter 4: Electric power infrastructure capital investment and climate policy decision making under uncertainty

4.1 Introduction

Increasing concerns regarding high oil prices, oil dependency, and climate change have resulted in policymakers and the automobile industry evaluating alternative strategies for passenger transportation. Plug-in hybrid electric vehicle (PHEV) technology offers a possible approach to reducing life cycle GHG emissions and dependency on oil as a transportation fuel via the use of large rechargeable storage batteries that enable electricity from the grid to provide a portion of the propulsion requirements of a passenger vehicle (*1-3*). Since approximately 60% of United States (US) passenger vehicle miles are traveled by vehicles driving less than 30 miles per day (*4*), PHEVs may be able to displace a large portion of gasoline consumption with electricity. While the US transportation sector is overwhelmingly powered by petroleum, oil-fired power plants only provide about 3% of US electricity. The balance of the 2004 electricity mix predominately includes coal (51%), nuclear (20%) natural gas (18%), hydroelectric (7%), and renewables (1%) (*5*).

Major automakers plan to introduce plug-in hybrid electric vehicles (PHEVs) in the coming years, but automotive fleet cycles and turnover are on much shorter timescales than electricity capital investment and turnover. Because the life cycle GHG emissions reductions from PHEVs compared to traditional hybrids (HEVs) and conventional vehicles (CVs) depend on the types of power plants used to charge the battery (*3*), the electricity sector is critically coupled to the transportation sector if large life cycle GHG reductions are desired with PHEVs.

Several works examine direct (*1, 6, 7*) and life-cycle GHG emissions (*3*) of PHEVs and conclude that charging with low-carbon electricity greatly increases the GHG emissions reductions achievable with PHEVs. In order to minimize needs for new generation, avoid increased load during peak periods, and take advantage of overnight spare capacity, PHEV charging should be intelligently scheduled during off-peak times (*6, 8*). The GHG emissions from PHEVs will depend on what types of power plants are available and dispatched to serve the additional overnight load represented by PHEVs. In restructured electricity areas, power plants are dispatched in merit-order based on their marginal cost. In the short run, additional overnight demand from PHEVs will be largely met by lower cost baseload power plants. Without appropriate polices, this demand will largely be met by conventional coal power in many regions, which would reduce the GHG emission benefits from PHEVs. In the long-run, greenhouse gas mitigation policy in the electricity sector can encourage introduction of additional low-carbon generation to serve potential overnight PHEV demand.

This chapter will answer three questions: 1) What are potential levels of PHEV adoption in the US? 2) What are the electricity requirements and charging profiles of various levels of adoption? 3) How much low-carbon generation is potentially needed to serve various levels of PHEV adoption from 2010-2030? This research takes an approach to inform the set of decisions that bound a future desired outcome – large GHG emissions reductions from plug-in hybrid vehicles.

4.2 Method

4.2.1 Growth of Light Duty Vehicle Sales

The cumulative effect of PHEVs on GHG emissions and power demand will be influenced by the rate of consumer adoption and infiltration into the vehicle fleet. The composition of the US light duty vehicle (LDV) fleet is shaped by the mix of new vehicles entering the fleet and older vehicles that are retired. Considerable uncertainty is involved in forecasting the characteristics of the vehicle fleet. For example, largely unforeseen new consumer preferences in the 1990s resulted in large growth in the sales of light trucks (SUVs). Light trucks comprised about 33% of LDV sales in 1990 and grew to nearly 55% in 2005 (*9*) . Higher gasoline prices appeared to have abruptly reversed this trend, with light truck sales for the first five months of 2008 down nearly 16% compared to the same period in 2007 while passenger car sales remained largely unchanged (*10*). While uncertain preferences determine the types of vehicles purchased in any given period, overall market conditions determine the number of vehicles purchased. **Figure 4.1** depicts considerable observed variability in individual year new vehicle sales and growth of the LDV fleet, which appear to be correlated to changing economic conditions.

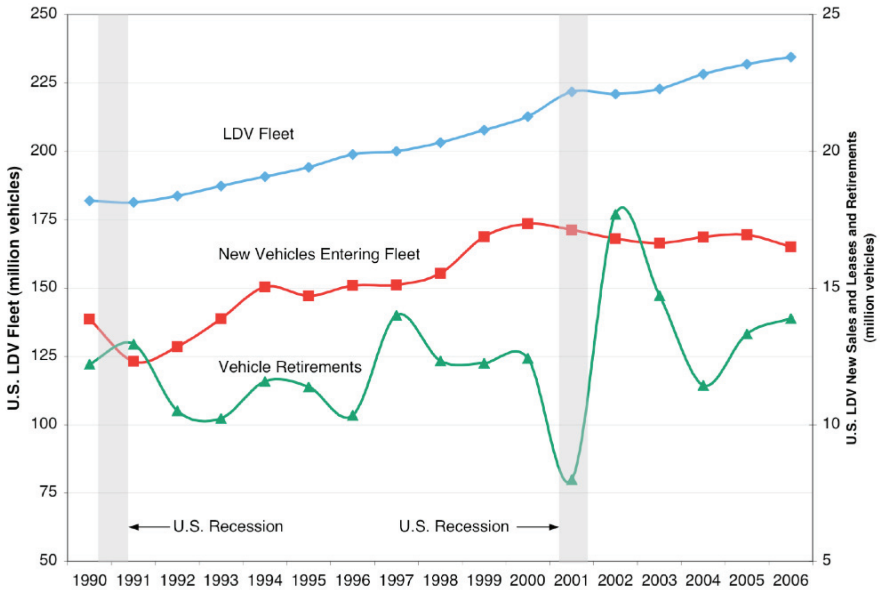

Figure 4.1. Annual US light duty vehicle fleet size, sales and leases, and retirements. Constructed using data from (*11*) and (*12*)

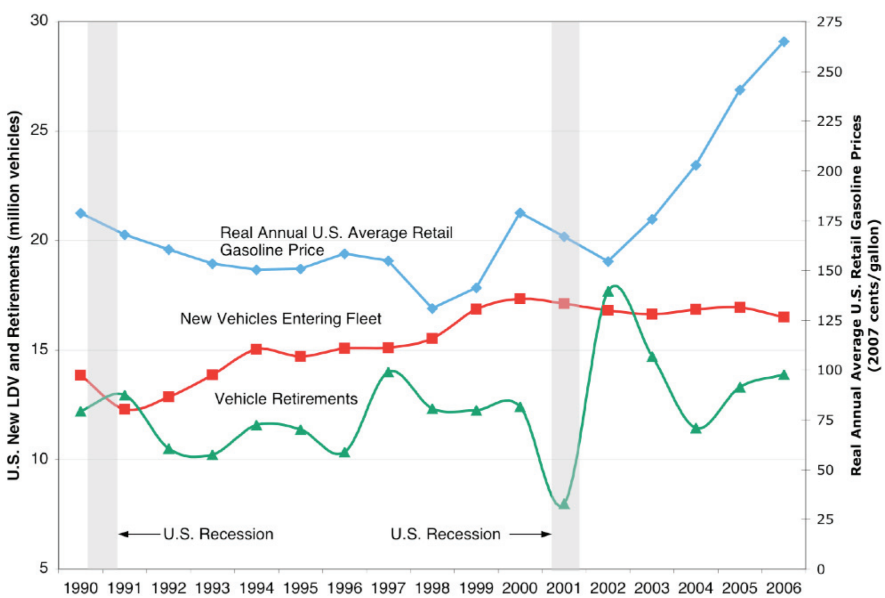

Figure 4.2. US LDV entering the vehicle fleet and retirements, and real annual average US retail gasoline prices. Constructed using data from (*11, 13*).

To forecast the future of LDV fleet, researchers typically extrapolate from existing trends (*14*), construct multi-variable models (*15*), define dynamic fleet functions and scenarios (*16*), or a combination of methods. This work conducts a bounding analysis to estimate the growth of the LDV fleet, which is used as an input parameter to PHEV adoption cycles. The observed annual average growth rate for the LDV fleet from 1990-2007 was 1.4% and annual rates varied between -0.35% and 4.3% (*11*). The survival rate (or the reciprocal of the retirement rate) of vehicles by vintage year is an essential piece for modeling the total number of LDV vehicles in use. The last data for survival rate are from model year 1990, which did not include any hybrid vehicles and is not representative of the current cumulative fleet mix. In addition to issues of data quality with existing survival rates, survival rates may be considerably different for PHEVs than for traditional vehicles. Because electricity demand from PHEVs is a function of PHEVs sold and in operation, and because of the discussed uncertainty in LDV size, this analysis will parameterize PHEV new sales and adoption.

Building on the method presented by (*16*), vehicle sales grow by an annual growth rate g such that the total number of new vehicles entering the fleet at time t is M_t and estimated by:

$$M_t = M_{t-1}\left[1+g\right]$$

An upper bound, lower bound, and best approximation on growth of new LDV sales and leases is used. As an upper bound, this paper uses a 2% average annual growth rate in the LDV sales and leases, as in (*16*). The average annual growth rate of new LDV sales and leases from 1990-2007 was 1.4%, and is used as a best approximation of growth of new LDV sales and leases. As discussed in (*15*), long-term growth in vehicle sales may not remain on the past trajectory, as US vehicles in operation exceed the number of licensed drivers. Sustained high gasoline prices may also lead to lower growth in LDV sales. The lower bound value of long-term LDV new sales and leases in this study tracks the projected growth in US population. US Census population estimates project a growth rate of 0.9% through 2015 that slows to 0.7% by 2050 (*17*), and an annual average growth rate of 0.78%.

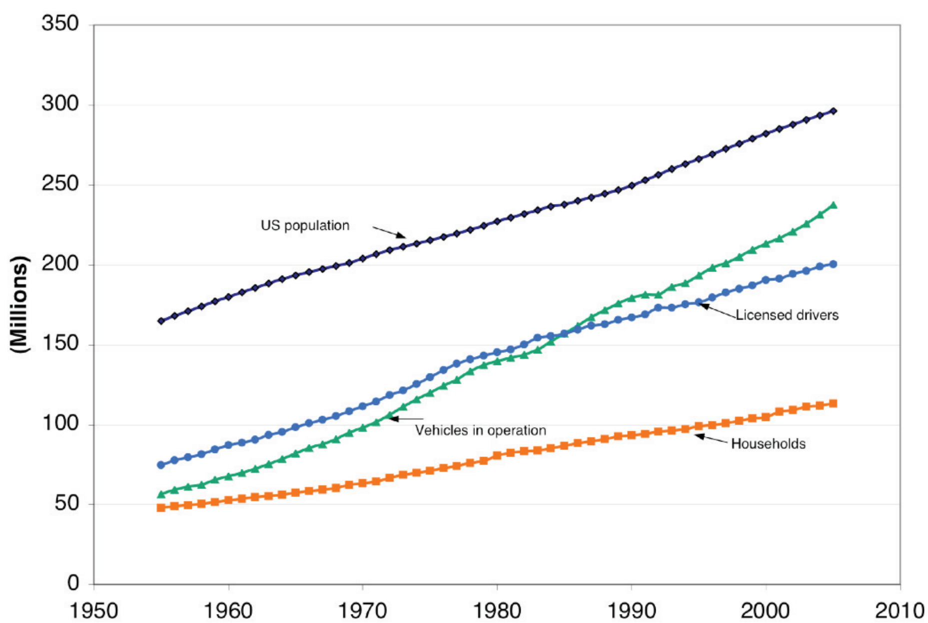

Figure 4.3. US population, vehicles in operation, licensed drivers, and households. Constructed using data from (*9*)

4.2.2 Plug-in hybrid adoption scenarios

Diffusion of new technologies generally follows a logistic or S-curve pattern (*18*), where diffusion is slow during a period of early adoption, then rapid as the technology gains acceptance, then slows again as market penetration approaches saturation. Diffusion rates of PHEVs will depend on the economic characteristics of PHEVs compared to competing technologies, and the existence and magnitude of distorting policies. Geroski (*18*) examines the two leading models used to generate S-curve diffusion functions- epidemic and probit, as well as two variants of epidemic modeling, legitimation and competition, and information cascades (*19*). While there exists a vast literature on the modeling of the diffusion of innovations (for example, see (*19-25*)), this work focuses on the parametric impacts of varying levels of diffusion rather than modeling the diffusion network itself. Hence, a standard logistic epidemic model of diffusion (*21*) is used and market saturation parameters are applied parametrically to various penetration scenarios, as in (*26*).

Logistic growth of the penetration percentage of new PHEV sales, P_t, is represented by:

$$P_t = \frac{1}{1 + e^{-(\alpha + \beta \cdot \Delta t)}}$$

Where α positions the curve depending on initial penetration levels, and β represents the rate of growth, as in (*21, 26*). New PHEV sales in year t, given by N_t, are modeled as a product of the P_t and the total number of LDV sales, M_t over the various scenarios.

In a 2007 PHEV study, EPRI (*1*) examined the effects of high PHEV penetration levels on air quality. That study assumed that PHEV new sales would represent 50 percent of all new LDV sales in 2030. This paper uses the EPRI 2030 value to represent the high value of saturation penetration levels of logistic diffusion, and assumes a baseline value of 30% of new sales in 2030. The low penetration scenario is modeled as exponential growth achieving 10% market share in 2030, representing slow PHEV adoption. Assumed initial PHEV penetration levels are listed in **Table 4.1**. J.D. Power and Associates estimates that General Motors may sell 300,000 Chevy Volt PHEVs by 2014 (*27*). Other likely manufacturer sales would increase this figure, which bound the baseline and high assumptions. Since it is likely that up to 58,333 PHEVs will be sold in California by 2014 due to the state Zero Emissions Vehicle Ruling (*28*), all of the scenarios approximately allow at least this level of penetration.

Table 4.1. 2010 and 2030 PHEV penetration as a percentage of new LDV sales

	Low PHEV Penetration	Baseline PHEV Penetration	High PHEV Penetration
% of 2010 New Market Share	0.1%	0.5%	1.0%
% of 2030 New Market Share	10%	30%	50%

Together, the three PHEV penetration rates and the three LDV new sales growth rates described above map the space of potential PHEVs considered in this study, shown in **Figure 4.4**.

