Prospects for Plug-in Hybrid Electric Vehicles in the United States: A General Equilibrium Analysis

by

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Submitted to the Engineering Systems Division
and the Department of Civil and Environmental Engineering
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ABSTRACT

The plug-in hybrid electric vehicle (PHEV) could significantly contribute to reductions in carbon dioxide emissions from personal vehicle transportation in the United States over the next century, depending on the cost-competitiveness of the vehicle, the relative cost of refined fuels and electricity, and the existence of an economy-wide carbon emissions constraint. Using a computable general equilibrium model, I evaluated the potential for the PHEV to enter the U.S. personal vehicle market before 2100 and alter electricity output, refined oil consumption, carbon dioxide emissions, and the economic welfare losses associated with the imposition of a strict climate policy. The PHEV is defined by its ability to run on battery-stored electricity supplied from the grid as well as on refined fuel in an internal combustion engine. Sectors that produce PHEV transportation as well as other electric-drive vehicle technologies were added to the MIT Emissions Prediction and Policy Analysis (EPPA) Model as a perfect substitute for internal combustion engine (ICE)-only vehicles. Engineering cost estimates for the PHEV, as well as information about the pre-existing fleet, were used to specify PHEV sector input shares and substitution elasticities in the model.

Based on the model results, several conclusions emerged from this work. First, lower vehicle cost markups may hasten PHEV market entry, especially in the absence of a climate policy. Second, in the short term, the lower cost of electricity compared with refined fuels on a per mile basis is likely to favor adoption of vehicles with longer all-electric ranges. However, realizing the electricity advantage will depend on whether or not current battery cost and performance limitations can be overcome. Third, the availability of biofuels as a carbon neutral fuel substitute could delay PHEV market entry, especially when a climate policy is imposed. Fourth, large-scale adoption of the PHEV will increase electricity demand, reduce refined oil consumption, and could offset the economic welfare cost of pursuing a climate policy, especially if biofuels are not available. Fifth, realizing the maximum carbon emissions reduction potential of grid-charged electric-drive vehicles such as the PHEV will depend on concurrent reductions in power sector emissions.

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Jedem Anfang wohnt ein Zauber inne.
Herman Hesse

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I dedicate this thesis to my brother Paul T. Karplus, whose passion for well-designed and well-engineered cars has brought us closer as this work progressed. As this thesis draws two years of research to a close, I hope that its pages can begin to inform the efforts of the policy, business, and academic communities to reduce the environmental footprint of personal vehicle transportation in the United States.

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1. Introduction

The fleet of personal cars and trucks in the United States is responsible for a substantial and growing fraction of domestic energy use and greenhouse gas emissions. Proposed strategies to counter these trends include promoting cleaner fuel and vehicle propulsion technology, encouraging changes in driver behavior that promote efficiency and conservation, and reducing vehicle size and weight. The magnitude of the existing fleet, combined with upward trends in vehicle ownership and annual miles traveled, suggests that perhaps all three approaches—and more—will be needed (Cheah et al., 2007).

This work focuses on the potential of one novel vehicle technology, the plug-in hybrid electric vehicle (PHEV), to enter the U.S. vehicle market and change the energy use and environmental footprint of personal transportation. A PHEV is defined by its ability to run on both electricity and refined oil. This fuel flexibility is expected to be advantageous because reduced carbon primary energy sources could in theory be substituted for the carbon intensive processes used in electricity generation today. However, reliance on electricity is limited by the energy storage capacity and cost of the on-board battery. So far, no PHEV models are commercially available, and the vehicle cost and technical specifications remain undetermined. This thesis work thus focuses on two related questions central to the future prospects for the PHEV. First, under what cost and technology scenarios could the PHEV enter the U.S. market? Second, what impact would large-scale adoption have on U.S. energy use and carbon dioxide emissions?

To investigate these questions, I used a computable general equilibrium model of the world economy to investigate how several factors could affect the timing of PHEV market entry as well as its potential environmental and economic impact. These factors include attributes specific to the vehicle, such as incremental vehicle cost (or vehicle "markup") and battery all-electric range. I then use the model to ask how the availability of competing low carbon technologies could affect the timing of entry. These technologies include advanced lignocellulosic biofuels as a reduced carbon substitute for refined oil, and two additional electric-drive vehicle technologies, the conventional (non-plug-in) hybrid electric vehicle and the electric-only vehicle.