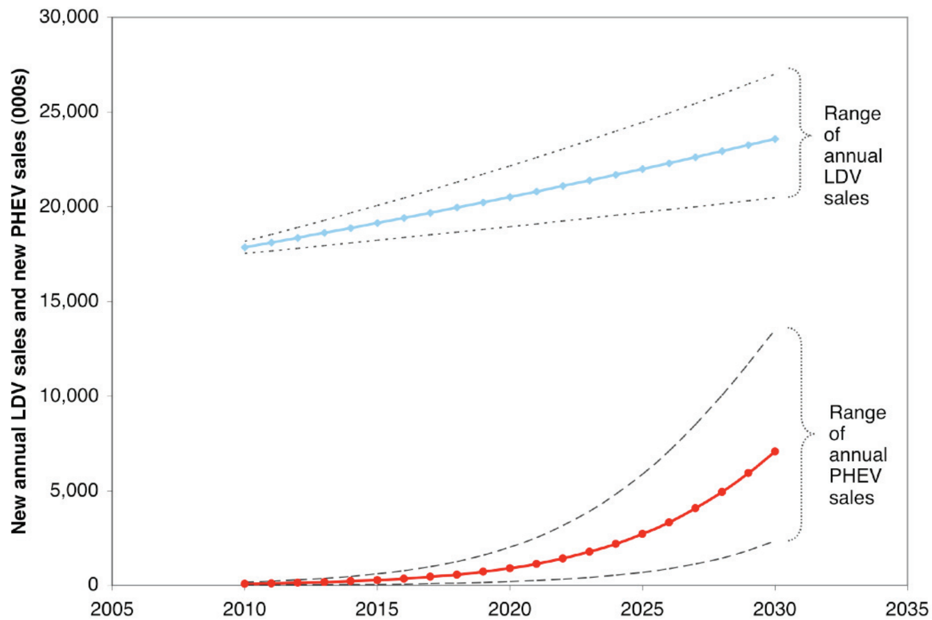

Figure 4.4. Range of potential annual LDV and PHEV sales considered.

While annual PHEV sales projections are important to subsidy policy and manufacturing planning, the cumulative number of PHEVs on the road will determine potential demand for electricity (and associated infrastructure). As discussed, uncertainty exists in the retirement rate of vehicles, and median age of on-road vehicles is increasing (*9*). Via informal discussions with major battery manufacturers, the goal is to offer a PHEV battery with a warranty of at least 10 years. We assume that PHEVs will be in operation as a PHEV for an average of 12 years. After the PHEV battery has lost considerable storage capacity, the vehicle may be operated further as a limited PHEV or solely a HEV. While some PHEVs may be on the road for longer than 12 years, by selecting a 12-year life for a PHEV we also implicitly address the fact that vehicle miles traveled typically decline as vehicle age increases (*9*). The baseline forecast for PHEVs on the road in US are about 1 million in 2015, about 4 million in 2020, and about 37 million in 2030, as shown in **Figure 4.5** and **Table 4.2**.

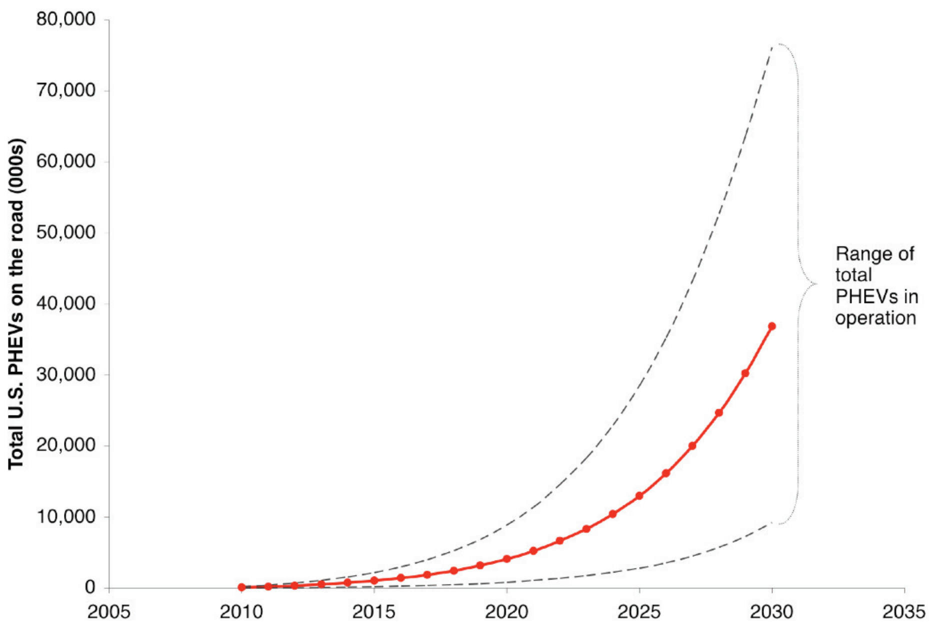

Figure 4.5. Range of potential PHEVs on the road

Table 4.2. Range of plug-in hybrid vehicles in-use in the United States under various PHEV adoption and LDV sales growth scenarios. PHEVs assumed to have 12-year operating life as a PHEV. Numbers rounded to appropriate significant figures.

Year	Low PHEV adoption	Baseline PHEV adoption	High PHEV adoption
2010	18,000	90,000	180,000
2015	200,000	1,040,000	2,200,000
2020	830,000	4,080,000	8,900,000
2025	2,800,000	13,000,000	28,500,000
2030	9,200,000	36,900,000	76,100,000

4.2.3 PHEV charging profiles

Since off-peak overnight PHEV charging provides the greatest flexibility for utilizing existing capacity (*6, 8*), we examine demand from PHEVs charged with standard household electrical infrastructure. Charging demand will depend on which type of outlet is used, as listed in **Table 4.3**. High power three-phase charging in commercial areas is not evaluated in this study, as most manufacturers are initially targeting standard home outlet charging.

Table 4.3. Power demand depending on characteristics of standard home outlets for PHEV charging. Adapted from (*29, 30*), using an 88% charger and battery efficiency (*1*) and 91% electrical transmission and distribution efficiency (*31*).

Voltage (AC)	Current (Amps)	Power delivered to the battery (kW)	Power demand at wall outlet (kW)	Power demand at power plant (kW)
120	15	1.2	1.4	1.5
120	20	1.8	2	2.2
240	30	5.3	6	6.6

As in (*3*), we assume PHEVs will be powered by electricity until the battery reaches an 80% depth of discharge (DOD), at which point the PHEV will operate as a HEV. Using a PHEV efficiency of 3.15 mi/kWh (0.318 kWh/mi) (*1*), the battery is sized by determining the desired range and accounting for the unused 20 percent charge necessary to conserve battery life and facilitate HEV operation. For example, a PHEV20 with 20 miles of electric range would need 20*0.318= 6.4 kWh to travel on electricity for 20 miles. The battery would have to be sized for so that travel energy is 80% of battery capacity, so the total battery capacity for a PHEV20 under these assumptions is 8 kWh. **Table 4.4** lists the battery size requirements for different desired electric ranges. Although larger trucks and SUVs would have lower PHEV efficiencies and heavier batteries, we assume an average efficiency of 3.15 mi/kWh will be required for the potential PHEV fleet.

Table 4.4. Battery sizes to travel a specified electric range with a battery DOD of 80%.

	PHEV10	PHEV20	PHEV30	PHEV40	PHEV50
Electric range (mi)	10	20	30	40	50
Energy required from battery for travel (kWh)	3.2	6.4	9.5	12.7	15.9
Total battery capacity (kWh)	4	8	11.9	15.9	19.9

The total power demand from a potential PHEV fleet will be the demand required to recharge the battery after a day's driving. We assume as a bounding condition that PHEVs will be in use every day and deplete their full electric charge. Given the power demand requirements in **Table 4.3** and the energy required for travel in **Table 4.4**, an estimation of hourly load at the power plant is presented in **Figure 4.6.**

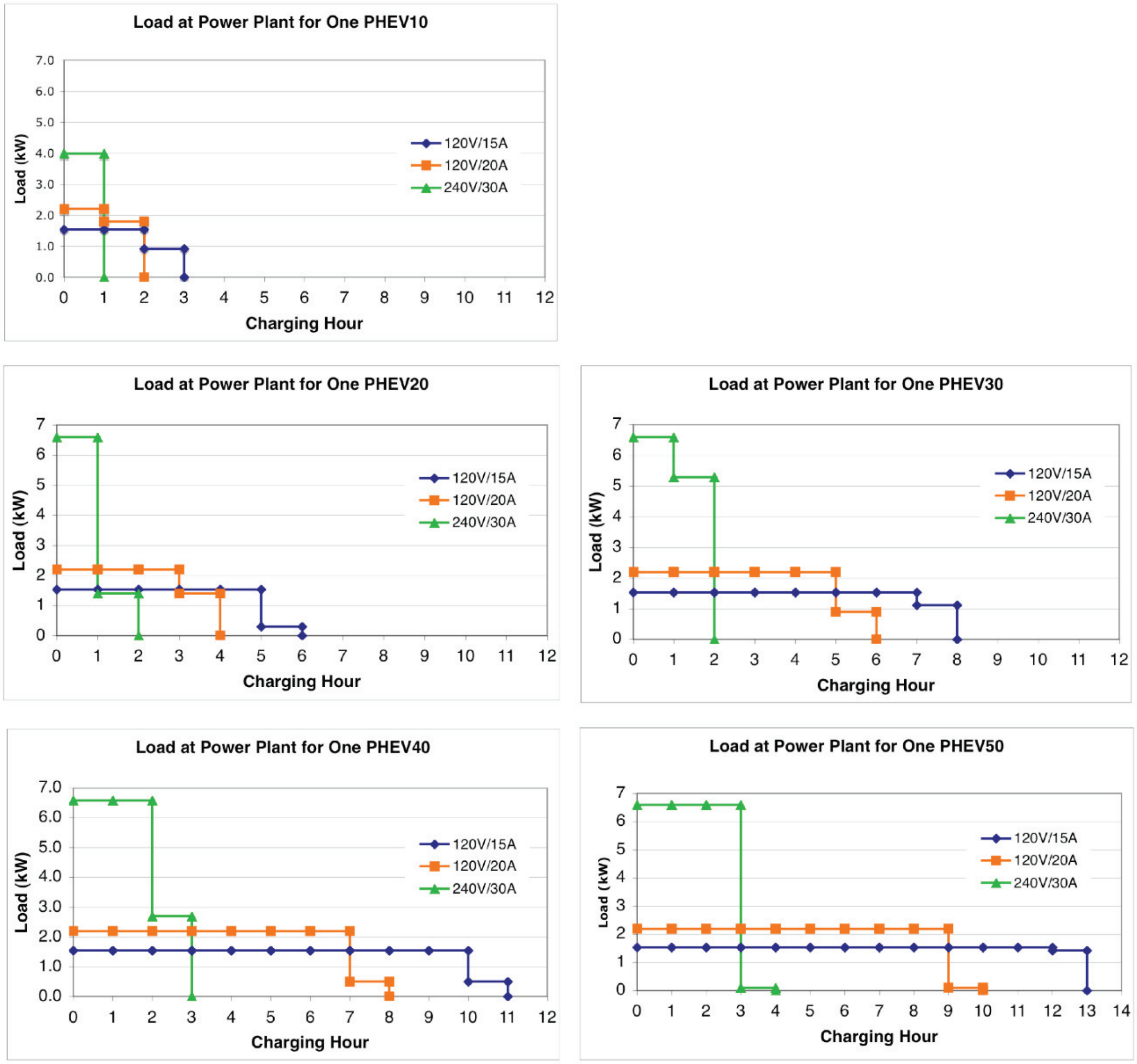

Figure 4.6. Estimation of hourly charging load at the power plant for a range of PHEV battery sizes and household charging infrastructure. If additional power for battery conditioning is required after charging is complete, charging load profiles would be slightly extended.

4.2.4 Electricity load profiles

We use two distinct electricity independent system operators (ISOs) or regional transmission organizations (RTOs) as case studies, the Electric Reliability Council of Texas (ERCOT), and the Midwest ISO (MISO). ERCOT serves about 85 percent of the load in Texas, with about 20 million customers (*32*). Natural gas generation is more prevalent in ERCOT than the US average, representing more than 46 % of MWhs generated. ERCOT also has substantial wind resources and had approximately 2,370 MW of installed wind power in 2006, which accounted for 2% of generation in 2006. Wind power in ERCOT grew to more than 4,800 MW in 2007 (*32*). MISO serves fifteen states in the upper Midwest, with a capacity of about 156,000 MW. MISO has a majority of coal-fired generation, with coal plants representing about 52 percent of capacity (*33*).

Electricity demand generally peaks during the day and troughs during the night, and is typically highest in the summer and lowest in the spring. As discussed in (*6, 8*), the additional potential load from millions of PHEVs will be manageable by the existing grid if off-peak charging is employed. The rate of charging, determined by the household or commercial infrastructure used as discussed above, is also a factor influencing the effects of PHEVs on electricity infrastructure and emissions. If PHEV batteries accommodate higher power 240V/30A charging, consumers may choose to install this type of infrastructure to gain the benefits of faster charging times. While the total load to the power plant will be the same between a 240V and 120V connection, 240V charging delivers a higher amount of energy over a shorter time period. Hence, 240V charging has the potential to measurably increase demand and affect capacity if charging occurs during the peak. **Figure 4.7** and **Figure 4.8** show the additional load of one million PHEV30s to the summer loads of ERCOT and MISO charging on either 240V or 120V and beginning charging at either 6:00 PM (representing charging during peak periods) or 12:00AM (representing charging during off-peak). Electricity demands on a Tuesday in August and April of 2006, representing typical weekday demand conditions, are shown in the plots below.

240V infrastructure, while providing faster charging for the consumer, has the ability to raise power demand considerably, as shown in the figures below. If one million PHEVs were charging in ERCOT and MISO at 6:00PM using 240V infrastructure, this would raise total load by about 7% in MISO and 10-14% in ERCOT. This would increase peak loads and could strain resources and/or transmission and distribution systems. Prudent planning and intelligent charging could minimize these effects.

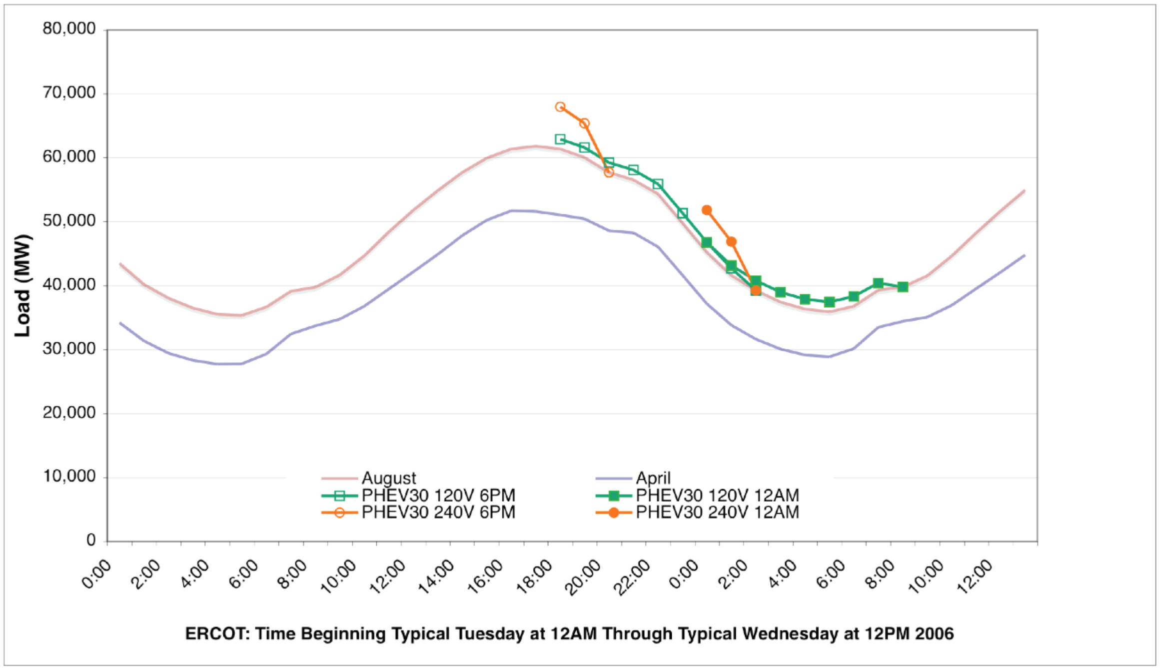

Figure 4.7. Hourly load profile of electricity demand in ERCOT in April and August of 2006. Typical load beginning Tuesday at 12:00am depicted. The load at the power plant of one million PHEV30s depicted as additional load during the summer.

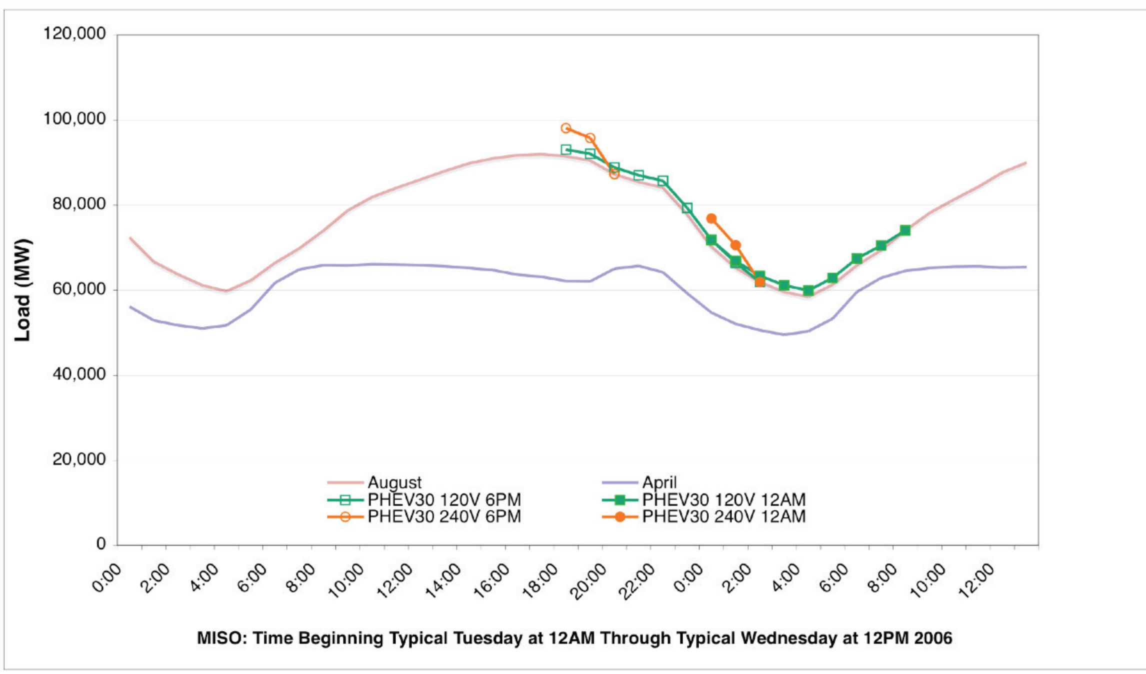

Figure 4.8. Hourly load profile of electricity demand in MISO in April and August of 2006. Typical load beginning Tuesday at 12:00am depicted. The load at the power plant of one million PHEV30s depicted as additional load during the summer.

4.2.5 Marginal Power Plants Serving PHEVs

PHEVs on average, begin to have lower life cycle GHG emissions than traditional hybrids when the electricity used for charging has life cycle GHG emissions less than about 650-750 g/kWh (*3*). **Table 4.5** depicts typical life cycle GHG emission values for various electricity fuels, and shows that with the exception of coal and oil-fired generation, electricity can have a GHG profile below the 650-750 g/kWh range, assuming plants are running close to design efficiencies.

Table 4.5. Estimates of direct and upstream GHG emissions of various electricity fuels and sources. CCS = Carbon capture and storage; PV = photovoltaic (direct conversion of sunlight to electricity). Coal and natural gas carbon content from EPA (*34*); Efficiency of fossil fuel generation and CCS emissions from IECM (*35*); Upstream emissions from coal and natural gas from Jaramillo et al. (*36*); Nuclear, hydro, wind, and PV from Weisser (*37*).

Fuel (source)	**Direct (g CO_2 / kWh)**	**Upstream (g CO_2-eq / kWh)**	**Total life cycle emissions (g CO_2-eq / kWh)**
Coal	800	50	850
Coal w/ CCS	100	50	150
Natural gas combined cycle	400	75	475
Nuclear	0	10	10
Hydro	0	8	8
Wind	0	15	15
Oil/Diesel	700	200	900
PV	0	60	60

Given that large GHG reductions in the transportation sector are possible with PHEVs charged on low-carbon electricity, we investigate marginally charging fuel in ERCOT and MISO under grid conditions that are similar to 2006. **Figure 4.9** and **Figure 4.10** show the merit order dispatch of different power plants for a typical Tuesday in August in 2006 for ERCOT and MISO (*38, 39*). As electricity demand increases, additional plants are dispatched to serve the load, generally from lowest cost to highest. Fuel cost is an input to an economic dispatch, in that plants that have lower fuel costs (e.g. coal vs. natural gas) and/or use less fuel per kWh (e.g. efficient coal plant vs. a less efficient coal plant) can charge a lower price to recover costs. The plants that use more fuel to produce a kWh (higher heat rate plants), will generally have higher emissions than plants with lower heat rates using the same fuel.

Typical existing power demand for 6:00PM and 12:00AM are shown in the plots below, and all generators up to that level of load have been dispatched. Marginal power demand from one million PHEV30s is represented by the additional demand beyond existing load levels. As discussed above, 120V outlets will require less instantaneous power demand and require a longer charging duration, while 240V outlets will require more instantaneous power demand and provide shorter charging durations.

The dispatch plots below show that under conditions similar to those in 2006, PHEVs charging in ERCOT in both the off-peak and peak times will charge with natural gas. However, charging during the peak period will likely results in higher emissions as less efficient single-cycle natural gas plants are prevalent during peak charging, compared to combined-cycle natural gas plants available during off-peak periods. In MISO, the marginal off-peak load would likely be served by coal, while peak-load would be served by natural gas and fuel oil.

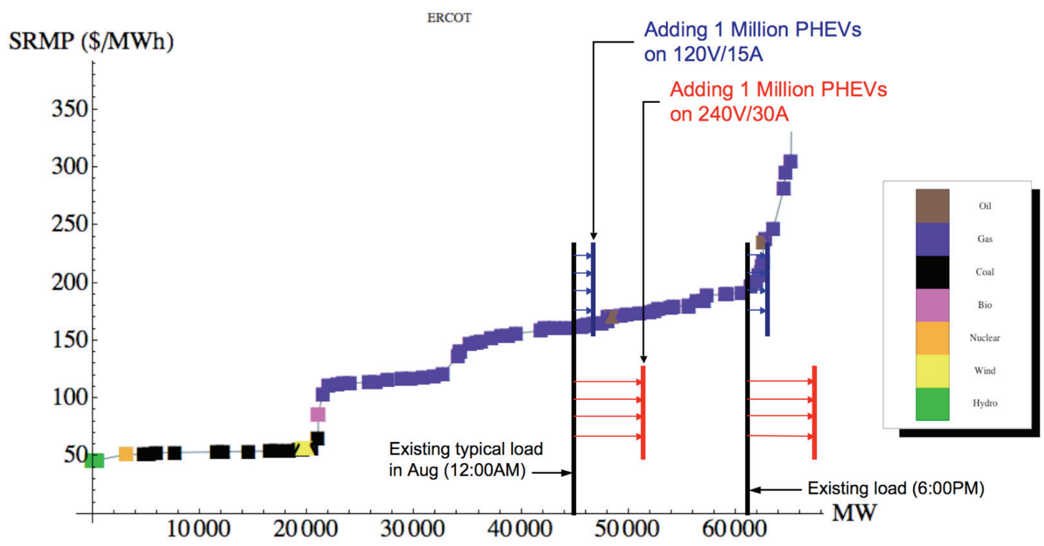

Figure 4.9. Short run marginal price curve (SRMP) for generation assets in ERCOT for a typical August Tuesday in 2006 using an economic dispatch model. The shift in additional load from one million PHEV30s charging with 120V (shown in blue) or 240V (shown in red) outlets beginning at 6:00PM or 12:00AM. SRMP curve from (*38, 39*).

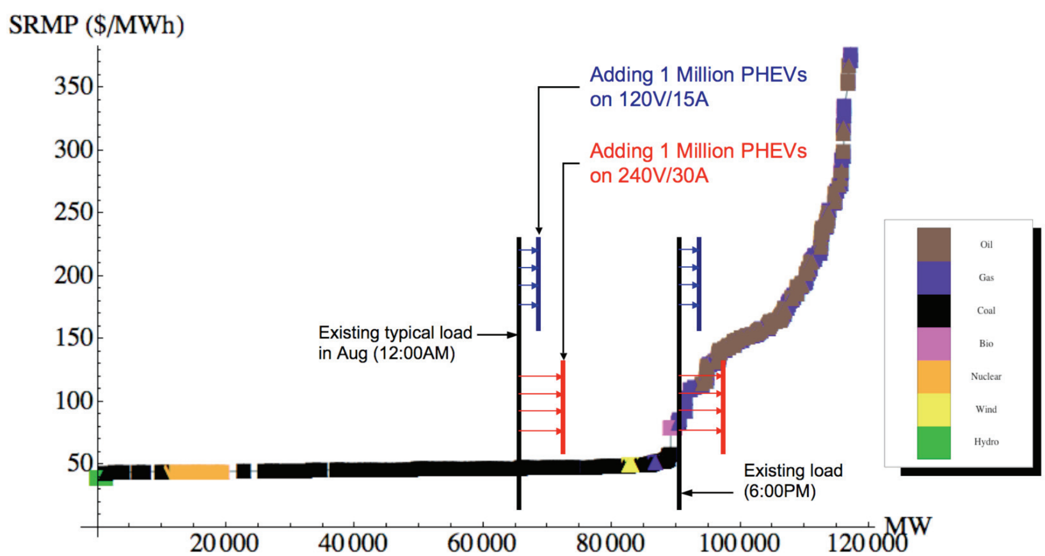

Figure 4.10. Short run marginal price curve (SRMP) for generation assets in MISO for a typical August Tuesday in 2006 using an economic dispatch model. The shift in additional load from one million PHEV30s charging with 120V (shown in blue) or 240V (shown in red) outlets beginning at 6:00PM or 12:00AM. SRMP curve from (*38, 39*).

Peak charging in MISO, while undesirable from a grid and electricity cost perspective, would likely have lower GHGs charging on gas than charging on coal during the off-peak period. Conversely, off-peak charging in ERCOT would likely have lower GHGs than peak charging because higher efficiency natural gas plants would be utilized. The challenge for achieving and verifying large GHG reductions with PHEVs is that the marginal fuel used to charge the battery will vary by ISO, season, and time of day (*3*). Adding a $50/tonne price on CO_2 will likely not rearrange the dispatch order so that natural gas is dispatched before coal in the short run, because the differences in embodied CO_2 in the fuel generally are not large enough to make natural gas generation cheaper per unit of power produced (*38, 39*). A CO_2 price will however, reduce existing power demand (*39*), and provides a signal for low-carbon generation construction (*40, 41*).

While the power plant dispatch plots provide a snapshot of conditions in 2006, we can derive larger policy implications of off-peak PHEV charging by estimating the shift in demand from various PHEV loads. If the electricity system in 2030 is similar in composition to that in 2006, we could expect similar results. The magnitude and extent of capital turnover and decarbonization in the electricity system between 2006 and 2030 depends on policy. Low-carbon transportation via PHEVs is coupled to the existence of low-carbon electricity, and we explore how much additional low-carbon supply may be required to offset PHEV charging in the next section.

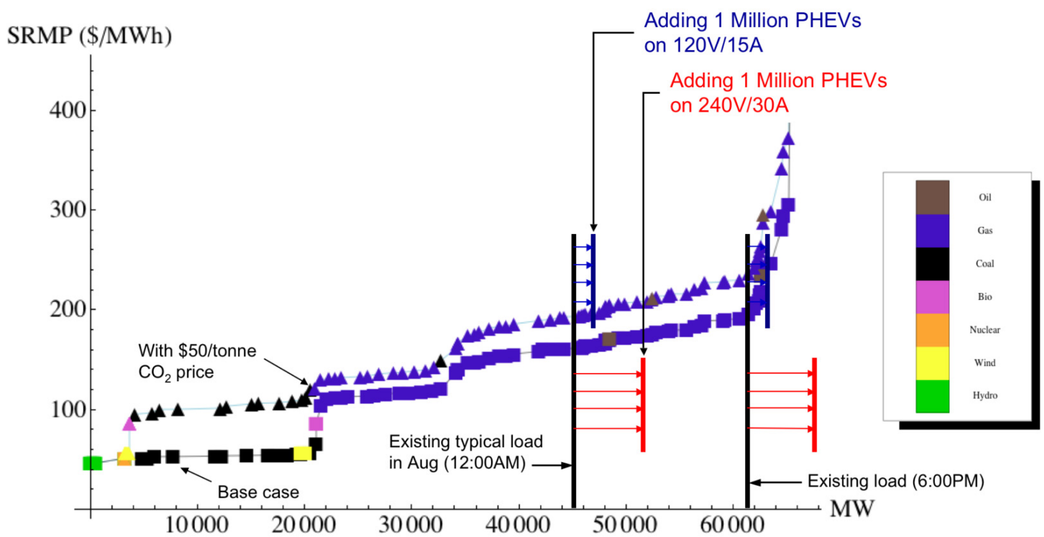

Figure 4.11. Short run marginal price curve (SRMP) for generation assets in ERCOT for a typical August Tuesday in 2006 using an economic dispatch model, shown with and without a $50/tonne CO_2 price. The shift in additional load from one million PHEV30s charging with 120V (shown in blue) or 240V (shown in red) outlets beginning at 6:00PM or 12:00AM. SRMP curve from (*38, 39*).