Based on this analysis, several conclusions emerge. First, the model results suggest that higher vehicle cost could delay PHEV market entry. The effect of the vehicle markup on market entry is especially pronounced in the absence of an economy-wide carbon constraint. Second, electricity is an important source of cost savings for the PHEV, particularly when a climate policy is imposed, due to the fuel flexibility of generation. Therefore, PHEV configurations that allow greater reliance on electricity relative to refined fuels are likely to be the most attractive, especially if refined oil prices continue to rise. However, the electricity advantage will depend on whether or not current battery cost and performance limitations can be overcome. Third, the availability of related low carbon technologies, such as biofuels, could reduce the attractiveness of the PHEV, especially when a strict carbon constraint is imposed. Fourth, large-scale adoption of the PHEV would increase electricity demand, but reduce refined oil consumption and could potentially offset the economic welfare cost of pursuing a climate policy. Fifth, realizing the maximum carbon reduction potential of grid-charged plug-in hybrid electric and all-electric vehicles will require corresponding reductions in power sector emissions. Otherwise, conventional hybrid vehicles (as well as other highly efficient internal combustion engine-based vehicles) are likely to achieve lower per mile emissions than the PHEV.

1.1 Motivation

If GM had kept up with technology like the computer industry has, we would all be driving $25 cars that got 1,000 MPG.

Bill Gates

Bill Gates' words fail to tell the whole story. Like personal computers, personal vehicles have evolved to provide drivers with more power, performance, and comfort, which have in turn offset gains in fuel economy that occurred over the same period (Heavenrich, 2006). Personal computers also did not have to contend initially with a large pre-existing capital stock, slow turnover rates, and high up-front cost, which is perhaps an order of magnitude higher for vehicles than for personal computers. Given these characteristics, it is perhaps unsurprising that the incumbent internal combustion engine (ICE) has remained the dominant propulsion technology in the light-duty vehicle fleet, with little to no net improvement in fuel economy over the past several decades. Looking to the future, concerns about reliability, cost, and ease of use may further prevent increases in the contribution of alternative vehicle technologies to new vehicle sales.

Continued reliance on the internal combustion engine, even with significant fuel economy improvements, is unlikely to be consistent with significant reductions in GHG emissions from the transportation sector, particularly if fleet growth trends and usage patterns remain unaltered (WBCSD, 2004). Changes in the energy and emissions intensity of conventional fuels production have further complicated efforts to reduce carbon emissions from internal combustion engine vehicles (here referred to as ICE-only vehicles). The share of refined fuels that originate from non-conventional hydrocarbon reserves is increasing, and with it the carbon intensity of extraction and refining activities. As an example, the oil sands in Alberta, Canada, are currently proving highly carbon intensive to extract and refine (NEB, 2006). In the future, carbon intensive oil shale and coal-to-liquids production could be increasingly important to the transportation fuels market. The trend towards a "heavier barrel" translates into an increase in well-to-tank emissions for ICE-only vehicles, which could offset any corresponding decrease in tank-to-wheels emissions due to, for instance, increases in the efficiency of fuel usage or decreases in vehicle-miles traveled. If the overall (well-to-wheels) emissions footprint from current ICE-only transportation technology (both vehicle and fuel) continues to expand, the attractiveness of low carbon vehicle and fuel alternatives will grow ever greater, especially if a national policy constraining carbon emissions is implemented.

The plug-in hybrid electric vehicle (PHEV) has recently been proposed as a low carbon alternative to the ICE-only vehicle that could enter the market within the next decade (Sanna, 2005). A PHEV is defined by its ability to run on grid-supplied electricity stored in an on-board battery over a fixed range, before switching to use gasoline or diesel in a downsized internal combustion engine. The term "hybrid" refers to the ability of the vehicle to use more than one fuel. The PHEV was designed to overcome the limited battery all-electric range and associated cost hurdles that have historically dampened the prospects for electric-only vehicles.

Beyond the PHEV and electric-only vehicles, a wide range of other low carbon transportation technologies are currently being considered. On the fuels side, biomass-based alternatives to refined fuels are already available on a limited scale. In the U.S., the dominant form is ethanol derived from corn, which is blended with gasoline. It is questionable whether or not corn-based ethanol could ever supply a large market economically without having an effect on food prices (Reilly & Paltsev, 2007). Ongoing research is aimed at developing advanced biofuel formulations derived from the lignocellulosic plant material. On the vehicles side, alternatives to the ICE-only vehicle include conventional (off-grid) hybrid electric vehicles, electric-only vehicles, natural gas vehicles, and hydrogen used in fuel cells or in direct combustion. Hydrogen transportation, particularly if powered by fuel cells (which are very costly at present), is not expected to be economically viable in the near term due to vehicle cost hurdles and fueling infrastructure requirements (NRC, 2004; Sandoval et al., 2007).