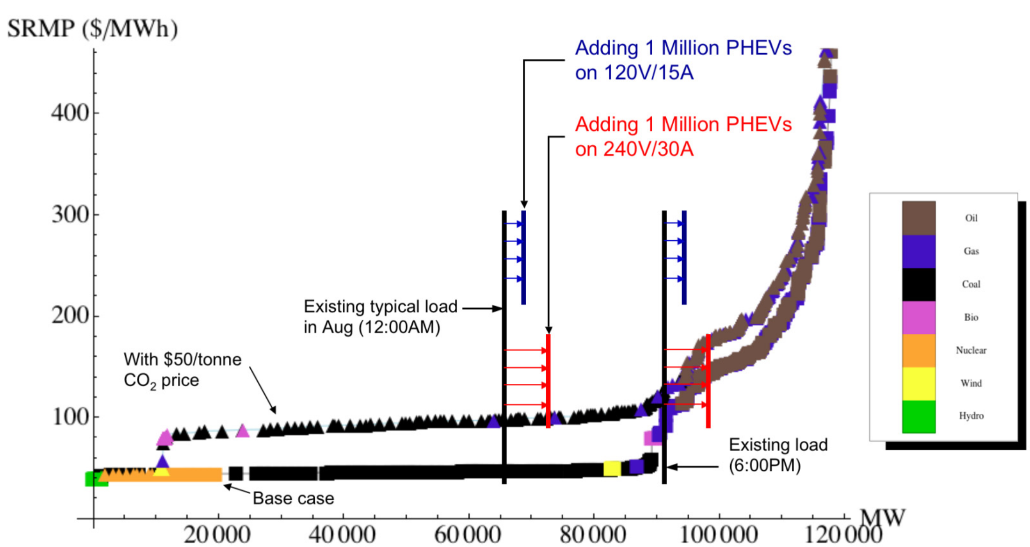

Figure 4.12. Short run marginal price curve (SRMP) for generation assets in MISO for a typical August Tuesday in 2006 using an economic dispatch model, shown with and without a $50/tonne CO_2 price. The shift in additional load from one million PHEV30s charging with 120V (shown in blue) or 240V (shown in red) outlets beginning at 6:00PM or 12:00AM. SRMP curve from (*38, 39*).

4.2.6 Potential Low-Carbon Supply

As discussed, increased power demand from shifting a portion of passenger transportation to the electric power sector would be met by existing marginal generation assets, which may or may not have desirable CO_2 profiles. With an advanced grid and charger intelligence, chargers could encourage matching PHEV demand with low-carbon electricity through prices or credits (*3*), provided adequate supply was available. Alternatively, PHEV demand could be met by adding proportional new low-carbon supply for aggregate new PHEV power demand.

Using the logistic adoption model and charging profile described above for a PHEV30 (11.9 kWh total battery capacity), parametric estimates of annual power demand for PHEV adoption are presented in **Figure 4.13**.

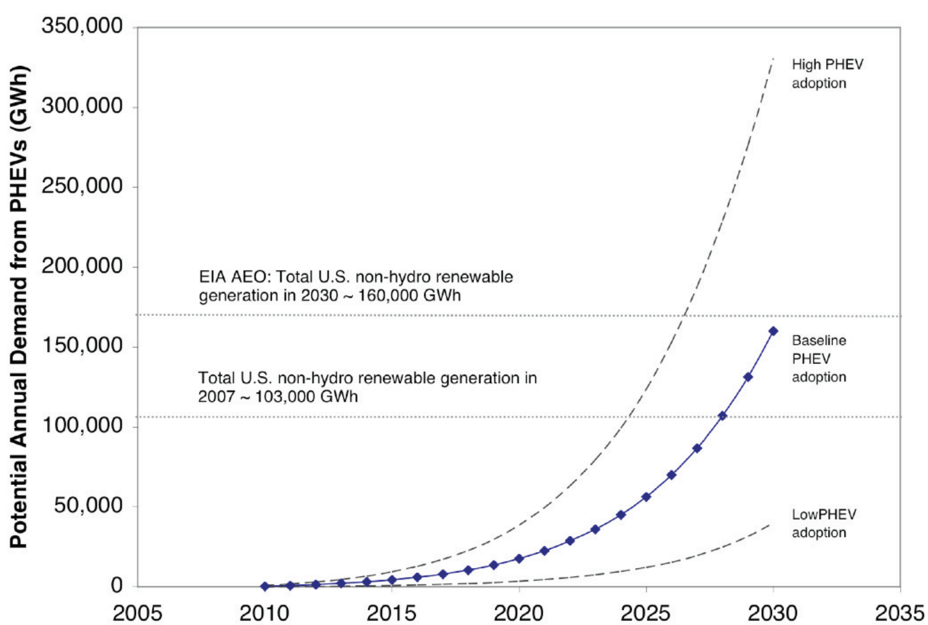

Figure 4.13. Potential annual power demand from PHEV adoption

Total US electricity generation was 4,160,000 GWh in 2007 (*42*), and under the assumptions in this paper PHEV adoption would represent a small portion of overall demand. However, total non-hydro renewable generation was about 103,000 GWh in 2007, so planning for additional renewable capacity to serve PHEV demand is necessary.

Renewable Portfolio Standards (RPSs), generally requiring that a percentage of annual electricity supplies is supplied by renewables, are in place in twenty-five states and the District of Columbia in 2007 (see **Figure 4.14**). Wiser and Barbose estimate that nearly all (93%) of new non-hydro renewable capacity installed in states with an RPS from 1998-2007 has been wind power (*43*). The authors go on to estimate that 61 GW of additional renewable capacity will be required by 2025 if states fully comply with RPS obligations.

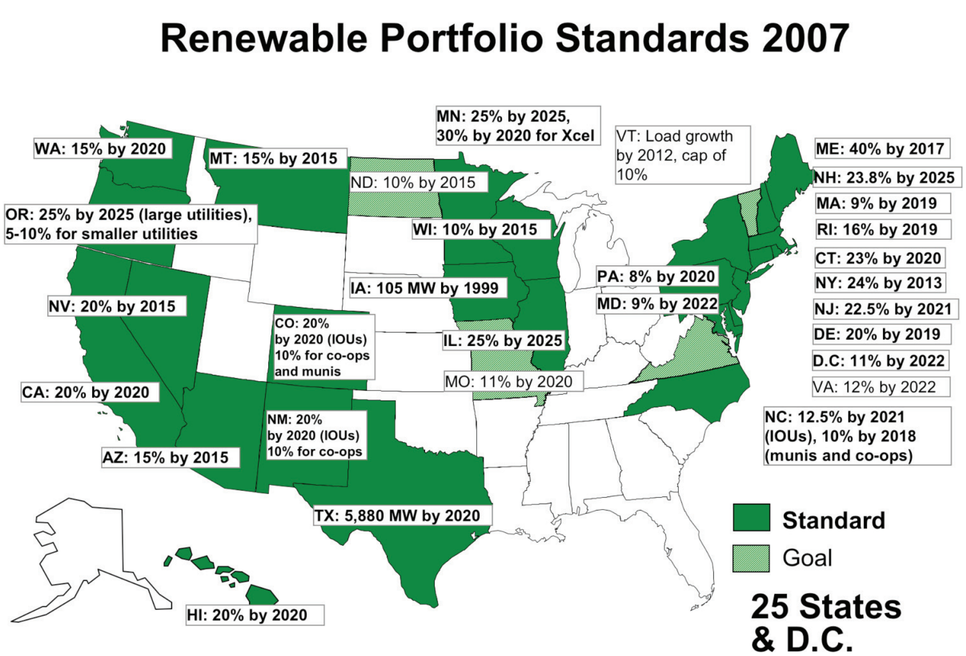

Figure 4.14. US Renewable Electricity Portfolio Standards and Goals in 2007. Constructed using data from (*43*); map template from Union of Concerned Scientists.

If PHEV electricity demand growth is to be served with new renewables supply, renewables capacity would be required in addition to the 61 GW estimated by Wiser and Barbose. If all marginal PHEV load was served with wind having a 35 percent capacity factor, between 4-40 GW of additional nameplate wind capacity would be required by 2025, and 13-108GW would be required by 2030, as shown in **Figure 4.15**. Current total installed wind capacity is about 18 GW (*44*). As adoption begins to enter the steep section of the logistic curve in 2025, considerable new renewable generation would be required and rapidly installed to keep up with demand.

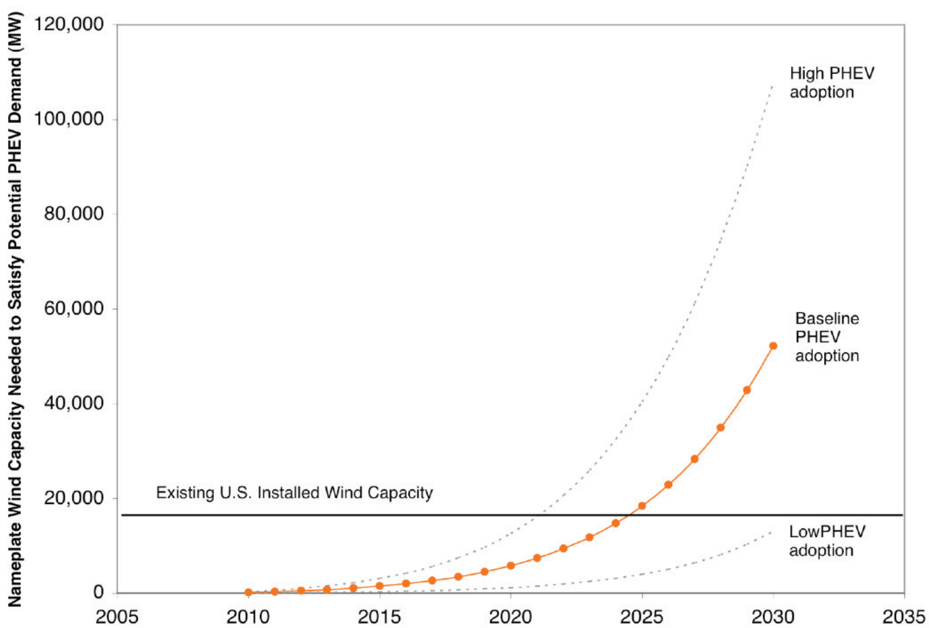

Figure 4.15. Potential cumulative nameplate wind power capacity required to serve various levels of PHEV adoption, assuming a 35% capacity factor for wind power.

Matching PHEV charging with wind may begin to alleviate intermittency issues that arise with wind power (*45*). Future research can investigate the policies and mechanisms to facilitate controlled charging, as well as potential back-up capacity needed for intermittency if controlled charging is not in place.

4.3 Discussion

Transitioning to a passenger transportation system partially powered by electricity carries considerable advantages – reduced oil consumption, diversity in fuel choice, and GHG reductions compared with conventional vehicles. Based on a logistic technology diffusion model, we estimate that about 1 million PHEVs could be on the road by 2015, 4 million by 2020, and 37 million by 2030. While the observed values will depend on policies to support and promote PHEVs, these policies should be coupled with environmental, capacity planning, and reliability goals in the electric power sector.

Baseline PHEV adoption could result in an additional 160,000 GWh of electricity demand by 2030, with low and high ranges of 40,000 GWh to more than 330,000 GWh. This would represent a small portion of estimated 2030 load (1-6%), but could result in 25 percent (for the low PHEV adoption), 100 percent (for the baseline PHEV adoption), or about 200 percent (for high PHEV adoption) of estimated 2030 non-hydro renewable generation. Logistic adoption occurs rapidly during the middle of the adoption cycle when the majority of consumers choose new technology deemed successful by early adopters. Without prudent planning, rapid adoption of PHEVs could add large new power demands without the long planning periods the electric power sector prefers.

Because baseload off-peak power may have an unfavorable GHG profile in many regions of the country, policies are necessary to match PHEV charging with low-carbon electricity if large GHG reductions with PHEVs are desired. PHEVs reduce GHGs compared to traditional hybrids when the life cycle GHG emissions from electricity are about 650-750 g/kWh or below. Electricity GHG performance standards that become more stringent over time is one method to move toward low-carbon generation, as are renewable portfolio standards. Still, the rapid PHEV adoption possible may present challenges for providing adequate low-carbon generation. While cumulative US installed wind power is currently about 18 GW, that full 18 GW of wind would be required to serve baseline PHEV adoption load in 2025, with 52 GW required just five years later in 2030. This highlights the need for integrated system capacity and transmission planning for low-carbon generation assets in the context of government PHEV support policies.

4.4 References

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Chapter 4: Electric power infrastructure capital investment and climate policy decision making under uncertainty

Chapter 5: Technical Change and Public Policies for Emerging Low-Carbon Energy Technologies

5.1 Introduction

If plug-in hybrid electric vehicles (PHEVs) are to be powered with electricity generated from sources that do not involve the emission of carbon dioxide (CO_2), many have argued that wind – that blows both night and day – is an obvious option. Even without considering the CO_2 emissions of fossil fired power plants, the cost of wind is now close to competitive (*1*). As wind assumes a larger role in the electricity supply, its intermittent nature will become a greater challenge (*2*). Advanced vehicle to grid services hold the potential to help ameliorate that problem (*3*), so PHEVs and wind power (and potentially other renewable technologies) could become coupled systems going forward.

For all these reasons, in this final Chapter we explore the different but related question of how the cost of wind became competitive, paying particular attention to the relative contributions made by government research, transfers of technology from other domains, and government policies to promote deployment.

With or without PHEVs, concerns regarding climate change have made it apparent large-scale transition to low-carbon electricity is necessary for reducing anthropogenic greenhouse gas [GHG] emissions (*4, 5*). The Intergovernmental Panel on Climate Change (IPCC) fourth assessment report states that greenhouse gases (GHGs) should be reduced to 50-80% of 2000 levels by 2050 to increase the likelihood of stabilizing atmospheric CO_2 concentrations at twice pre-industrial levels (*4*). Efforts to approach this target would require terawatt-scale installation of low-carbon generation in this century. In the

United States (US), low carbon generation, consisting of nuclear, hydroelectric, and renewables, comprise approximately 30 percent of the generation portfolio (*6*). However, wind and solar power currently comprise a small share of total supply - about 1 percent and 0.1 percent of US capacity, respectively. The US Department of Energy forecasts in a reference case that the US mix will be more carbon intensive in 2030 and that new demand is largely met with coal and natural gas (*7*). Since capital in the power sector is long-lived (*8-10*), a considerable share of new plant construction will likely need to be low-carbon generation in order for the US to measurably reduce carbon emissions from the power sector by mid-century.

Currently operating technologies for low-carbon electricity generation are viable, but have limitations: security, siting, and waste disposal for nuclear, site availability and ecosystem concerns for new large hydroelectric, land availability for biomass, and power intermittency from wind, solar and other geophysical energy flows. These limitations, along with capital cost barriers generally increase the private cost difference between electricity from low-carbon sources and traditional conventional fossil-fired generation. In order to reduce the cost of low-carbon electricity and internalize carbon impacts, the government has a vast array of policy actions to choose from to promote low-carbon electricity. These range from supply side, such as basic and applied research and development (R&D), to demand side policies such as production tax credits (PTC), capital cost rebates, and government-backed loans.

Wind power is experiencing exponential capacity growth and is encouraged through both supply-push and demand-pull policy actions at the federal and state level. However, technological and economic characteristics cause different electricity technologies to respond better to one particular promotion policy or another. Emerging energy technologies may benefit from R&D, learning effects, and spillovers from outside industries at different rates. As US national R&D and policy priorities shift toward energy, it is important to understand these differences in order to maximize policy effectiveness. Several works have argued for increased attention to technical change, both endogenous and exogenous, in modeling climate and energy scenarios; see for example (*11-13*). This analysis examines onshore wind power in the US, a low-carbon technology that has matured from an emerging power source to a utility-scale technology. By assessing the success and challenges of wind, it is possible to inform the most appropriate integrated policy strategy for developing a robust low-carbon electricity system.

Wind power has evolved from its mechanical "windmill" roots to become a viable zero-emission utility-scale energy source in the 21st century, with costs that are now close to competitive in commercial power markets. The nexus of concerns about energy security, high fossil fuel prices, and carbon dioxide emissions has made wind power a focus of great interest. This research investigates how wind power got to the point that it may be poised to become a serious player in supplying electricity. Specifically it explores the relative role played by institutional research and development (R&D), incremental innovations, and advances in and transfers from industries outside of wind energy in bringing wind to its current status. By analyzing wind in this context, a framework is proposed to encourage innovation and adoption in low-carbon energy technologies.

As with other technologies that provide a societal benefit not currently valued in the marketplace, wind power has benefited from both favorable public policies as well as a diversified R&D agenda conducted by both government and public-private partnerships. While there is little doubt that the growth of wind has benefited from public policy, such as feed-in tariffs and production tax credits, the sources of technical innovations in design and manufacturing which have contributed to cost reductions are less clear. Loiter and Norberg-Bohm (1997 and 1999) have argued that the majority of radical advances in wind energy originated from transfers from other industrial sectors and not from governmental research in advanced wind turbine designs (*14, 15*).

Through both a careful review of the academic literature, governmental and institutional reports, conference proceedings, and trade publications, as well as interviews with officials, both in government and across the wind industry, this research confirms this finding and examines recent advances in industries outside of wind energy that have been a primary driver for continued cost reductions in the cost of wind generated electricity.

Previous research in this area includes the aforementioned work of Loiter and Norberg-Bohm, as well as Sawin (2001) who both included the US in their analyses, and Kamp et al. (2004), Astrand and Neij (2006), Buen (2006) and others who examined European nations exclusively (*16-19*). The indicators used to evaluate the relationship between R&D, public policy and wind power include technology cost and performance-based metrics, as well as technology adoption rates. This work adds to the current literature by further examining these relationships from the perspective of the US experience, and analyzes the recent significant impacts of inter-industry spillovers on the adoption of wind energy.

5.2 Wind turbine installation expansion and capital cost decline

World cumulative installed capacity for wind power was more than 94,100 megawatts (MW) in 2007 (*20*) as shown in **Figure 5.1**. Installations have grown by a compound annual average growth rate of 28 percent from 2000-2007, and the industry has experienced six doublings of installed capacity since 1986. Wind power development is presently concentrated heavily in Europe, comprising approximately 61 percent of the world capacity and to a lesser extent the United States, comprising approximately 19 percent. Germany, the United States, and Spain have the first, second and third largest wind markets, with 2007 installed capacities of about 22 GW, 17 GW and nearly17 GW, respectively (*20*).

Wind power currently represents about 1 percent of the approximately 1000 GW of installed summer electricity capacity in the US (*6*). In 2007, wind power installations represented 35% of net capacity additions to the US portfolio, second only to natural gas units (*1*). The US wind resource is the largest regional wind resource globally, with a technical potential of 21,000 TWhs per year (*21*). Between 9-90 km off the US coastline, the offshore wind power resource represents considerable additional technical potential (*22, 23*).

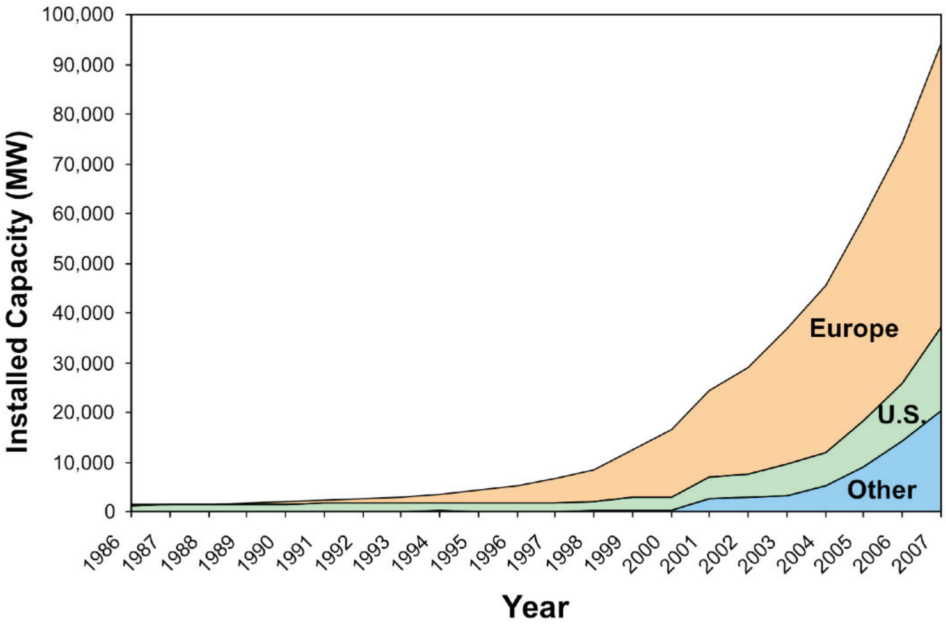

Figure 5.1. Total global installed wind power capacity, 1986-2007. Constructed with data from (*20*)

Without a fuel price input or risk, the relatively high capital cost of wind turbines has been the primary financial barrier to entry into the electricity markets. The wind turbine itself comprises approximately 70 percent of the capital cost required, with the remaining 30 percent allocated to balance of system (BOS) costs (*24-27*). These balance of system costs include soft costs such as planning and engineering, as well as installation, transportation, and interconnection. These costs however would only represent installations in locations without adverse site conditions, which could raise the BOS costs significantly. Installation costs rise considerably for sites with difficult terrain or those without access to adequate transmission.

Since the 1970s, real installed costs of wind power per kW have decreased approximately ten-fold, and installations have grown to more than 94,100 MW worldwide. Both the technology and performance of wind turbines have improved dramatically, resulting in larger sizes, greater capacity factors, and much higher energy capture. Turbines have evolved technically from simple machines constructed with off-the-shelf motor components to carefully optimized advanced power generation systems with a worldwide manufacturer and supplier base including large multinational firms such as General Electric and Siemens. Capital costs for wind turbines are defined as the installed cost per kilowatt (kW) of rated capacity. Installed capital costs per kW for wind turbines have fallen in real terms from approximately $7500/kW in 1982 to an average of $1,710/kW in 2007 (*1, 24, 27, 28*) as shown in **Figure 5.2** and **Figure 5.3**.

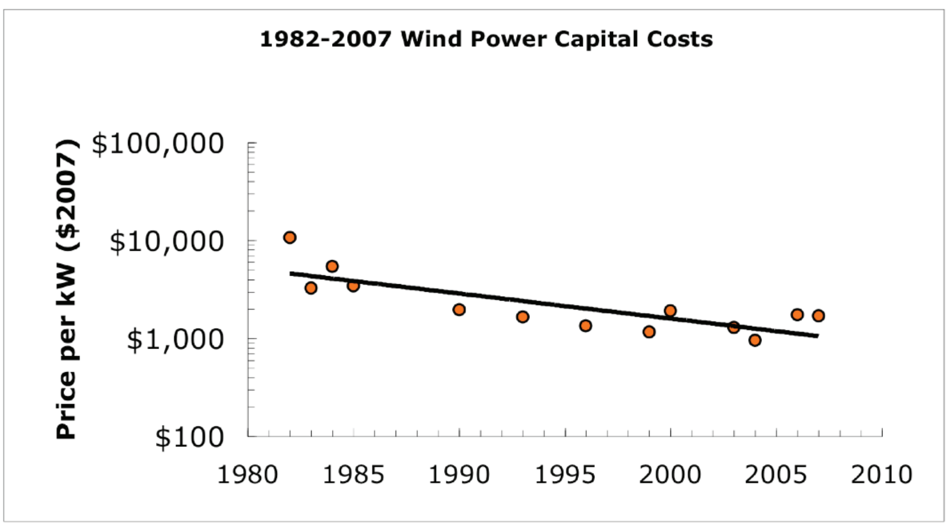

Figure 5.2. Decline in wind power capital cost, 1982-2007. Constructed with data from (*1, 20, 24, 27-33*)

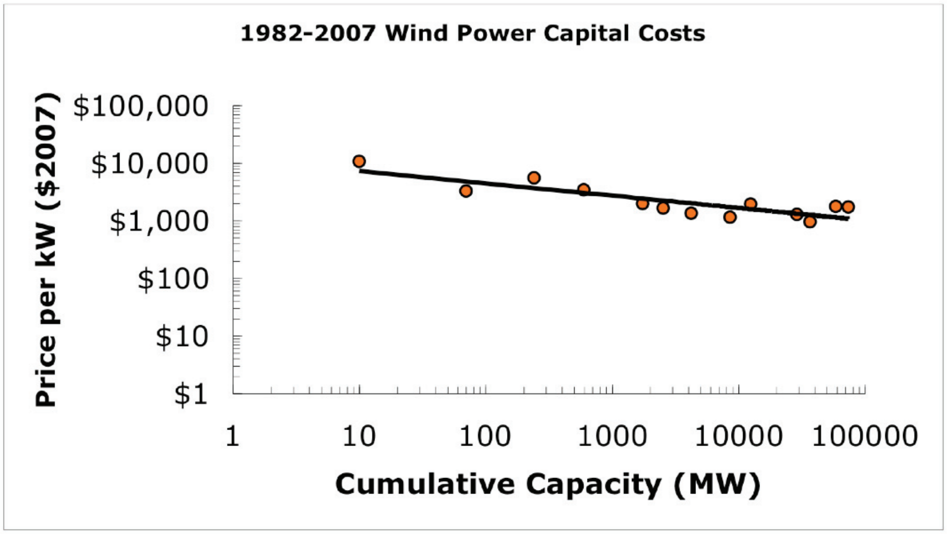

Figure 5.3. Decline in wind power capital cost with cumulative installed capacity. Constructed with data from (*1, 20, 24, 27-33*)

Operations and Maintenance (O&M) costs for wind turbines are relatively small when compared with annual payments required to cover capital costs. Reliable data for O&M costs are often difficult to obtain, as manufacturers are reluctant to release what they perceive to be competitive information. Most estimates for total annual O&M costs are between 1 and 5 percent of initial capital costs and vary depending on the number of installed turbines in the wind farm under contract (*26, 34*). Typically, the turbine purchaser initiates a full service O&M contract and warranty with the manufacturer either as part of the comprehensive price or as a separate subcontract. EPRI (2002) reported actual submitted O&M contract bid amounts for a wind turbine project in the range of approximately $12-16/ kW, which would be consistent with the low end of the above estimates (*35*). O&M costs/kW have also declined over time and as turbines have increased in size. Manwell et al. (2002) reports that O&M costs per kW decrease both as nameplate capacity increases as well as age of installed turbine decreases (*34*).

Busbar cost of energy for wind projects in 2007 was estimated to be an average of 4 cents/kWh with one standard deviation between 2.4-5.5 cents / kWh, prior to any tax incentives (*1*). This does not represent real or external costs due to the intermittency of wind power. Reductions in the cost of energy are achieved by reduced capital costs, higher capacity factors, or more favorable financing terms.

Decreases in the cost of energy from wind power can result from improvements per kW of capacity in one of three areas: decreased capital costs, decreased O&M costs, or improved annual energy capture (*27*). These factors can be affected by technical change, public policies, and/or scale economies.

5.3 Energy Research, Development and Deployment

Research, Development, and Deployment (RD&D) in the energy sector is an essential part of the innovation system, and a sustained and massive commitment is critical in a world with carbon constraints. RD&D will assist in reducing the costs of emerging low-carbon technologies as well as increase codified and tacit knowledge in the low-carbon science and technology innovation systems. RD&D will also be crucial in characterizing climate change adaptation priorities and mechanisms.

To date, calls for increased energy RD&D (*36*) have not yielded the level of commitment necessary to achieve low climate stabilization targets such as 450 ppm. Because of the asymmetric returns to RD&D (*37*) and national economic and political constraints, US and global RD&D in energy has been limited for several decades as shown in **Figure 5.4**. It is estimated that at least a doubling of current energy R&D efforts will be required (*38*). Energy R&D by International Energy Agency Member countries increased only incrementally in the last two decades, with current real R&D lower than R&D spending in the late 1970s (*39*).

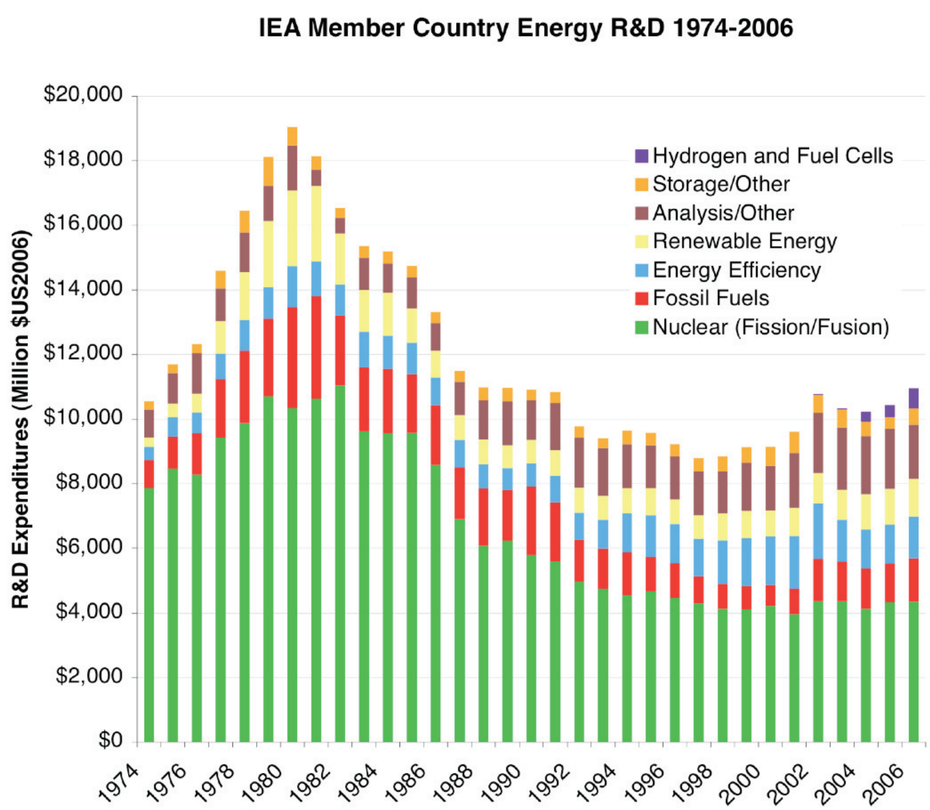

Figure 5.4. International Energy Agency member country energy R&D 1974-2008. Constructed with data from (*39*).