What part, if any, will the PHEV play in the future of U.S. transportation? Answers to this question are subject to many sources of uncertainty. First, we do not know which battery chemistry will prevail, or what all-electric range and fuel flexibility attributes drivers will prefer. Second, we have only rough estimates of what a PHEV will cost to manufacture at scale, and how that cost will vary with the features of the vehicle, such as battery all-electric range. Third, we do not know if the U.S. will adopt a policy that constrains total carbon emissions, nor do we know how existing and future policies aimed at reducing emissions from transportation alone may evolve and interact with any economy-wide carbon constraint. Finally, the development trajectories of alternative low carbon vehicle, fuel, and electricity generation technologies likely to affect the economic and environmental impact of the PHEV are difficult, if not impossible, to predict.

Understanding the potential impact of these sources of uncertainty on the future of the PHEV is important as a guide for investment in research and development (R&D) and commercialization for an as-yet pre-commercial technology. The results reported here may interest the leadership of energy companies, automotive manufacturers, and electric utilities; the engineers and scientists working on advanced vehicles, batteries, and fuels; policymakers at the federal, state, and municipal levels concerned with reducing emissions from transportation; and the average U.S. driver, as he or she contemplates an upcoming vehicle purchase. Beyond this broad range of stakeholders, this research is among the first attempts to represent advanced electric-drive vehicle technologies in a computable general equilibrium framework. The methods and results of this work further develop a tool that improves our ability to explore the interaction of environmental regulation, technological change, and market transformation in the household transportation sector.

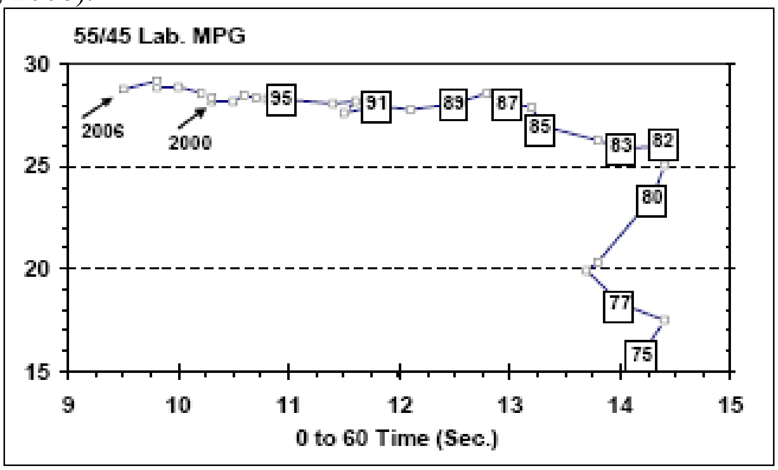
1.2 U.S. Transportation: Context

Understanding the magnitude of the challenge facing any new vehicle technology is essential to evaluating its prospects. Since the first cars took to the roads in the early part of the twentieth century, the U.S. vehicle fleet has relied overwhelmingly on the internal combustion engine to extract energy from petroleum-based fuels. For more than a century, the high energy density of these fuels—nearly 1,000 times the chemical energy storage density of the best batteries available today—has delivered mobility at a reasonable cost to consumers. The adoption of automobiles encouraged (and was in turn accelerated by) the development of an extensive network of roadways and fueling stations that serves as the backbone of personal vehicle transportation. Growing demand for refined fuels to power personal vehicles motivated the search for new petroleum reserves in distant corners of the world (Yergin, 1993). In 2003, petroleum-based fuels such as gasoline and diesel powered nearly 97 percent of all transportation in the United States (including aircraft, buses, and personal vehicles) (EPA, 2006).