The oil shocks of the 1970s resulted in considerable government R&D resources concentrated into wind energy research programs. From 1975 to 2003, total US federal expenditures on wind energy were $1.2 billion while Germany, Denmark, and Spain spent $550 million, $170 million, and $85 million, respectively using 2003 dollars[i] (*39*). A comparison of the public R&D investment[ii] in wind power made by the US, Germany, Spain and Denmark is presented in **Figure 5.5**.

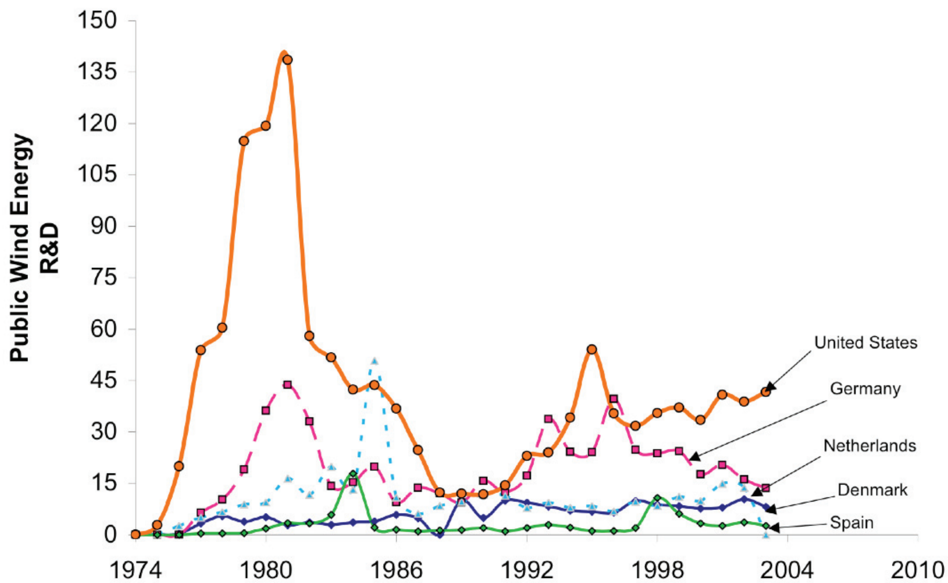

Figure 5.5. Public wind energy R&D. Constructed with data from (*39*).

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[i] For consistency, all real dollar figures reported in this work are calculated using a U.S. gross domestic product implicit price deflator index (2000 = 100). The Gross Domestic Product Implicit Price Deflator is calculated from the September issues of the Survey in Current Business, published by the Bureau of Economic Analysis in the Department of Commerce, http://www.bea.doc.gov/bea/pubs.htm, and also compiled by the EIA in the 2005 Annual Energy Review, http://www.eia.doe.gov/emeu/aer/txt/ptb1601.html. The implicit price deflator (IPD) measures the change in prices in a determined bundle of goods however unlike the Consumer Price Index (CPI), the IPD allows the bundle of goods to change with consumption patterns. For the purpose of demonstrating macro trends in R&D levels, there should be minimal difference in using the IPD or CPI and the IPD will be used for consistency.

[ii] Due to the inherent differences in Gross Domestic Product (GDP) and total energy R&D in each country, wind energy R&D as a percentage of GDP and as a percentage of total national energy R&D were also analyzed. Denmark dedicated a higher percentage of energy to R&D to wind energy than the other nations. Comparatively, Denmark spent the largest percentage of GDP on wind R&D, with the one exception of 1982, when US wind spending was at its peak. However, assuming the cost of a R&D program for an immature technology are comparable between these countries, then Denmark's dedication of a higher percentage of resources only perhaps indicates government and public priorities, and not necessarily a more robust research agenda.

The majority of the US wind research program from 1974-2003 invested in large multi-megawatt turbines. US Department of Energy (DOE) program engineers attempted the rapid scale-up of existing designs, even before the previous designs were constructed. According to Gipe (1995), the early US wind demonstration projects resulted largely in failures, yielding no commercial successes (*28*). Unlike the US program, the Danish sought direct involvement of the end-users, the utilities, from the program's commencement[iii], and focused on incremental innovations. Denmark currently generates up to 20 percent[iv] of its electricity by wind power, compared with less than 1 percent in the US (*40, 41*). By marketing proven technologies and turbines certified by the national laboratory, Denmark's manufacturers established a worldwide reputation and have acquired approximately 43 percent of the world cumulative market share in 2004. Denmark's largest wind firm, Vestas, exports nearly 99 percent of its turbines to other countries (*42*). While the US firm, General Electric[v], is currently a serious player in the wind industry (*1*) , it is difficult to trace their success and technology to the US federal program of the 1970s and 1980s, as their initial wind technology was largely obtained through acquisitions.

[iii] The Danish counterpart to EPRI, the research institute of the Danish Utilities (DEFU) jointly administered the Danish wind R&D effort with the Danish Ministry of Trade (Van Est, 1999)

[iv] If a smaller disparity between US and Danish percentages of wind in their generation mixes existed, additional emphasis would be warranted on the caveats of this comparison. Denmark has several comparative advantages that discount the value of an equal country comparison, most notably the access to large shares of fast-ramping hydropower from Nordpool in Scandanavia that allows large variations in available wind to be rapidly replaced with hydropower.

[v] GE exited the wind industry in the 1980s and only returned after the acquisition of Enron Wind in 2002. All of GE's currently commercial wind turbines are modeled after the original "Danish design" of a three-bladed, upwind turbine, a design acquired by Enron in their 1997 purchase of German wind firm Tacke (Sawin, 2001).

5.4 Sources of innovation

Wind power has benefited considerably from adapting technology and innovations that were researched and developed outside of the wind energy field. These borrowed innovations, or technology spillovers, allow the user to reap the benefits of a new technology without the full cost of development[vi]. Many initial product spillover technologies in wind power included components of motors and generators commonly available off-the-shelf during the early development of the modern wind turbines in the 1970s and 1980s. These included gearboxes, ball bearings, and automotive brakes (*43*). The evolution of modern wind power occurred concurrently with vast improvements and advancements in computing and communications power, power electronics, aerodynamics, materials science and testing. Appropriate products and processes in these endeavors were imported to the wind industry and have enabled large advances in wind power (*34*).

Loiter and Norberg-Bohm (1999) argue that innovation in wind energy was achieved incrementally, by benefiting from technological advances from outside industries and using public and private research for specialized adaptation of these borrowed advances. Several key exceptions, such as advanced airfoils, were developed directly, and were essential in the success of commercial wind power. This research is largely consistent with this earlier hypothesis and also finds that spillovers became even more important in the wind industry from 1999 to 2005. **Table 5.1** lists some of the major spillover technologies for wind power. Improvements in power electronics and their role in

[vi] Although the technology is developed in other industries, R&D for adaptation is often required for beneficial use in the borrowing industry. See Loiter and Norberg-Bohm (1999).

variable speed drives, as well as advances in blade manufacturing are discussed further in this section.

Table 5.1. Spillover technologies into wind power and their effects (*14, 15, 26, 44*).

Spillover into Wind Industry	Original Industry	Reduces Capital Cost	Reduces O&M Cost	Increases Annual Energy Production
Megawatt power electronics	Traction power, utilities		•	•
Variable speed drives	AC motor control		•	•
Advanced blade manufacturing	Boatbuilding, aerospace	•	•	•
Direct drive generator	Low-speed hydropower		•	•

5.4.1 Improvements in power electronics and variable speed drives

One of the most significant advances in wind technology was the variable speed wind turbine enabled by power electronics. As shown in **Table 5.1**, spillovers and adaptation played an essential role for these technologies. Variable speed wind turbines with partial frequency conversion became the dominant wind turbine by annual sales in 2001 (*45*).

With a variable resource such as wind acting as prime mover of the power generating system, wind power as a meaningful contributor to an electricity generation portfolio requires modification to supply power of consistent quality and frequency. The traditional design of allowing the wind turbine rotor to only operate at a constant speed and fixed frequency, results in the wind turbine operating over a very narrow range of wind speeds. By allowing the rotor speed to vary with wind speed on a variable speed turbine, the optimum tip speed/wind speed ratio for maximum efficiency can be maintained across a distribution of wind speeds, yielding greater energy output. Traditional wind turbines without power electronics for frequency conversion utilized capacitor banks to reduce the reactive power consumed and had limited controllability (*46*).

Wind turbines utilizing power electronics can produce real and reactive power up to the full range of its operating capacity resulting in smooth power with low distortions, making wind more appealing to grid operators. For variable speed wind turbines, the adaptations from the rapidly developing field of solid state power electronics has resulted in significant cost reductions. **Figure 5.6** presents the order of magnitude improvement in power rating (volt-amperes, or watts) over time.

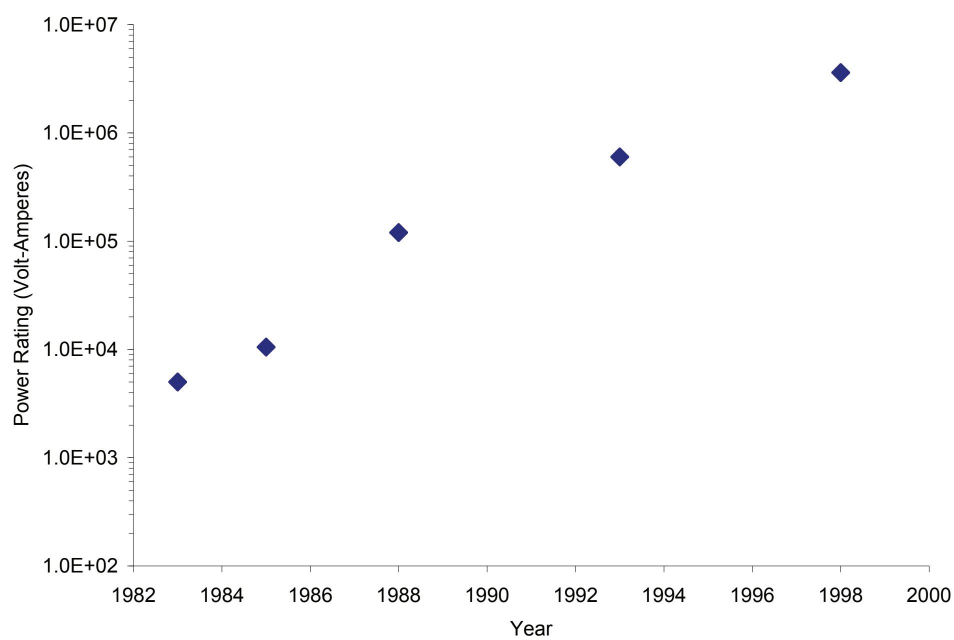

Figure 5.6. Order of magnitude power rating improvements of high power electronics. Constructed with data from (*44, 47*)

While low power electronics are used in applications such as computers and automobiles, high power electronics (> 1MW) are applicable to the wind power and utility industries

(*47*). High power electronics are typically used as switches, rectifiers, or inverters to either stabilize power supplies or control motor speed, acceleration, and torque (such as traction power for locomotives) (*48*). The first use of power electronics in the wind industry was for smoothing out load when a wind turbine begins to produce power. "Soft-start" technology using thyristors smoothed transition spikes from the generator, mitigating the adverse electrical effects. The technology was borrowed from AC motor control and first diffused into the wind industry in 1982 (*14*).

Kroposki (2005) identifies three major power converter configurations currently utilized in wind energy (*49*):

- Insulated Gate Bipolar Transistor (IGBT) rectifier and inverter
- Diode rectifier-IGBT inverter
- Silicon controlled rectifier (SCR), also known as a thyristor

Variable speed wind turbines rely on advanced megawatt solid state power electronics for conversion of the variable AC power produced by a variable speed turbine to stable grid power of constant frequency. This is typically accomplished though use of a converter to convert the variable frequency AC power supplied by the wind to stable DC, then inverted back to AC at synchronous frequency. Although the use of a variable speed drive allows the generator to produce an additional 10 to 15 percent more energy compared to a fixed-speed machine, the traditionally high cost of power electronics coupled with power conversion efficiencies losses at low speeds had typically eroded any significant gains (*50, 51*). However, the cost and performance of commercial power electronics improved dramatically beginning in the 1990s, which rapidly accelerated their diffusion into the wind industry. Higher quality power output, the ability to control power factor, and the ability to supply reactive power to the grid, even when the wind was not blowing, were strong incentives to pursue a variable speed deign and has led to wider utility acceptance and adoption of wind power (*51*). Variable speed technology for wind turbines was researched under the US federal R&D efforts (MOD-0A and MOD5-B turbines) using SCRs, but the resulting AC power was of poor quality and required significant filtering (*52*). Variable speed turbines with full frequency conversions were advanced by two separate parallel efforts in the US and Germany in the early 1990s. The US effort was a consortium consisting of private firm US Windpower (known as Kenetech after 1993), utilities Pacific Gas and Electric Company and Niagara Mohawk Power Corporation, and EPRI from 1989 to 1993. The German effort was undertaken by the German Wind Turbine manufacturer Enercon (*27*).

Although wind power supplies less than 1 percent of total US electricity generation, as wind power installations increase and reach higher penetration levels, utilities, system operators, and manufacturers have become concerned with smooth integration and improving the power quality of wind generated electricity (*27*). The Electric Power Research Institute (EPRI, 2004) contends that high power quality of wind power is essential for continued adoption and grid penetration. This is especially true for weak grids, remote areas, and areas without adequate transmission capacity, which often, as in the case of the upper US Midwest, possess some of the best wind resources and represent significant opportunities for future growth (*27*). Design of wind turbines has shifted in response to the demand for cleaner power away from cheaper, simpler fixed speed machines, toward variable speed machines with power electronic converters. The grid benefits of variable speed drives have been a major factor in utility acceptance on a large scale. Hence, their development, coupled with the adaptation of high power electronics were essential to wind's success, and potential higher levels of grid penetration in the future. The interaction between the electricity grid and other intermittent or distributed low-carbon energy sources would also benefit from increased development of power electronics.

5.4.2 Improvements in wind turbine blade manufacturing

Blade and rotor costs have declined considerably as a percentage of overall turbine capital costs. After experiencing significant fatigue failure and (to a lesser extent) electromagnetic interference issues with steel and aluminum blades in the early MOD program, manufacturers of medium and large wind turbines began to use glass fiber reinforced rotor blades in the early 1980s (*43*). Wood fiber with an epoxy binder was used as an alternative to glass reinforced polymers and was adapted from the high performance boat building industry (*34*). By the mid 1980s, glass fiber reinforced blades were the dominant technology in the wind industry (*14*). Several evolutions of glass fiber reinforced blade manufacturing techniques, imported from the boatbuilding and helicopter industries, have enabled larger rotors and cost decreases.

In the early part of the modern wind era and through the 1980s, fiberglass turbine blades were predominantly manufactured by the traditional method employed in the boatbuilding industry, a labor-intensive hand lay-up process. The cost of blades manufactured with a hand lay-up process is approximately 50 percent materials cost and 50 percent labor cost (*53*). The hand lay-up process also posed quality, standardization and mass production difficulties. The automated filament winding process, first used on one of the last MOD program turbines, allowed for stronger blades with drastically reduced labor costs (*53*). This technology was imported into wind manufacturing from the pipe and vessel manufacturing industries, and had it origins in military missile casing manufacturing (*15, 54, 55*). Filament winding also presented quality issues in manufacturing of outer blade sections, as the process could not easily achieve the precise smoothness required for optimum airfoil performance (*53*). However, the DOE's use of the filament winding process diffused into the wind industry, lowering manufacturing costs for many of the internal blade components. Another borrowed technology in blade manufacturing is the prepreg manufacturing process, which was adapted from the aerospace industry (*56*). The process uses fiber that is pre-impregnated with resin and is semi-solid at room temperature, providing an ease of handling and forming. Vestas Wind Systems, the largest single wind turbine manufacturer in the industry, uses prepreg technology to manufacture its blades (*56*). In the 1990s, the resin-transfer molding process was adopted for blade manufacturing. This automated process introduces a catalyst to dry fiberglass enclosed in a mold through either a vacuum or pressure. Because the process is enclosed, most of the volatile gases previously produced in blade manufacturing are contained, allowing for greater compliance with air-pollution standards (*53*). The resin-transfer molding process also reduces labor costs and material usage by 20 percent over previous methods (*53*). The dominant blade manufacturer for the wind industry worldwide, Danish firm LM Glasfiber (originally a boat manufacturer), has used a vacuum assisted resin-transfer molding process for blade manufacture since 1997 (*57*). To increase blade length without increasing weight proportionally, designers have been increasingly incorporating carbon fiber into blade designs, which is lighter and stronger than the glass reinforced plastic currently used.

5.5 Public policies and institutional framework

5.5.1 Public policies affecting wind power

Because the production price of wind power was not historically competitive with traditional fossil fuel electricity generation, policymakers sought to internalize the positive externalities of renewable energy through public initiatives. Policies designed to promote wind power adoption are described, for example, in Bird et al. (2005), European Commission (2005) and Patlitzianas et al. (2005) (*58-60*). These policies primarily seek to use fiscal incentives and subsidies to narrow the renewable energy premium, or mandate a specified quantity of renewable energy be purchased.

California, ranked only 17th in available wind resources in the US according to the American Wind Energy Association (AWEA), had a majority of the world's installed wind capacity throughout the 1980s. While other states were eligible for the federal investment credits and grid access mechanisms[vii], it was the California Interim Standard Offer 4 (ISO4) that guaranteed a fixed price for energy produced to wind turbine owners that began the rapid development of wind in California (*28*). This suggests even with

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[vii] Under PURPA, states could determine the amount of "avoided cost" payment they would enforce utilities to pay small providers, but Gipe (1995) argues that several other states had higher avoided cost payments than CA, suggesting an even stronger correlation toward the unique to CA ISO4.

adequate wind resources and financial incentives, in the early stage of wind's technological development, developers were hesitant to enter the market without the long-term price stability afforded by California's Interim Standard Offer 4 contract, explaining the first surge of wind installations in the early 1980s.

Table 5.2. US public policies affecting wind power (*15, 16, 58*). Notes: PURPA: Public Utilities Regulatory Act of 1978 established that utilities must purchase renewable power at avoided costs. PTC: Originally 1.5¢/kWh (inflation adjusted) production tax credit, REPI: 1.5¢/kWh (inflation adjusted and subject to annual appropriation) renewable production payment incentive for municipal and cooperative generators with no tax liabilities.

U.S. Policies Affecting Wind Energy	Affects Technology Development	Creates Market/ Reduces Technology Risk	Reduces Initial Investment	Reduces Cost of Energy
Federal Supply-Push				
Materials and aerodynamic research	●			
Component development research	●			
Large demonstration projects	●			
Cost-shared R&D contracts	●	●		
Federal Demand-Pull				
PURPA		●		
Wind resource maps		●	●	
Production credits/incentives (PTC/REPI)				●
Investment Credits			●	
Accelerated depreciation			●	
Turbine standards and certification		●		
State Supply-Push				
Wind resource maps		●	●	
State Demand-Pull				
Long term contracts		●		
RPS /Utility mandated purchases		●		
Production credits/incentives				●
Investment credits/incentives			●	
Sales/property tax exemptions			●	
State loans or loan guarantees		●	●	
System benefit funds		●	●	

The success of wind power from 1999-2007 has also been influenced by the Production Tax Credit (PTC) and by Renewable Portfolio Standards (RPS). The PTC provides a tax credit for each kWh produced from renewable electricity technologies for the first ten years of operation. The amount was originally $0.015/kWh and it is indexed to inflation (the PTC is $0.02/kWh in 2008). Although all projects installed after January of 1994 were eligible for the PTC, net US wind installations from 1994 to 1998 were only 192 MW or a little more than 10 percent of the initial 1994 capacity. The 1987 repeal of a 1978 law prohibiting new natural gas-fired generation plants coupled with cheap natural gas prices over the mid 1990s decreased the attractiveness of adding new wind capacity. Additionally, uncertainty surrounding the electricity restructuring debate in the mid 1990s resulted in an additional incentive to delay any new wind projects during this period (*16*). It appears that the impending expiration of the PTC is far more effective at inducing adoption than the PTC itself. The first production tax credit beginning in 1994 was set to expire in 1999. As the PTC advanced toward expiration at the end of 1999, turbine developers and manufacturers seeking to maximize revenue installed 663 MW in 1999. Similar boom and bust cycles characterized the next two PTC expirations in the end of 2001 and 2003, with 1,697 MW and 1,687 respectively added in the expiration years and 410 MW and 368 MW added in the years in between. The Energy Policy Act of 2005 established a three-year production tax credit cycle, and the industry has realized continued expansion from 2005-2007 (*61*). **Figure 5.7** shows the importance of policy consistency concerning emerging energy technologies.

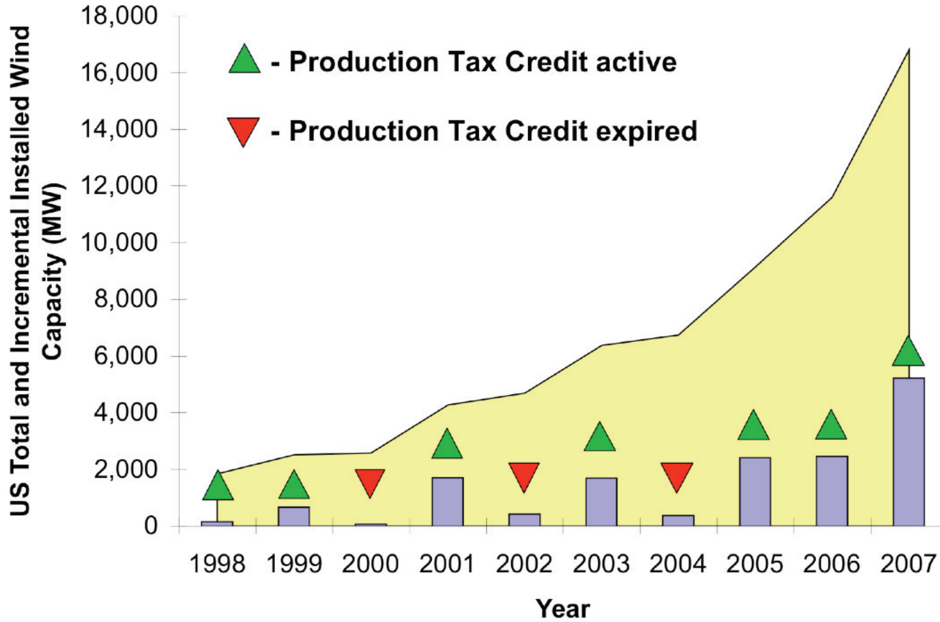

Figure 5.7. US cumulative and incremental wind installations from 1998-2007. The expiration of the PTC drastically affected incremental installations over this time period (*61, 62*) .

5.5.2 Institutional framework for leveraging spillovers in energy research

As structured, these policies assume technological learning and advancement in wind power to be endogenous, and will occur as adoption rates increase. Where existing policies are deficient is in nurturing and capturing exogenous change in the low-carbon energy sector, which have been found to play a major role in wind energy adoption.

Intermittent renewables share common challenges and technologies interacting with the grid. Common technologies can include power electronics, inverters, energy storage, and grid intelligence, among others. An integrated approach to low-carbon R&D can allocate scarce resources across shared technologies to increase the likelihood of success for individual technologies. For example, Curtright et al. found in their expert elicitation that solar photovoltaic (PV) panels were viewed as unlikely to achieve cost competitiveness in the next 40 years (*63*). They assumed that PV panel costs represented 50 percent of total costs, with the Balance of System (BOS) comprising the remainder. Hence, while continued and enhanced solar R&D in essential, focus on cost reductions of intermittent renewables such as solar PV and wind could also expand to investigating methods to reduce BOS and integration costs. Reducing integration costs would enhance the competitiveness of renewables across all intermittent technologies.

Policy is often designed with technology viewed as a “black-box”. Outcomes are projected from known inputs without adequate knowledge of intermediate paths or processes (*64*). To encourage wider adoption of low-carbon energy sources, the policy design and technology program development frameworks require substantial integration. This will allow designers and end-users to identify near- and long-term technology barriers and policymakers to invest the necessary resources to remove these obstacles. R&D in renewable energy technology is often technology-specific, even though spillovers such as power electronics can encourage renewable adoption across several technologies. An institutional framework for leveraging spillovers in low-carbon energy is shown in **Figure 5.8**.

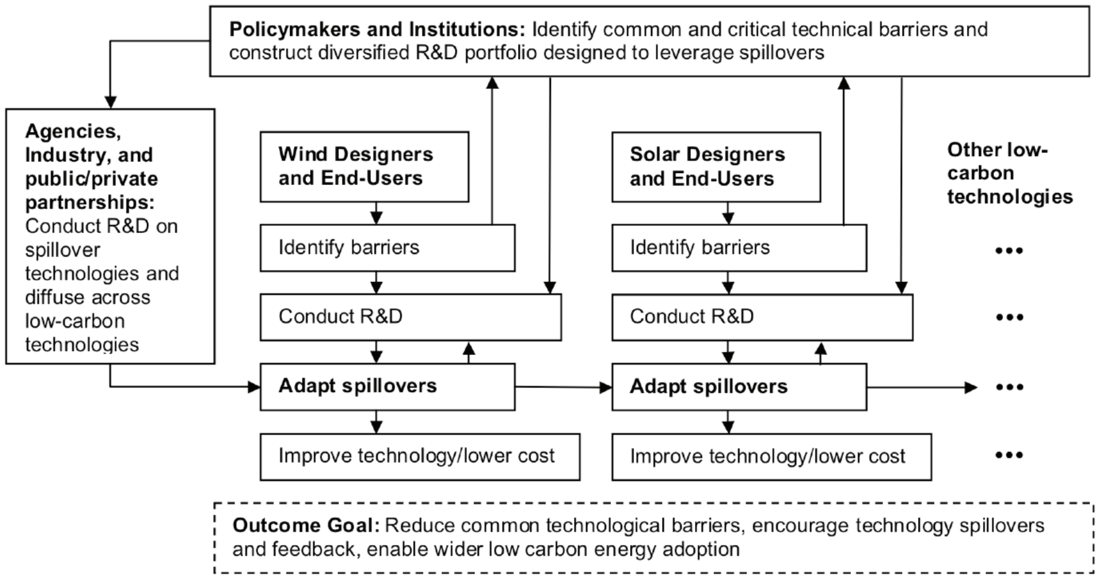

Figure 5.8. Institutional framework for leveraging spillovers and encouraging low-carbon energy diffusion

5.6 Discussion

Since the 1970s, real installed costs of wind power per kW have decreased by an order of magnitude, and installations have grown to more than 94,100 MW worldwide. Both the technology and performance of wind turbines have improved dramatically, resulting in larger sizes, greater capacity factors, and higher energy capture. By examining wind power's development and the various policy approaches undertaken, insight can be gained into the policies and actions that can encourage further low-carbon energy adoption.

The initial U.S approach to wind energy policy in the 1970s and early 1980s was an isolated supply-push policy of attempting radical technological breakthroughs with conventional aerospace manufacturers. The supply-push agenda focused on creating a radical new product, an advanced multi-megawatt wind turbine, for which there was then no market. Sawin (2001) notes that the US federal program was designing utility-scale, multi-megawatt wind turbines and did little early on to either involve the utilities or push for a policy agenda to encourage utility ownership of wind turbines (*16*). The US spent a considerable amount on R&D in an attempt to pick technology winners. Along the way this yielded some important innovations for the wind industry, but at enormous cost. US federal wind power research achieved advances in aerodynamics, computational fluid dynamics, and blade design, which have positively contributed to advancing the wind industry. However, this effort historically has played a lesser role in fostering wind energy adoption domestically or in transferring technology and tacit knowledge to local utility-scale turbine manufacturers.

In contrast, the supply-push efforts of Denmark largely focused on incremental knowledge and end-user feedback through the involvement of utilities. Feedback was further encouraged by the Danish supply-push policy of information dissemination. Unlike the early days of US policy, in order to be eligible to participate in any Danish government-sponsored wind subsidy, credit, or quota, manufacturers had to certify their turbines at the national laboratory which then published the results (*16*). This acted as a self-selection mechanism for technically committed firms, as well as simultaneously encouraged technology diffusion. Learning-by-doing, as described in the seminal work by Arrow (1962), played a significant role in the accumulation of knowledge stock in the Danish wind industry (*17, 65*). The vast tacit knowledge gained by manufacturers and government researchers from the extensive field experience of Danish turbines, both domestically and abroad, allowed for continuous incremental innovation and fostered a successful wind industry in Denmark. It is apparent that a successful supply-push policy must involve end-users of the technologies as primary stakeholders and also must encourage continuous feedback from market participants in order to amass knowledge stocks and benefit from incremental innovation.

Demand-pull mechanisms such as the production tax credit and financial incentives have only stimulated market participation when those incentives rendered the wind power investment marginally cost competitive in the generation market. However as discussed above, the uncertainty surrounding the duration and reauthorization of US demand pull policies have resulted in a boom and bust cycle in the wind industry. In such an environment private firms are loathe to invest in long-term R&D for both products and processes if no signals exist that policies that create a market will be in effect two years hence. This strategic view undertaken by firms as a survival strategy stagnates cost advances in both turbine design and manufacturing. Today it is more evident than in work previously reported by Loiter and Norberg-Bohm (*15*) and others that a combination of supply-push R&D to enable basic technology advances and sustained demand-pull mechanisms to encourage market adoption are essential for increased adoption of wind power.

The importance of inter-industry spillovers has become vastly more significant over the past several years as wider wind power adoption occurred. For example, the borrowed technology of variable speed drives and power electronics has removed some of the largest barriers to large-scale wind power penetration - the demand by utilities for clean power, little or no reactive power consumption, and recently the ability to produce reactive power and to ride through system faults. An OECD/IEA (2005) report stated a lag has occurred between the adaptability of electricity grids to accommodate intermittent resources and the exponential growth of installed wind power (*66*). Spillover technology developments from other industries, such as power electronics, possess the potential to address these types of critical technical barriers. Continuous cost and performance improvements in power electronics will not only contribute to cost declines in wind power, these improvements are essential for intermittent and distributed resources to become a serious player in utility-scale electricity generation.

The electricity generation sector is becoming increasingly dependent on high power electronics, information technology, and data analysis. If exogenous emerging or existing technologies, at a lower cost and/or higher performance rating, would significantly increase the probability of wider low-carbon energy adoption, then policy should be designed to create inter-industry spillovers from R&D and manufacturing in these sectors. Low-carbon energy policy should take a systems approach, leveraging investments and policies across interdependent industries to create feedback, innovation, and diffusion.

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Chapter 6: Contributions and Discussion

6.1 Research Questions Revisited

Policies for GHG mitigation face the challenge of reducing GHG intensity across multiple sectors in the economy. Business as ususal forecasts depict continued growth of GHG emissions and similar energy and fuel sources through 2030 (*1*). In order to achieve the 50-80% GHG reductions by 2050 recommended by the IPCC, a fundamental shift and evolution will be required in the energy system. Because the electric power and transportation sectors represent the largest GHG emissions sources, a unique opportunity for coupling these systems via electrified transportation could achieve synergistic GHG emissions and petroleum use reductions. Additionaly, by shifting energy demand from the transportation sector to the electricity sector, a large portion of petroleum use can be displaced, enhancing energy security.

The research questions investigated in this thesis and a summary of findings are:

1) **What are the life cycle GHG emissions and energy use of plug-in hybrid electric vehicles compared to traditional vehicles and hybrids?**

Plug-in hybrid electric vehicles (PHEVs), which use electricity from the grid to power a portion of travel, could play a major role in reducing greenhouse gas (GHG) emissions from the transport sector. However, as shown in Chapter 2, meaningful GHG emissions reductions with PHEVs are conditional on low-carbon electricity sources. We assess life cycle GHG emissions from PHEVs and find that they can reduce GHG emissions by 32%

compared to conventional vehicles, but have reductions of about 5% compared to traditional hybrids when charged with electricity sources that resemble the current United States (US) average portfolio. Batteries are an important component of PHEVs, and GHGs associated with battery materials and production account for 2-5% of life cycle emissions from PHEVs. We consider cellulosic ethanol use and various carbon intensities of electricity. The reduced liquid fuel requirements of PHEVs could leverage limited cellulosic ethanol resources.

To achieve large GHG reductions with plug-in hybrids, public policies that complement PHEV adoption should focus on encouraging charging with low-carbon electricity. As shown in Chapter 4, the marginal overnight electricity fuel may be coal in some regions, so promoting low-carbon electricity sources that are available during off-peak periods would assist enhance the potential GHG reductions with PHEVs. Policies could include adjusting renewable portfolio standards to account for potential off-peak charging. If PHEVs supply a sizeable portion of passenger travel, charging intelligence will likely be incorporated to maximize utilization of available resources and low-cost electricity, facilitate user billing and replacement of motor fuel taxes for infrastructure funding, as well as potentially enable two-way power flows between vehicles and the grid (*2*). Policy levers could utilize charging intelligence to minimize the carbon intensity of electricity used, either by prices or credits.

Long-term planning horizons in the automotive sector are much shorter than the power sector, with an automotive fleet cycle of 12-15 years. If PHEVs have high adoption in two or three fleet cycles from now, the electricity supply technology decisions made within the next ten years will affect the GHG intensity of the electricity system encountered by those vehicles. A commitment to developing a low-carbon electricity portfolio becomes even more important if large GHG reductions from PHEVs are desired within the current cycle of electricity capital turnover.

2) What are the economic factors, demand-side infrastructure conditions, and uncertainties comprising the decision space in scalable adoption of PHEVs?

The primary demand-side infrastructure need is access to an electrical outlet where the vehicle is parked overnight. About 94% of US households have access to either a garage, carport, or off-street parking at their residence, although this varies by region and between homeowners and renters (*3*). Home infrastructure upgrades, if required, would vary between about $200 and $1,000 per household and must be considered in the engineering economic analyses and public policies regarding PHEVs.

Based on PHEV size, the net present value terms for PHEVs to be economically competitive with traditional vehicles would range between no subsidy (PHEV10), a subsidy of about $5,500 (PHEV30) and a subsidy of about $13,000 (PHEV50). The results are highly sensitive to the battery cost, the price of gasoline, and the battery size, as shown in Chapter 3.

No subsidy is required to create a positive NPV for a PHEV10 because the small battery results in low additional capital costs and efficiency (both in electric and gasoline modes) but provides considerable fuel savings over a conventional vehicle (as does a HEV). However a PHEV10 might not satisfy oil displacement goals or environmental goals desired with PHEVs, and the trend toward more efficient ICEs and HEVs may achieve similar results to the PHEV10 and at lower cost. It appears that the supply curves for both

CO_2 and oil displacement become steep quickly as PHEV battery capacity (and hence premium) are increased.

3) What are the electricity requirements and charging profiles of various levels of PHEV adoption?

Transitioning to a passenger transportation system partially powered by electricity carries considerable advantages – reduced oil consumption, diversity in fuel choice, and GHG reductions compared with conventional vehicles. Based on a logistic technology diffusion model shown in Chapter 4, we estimate that about 1 million PHEVs could be on the road by 2015, 4 million by 2020, and 37 million by 2030. While the observed values will depend on policies to support and promote PHEVs, these policies should be coupled with environmental, capacity planning, and reliability goals in the electric power sector.

Baseline PHEV adoption could result in an additional 160,000 GWh of electricity demand by 2030, with low and high ranges of 40,000 GWh to more than 330,000 GWh. This would represent a small portion of estimated 2030 load (1-6%), but a could result in 25 percent (for the low PHEV adoption), 100 percent (for the baseline PHEV adoption), or about 200 percent (for high PHEV adoption) of estimated 2030 non-hydro renewable generation. Logistic adoption occurs rapidly during the middle of the adoption cycle when the majority of consumers choose new technology deemed successful by early adopters. Without prudent planning, rapid adoption of PHEVs could add large new power demands without the long planning periods the electric power sector prefers.

Because baseload off-peak power may have an unfavorable GHG profile in many regions of the country, policies are necessary to match PHEV charging with low-carbon electricity if large GHG reductions with PHEVs are desired. PHEVs reduce GHGs compared to traditional hybrids when the life cycle GHG emissions from electricity are about 650-750 g/kWh or below. Electricity GHG performance standards that become more stringent over time is one method to move toward low-carbon generation, as are renewable portfolio standards. Still, the rapid PHEV adoption possible may present challenges for providing adequate low-carbon generation. While cumulative US installed wind power is currently about 18 GW, that full 18 GW of wind would be required to serve baseline PHEV adoption load in 2025, with 52 GW required just five years later in 2030. This highlights the need for integrated system capacity and transmission planning for low-carbon generation assets in the context of government PHEV support policies.

4) How did federal R&D, technical change, and public policies affect the installation of wind energy in the US from 1970-2006?

If PHEVs are to be powered with electricity generated from sources that do not involve the emission of carbon dioxide, many have argued that wind – that blows both night and day – is an obvious option. Even without considering the CO_2 emissions of fossil fired power plants, the cost of wind is now close to competitive (*4*). As wind assumes a larger role in the electricity supply, its intermittent nature will become a greater challenge (*5*). Advanced vehicle to grid services hold the potential to help ameliorate that problem (*6*), so PHEVs and wind power (and potentially other renewable technologies) could become coupled systems going forward.

Since the 1970s, real installed costs of wind power per kW have decreased by an order of magnitude, and installations have grown to more than 94,100 MW worldwide. Both the technology and performance of wind turbines have improved dramatically, resulting in larger sizes, greater capacity factors, and higher energy capture. By examining wind power's development and the various policy approaches undertaken, insight can be gained into the policies and actions that can encourage further low-carbon energy adoption.

Contrasting the US and Danish federal wind energy R&D programs, it is apparent that a successful supply-push policy must involve end-users of the technologies as primary stakeholders and also must encourage continuous feedback from market participants in order to amass knowledge stocks and benefit from incremental innovation.

Demand-pull mechanisms such as the production tax credit and financial incentives have only stimulated wider market participation when those incentives rendered the wind power investment marginally cost competitive in the generation market, as happened beginning in the late 1990s. Long-term contracts and sustained demand-pull mechanisms provide the certainty necessary for sustainable growth in emerging energy technologies. Today it is more evident than in work previously reported by Loiter and Norberg-Bohm (*7*) and others that a combination of supply-push R&D to enable basic technology advances and sustained demand-pull mechanisms to encourage market adoption are essential for increased adoption of emerging energy technologies.

The importance of inter-industry spillovers has become vastly more significant over the past several years as wider wind power adoption occurred, as discussed in Chapter 5. Spillover technology developments from other industries, such as power electronics, high performance polymers and AC motor control, possess the potential to address these types of critical technical barriers.

The electricity generation sector is becoming increasingly dependent on high power electronics, information technology, and data analysis. If exogenous emerging or existing technologies, at a lower cost and/or higher performance rating, would significantly increase the probability of wider low-carbon energy adoption, then policy should be designed to create inter-industry spillovers from R&D and manufacturing in these sectors. An integrated approach to low-carbon R&D can allocate scarce resources across shared technologies to increase the likelihood of success for individual technologies. For example, Curtright et al. found in their expert elicitation that solar photovoltaic (PV) panels were viewed as unlikely to achieve cost competitiveness in the next 40 years (*8*). They assumed that PV panel costs represented 50 percent of total costs, with the Balance of System (BOS) comprising the remainder. Hence, while continued and enhanced solar R&D in essential, focus on cost reductions of intermittent renewables such as solar PV and wind could also expand to investigating methods to reduce BOS and integration costs. Reducing integration costs would enhance the competitiveness of renewables across all intermittent technologies. Low-carbon energy policy should take a systems approach, leveraging investments and policies across interdependent industries to create feedback, innovation, and diffusion.

6.2 Discussion

The need for integrated climate policy, energy policy, sustainability, and urban mobility solutions will accelerate in the next two decades as concerns regarding greenhouse gas emissions and oil resources continue to be environmental and economic priorities. To assist in informing the discussions on climate policy and low-carbon energy R&D, this research and its methods will provide stakeholders in government and industry with plug-in hybrid and energy policy choices based on life cycle assessment, engineering economics, and systems analysis.

PHEVs represent a technological pathway to reduced oil dependence and lower GHG emissions in the transportation sector, while utilizing existing infrastructure systems. Whether or not it will result in the large GHG reductions necessary to mitigate climate change (*9, 10*) depends on policies and investments in the electricity sector. Because life cycle GHG emissions from PHEVs depend on the electricity source that is used to charge the battery (*11*), and power plants and their associated GHGs are long-lived (*12, 13*), decisions made regarding new electricity supplies within this decade will affect the potential of plug-ins to play a role in a low-carbon future in the coming decades.

Policymakers seeking to maximize PHEV subsidy effectiveness can base subsidies on the installed battery capacity, with an optimum range between a PHEV10 and a PHEV30. Policies to support PHEVs should aim to provide a bundle of value to PHEV consumers to compensate for the technology risk and premium, if widespread adoption is desired. Consumers respond more positively to immediate savings such as rebates or sales tax exemptions, rather than income tax credits received after filing taxes, even if the income tax credits are more generous than the sales tax exemptions (*14*). This suggests that consumers place a higher discount rate on hybrid vehicle incentives, and that effective PHEV subsidy policies should seek to provide immediate benefits via sales tax exemptions, registration exemptions, and potentially rebates to maximize the effectiveness of the subsidy per dollar of government tax expense or expenditure. Additional mechanisms, such as free public charging/parking, HOV lane access, V2G, vouchers for home electrical upgrades or for a portion of home electricity usage could provide alternatives or additions to federal and state tax incentives.

The uncertainty surrounding the duration and reauthorization of US demand-pull policies for low-carbon energy have resulted in a boom and bust cycle in the wind industry. In such an environment private firms are loathe to invest in long-term R&D for both products and processes if no signals exist that policies that create a market will be in effect two years hence. This strategic view undertaken by firms as a survival strategy stagnates cost advances in both technology design and manufacturing. Policies to promote PHEVs can take lessons learned from the successes and challenges of wind power's development to optimize low-carbon energy policy going forward.

6.3 Intended Research Contributions

This research seeks to fill a critical gap in the literature as we estimate life cycle GHG of PHEVs, quantifies the the economic decision spaces for widespread plug-in hybrid adoption, attempts to couple policies for low-carbon infrastructure and PHEV development, and then identifies policy actions to encourage innovation, investment, and adoption of low-carbon energy infrastructure. The thesis focuses solely on impacts from passenger vehicle motor fuels and will exclude impacts freight and other modes of travel. The methods and results of this work however, could potentially be applied to any mode that would substitute electricity for petroleum (e.g., electrification of freight rail lines, increased use electrified mass transit, or use of PHEV buses or delivery vehicles).

This thesis is divided into four chapters, each written as a stand-alone research paper. The findings of this research will be communicated via peer-reviewed academic journals, issue briefs to stakeholders, professional conferences and societies, and both the popular press and non-traditional electronic and social media.

6.4 Derivative Works

In addition to the research paper based on Chapter 2 (*11*) and the forthcoming papers from the other Chapters, the methods and tools developed through this research have also been used for three collaborative derivative research papers appearing in or submitted to peer-reviewed journals that do not appear in this thesis. Life cycle assessment examining energy use and GHG emissions was used in two other papers. In Jaramillo et al. (*15*), we examine the GHG and policy implications of using coal as a passenger transportation fuel, and life cycle impacts of coal to liquids, plug-in hybrids using coal-fired electricity, and fuel cell vehicles using hydrogen produced with coal. The Jaramillo et al. paper was initiated during the consideration of subsidization of coal-to-liquids projects by the US Congress in 2007, with preliminary results distributed to stakeholders in 2007. In Meisterling et al. (*16*), we compare life cycle GHGs and energy use from agriculture and product transport and identify relevant decisions for producers, wholesalers, and consumers to reduce impacts of conventional and organic wheat. The engineering economic analysis for plug-in hybrids has been employed in Shiau et al. (*17*), where we examine the impact of battery weight and distances between charging on the environmental, economic, and gasoline displacement benefits of plug-in hybrids.

6.5 Future Work

Climate policy in the US is beginning to gain momentum and it is likely that a framework for greenhouse gas emissions trading will emerge over the next several years. The dominant policy mechanism appears to be a cap-and-trade program for greenhouse gases, with programmatic details such as an economy-wide or sector specific approach, and methods for initial allocation of permits still being debated. A disconnect remains, both in the literature and public discourse, between climate economic policy and climate infrastructure policy. It may be there exists overconfidence in the ability to construct sufficient low-carbon electricity generation assets to considerably reduce the carbon intensity of US electricity by 2050, absent a surprise climate event that induces a state of urgency.

Achieving large GHG reductions from the electricity sector, and hence from plug-ins, will require considerable investment in low-carbon electricity infrastructure in the coming decades. Future work can take a systems approach to climate economic policies, climate infrastructure policies, and climate innovation policies to increase the likelihood of a low-carbon energy system in place under likely increasingly stringent carbon constraints.

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