Two trends illustrate the strong and growing importance of personal vehicles in the United States. First, the number of total vehicle-miles traveled (VMT) nationwide has increased nearly 34 percent between 1990 and 2004 (EPA, 2006). Second, demand for personal vehicles has also grown over the past several decades, with recent new vehicle purchases increasingly favoring light trucks such as sport-utility vehicles (SUVs) and pick-ups (Pickrell & Schimek, 1998). As an example, the market share of sport-utility vehicles (SUVs), classified as light trucks, has risen from one percent of new sales in 1976 to over 25 percent in 1990 (EPA, 2006). Automotive technology has improved in its basic efficiency of fuel conversion, but these gains have not translated into improvements in the fuel economy (in miles per gallon) realized on the road. However, the weight and performance of vehicles has improved, while fuel economy has stayed relatively constant over the past decade. This trend is illustrated by the relationship between acceleration time and laboratory-measured fuel economy since 1975, which is shown in Figure 1.1.

Today, the United States of America is home to the largest vehicle market in the world. Of the 204 million personal vehicles in the United States, the average U.S. household owns 1.9 vehicles, which is slightly more than the average number of drivers per household (BTS, 2001). U.S. drivers travel an average distance of 40 person-miles per day (or 32 vehicle-miles per day), much of which is due to daily commuting to and from work (BTS, 2001). Most of personal vehicles rely on the ICE, and burn gasoline fuel at an average rate of one gallon every 20 miles (BTS, 2001; EPA, 2007). At least half of this fuel originates outside U.S. borders and its combustion products—of which the greenhouse gas carbon dioxide accounts for a significant fraction—end up suspended in the atmosphere, where their growing concentrations are linked to global climate change (EIA, 2007; IPCC, 2007).

Fig. 1.1 Relationship between laboratory-measured fuel economy for a typical car (y-axis) versus 0 to 60 miles per hour acceleration time (x-axis). Boxed numbers indicate the year, starting with 1975 (Heavenrich, 2006).



1.3 U.S. Transportation and Climate Change

Current trends in personal transportation are inconsistent with ambitious targets to cut emissions of greenhouse gases in the United States. The Intergovernmental Panel on Climate Change has established that anthropogenic emissions of greenhouse gases (GHGs) are "very likely" contributing to increases in global mean temperatures (IPCC, 2007). One of these greenhouse gases, carbon dioxide, comprises 96 percent of GHG emissions from the transportation sector (EPA, 2006).[1] Although carbon dioxide has a small impact (in terms of its global warming potential) compared with other GHGs, the fact that it is emitted in great quantities makes it the single largest anthropogenic contributor to climate change (IPCC, 2007).

Transportation is presently the single largest source of carbon dioxide emissions in the U.S., contributing just over 30 percent of total economy-wide emissions. Of total transportation-related carbon dioxide emissions, the light-duty fleet contributes around 60 percent (NRC, 2008). The growth rate of emissions from the transportation sector averaged 24 percent between 1990

[1] Other contributors to GHG emissions from transportation include nitrous oxide (N_2O), methane (CH_4), and the hydrofluorocarbons (HFCs) found in refrigeration and air conditioning systems.

and 2003, the fastest growth of any end-use sector (EPA, 2006). Growth of GHG emissions in other sectors averaged 9.5 percent over the same period (Greene & Schafer, 2003). This growth in emissions is expected to continue with increases in the size of the light-duty fleet and annual vehicle-miles traveled (NRC, 2008). Thus personal vehicle transportation is an important target for emissions reductions, given its current and expected contribution.

Urban air pollution also provides impetus for developing and promoting low or zero emissions vehicles (see, for example, ARB, 2008). Tailpipes emit the air pollutants carbon monoxide, nitrogen oxides, and volatile organic compounds, which adversely affect public health and air quality. Along with volatile organic compounds, nitrogen oxides are responsible for the smog formation prevalent in many U.S. urban centers. Although large-scale adoption of the PHEV would reduce these tailpipe pollutants, adoption could potentially also result in increased emissions of sulfur dioxide and other pollutants associated with electric power generation. The impact of the PHEV on local air pollutant emissions will not be considered explicitly in this work, although many other studies have explored this connection (Duvall & Knipping, 2007b; Parks et al., 2007).

1.4 Policy Issues

Attempts to use public policy to encourage a fleet-wide shift to lower carbon intensity are hardly new in the United States. In the past, policy action at the national level has focused on increasing the average fuel economy of the vehicle fleet as a whole. Prior to 1990, the impacts of growing vehicle ownership and usage have been partially offset by improvements in fuel economy. The CAFÉ standards, implemented in 1975 in response to rising oil prices, called for the average fuel economy of the automotive fleet to rise from 18.0 to 27.5 miles per gallon between 1978 and 1985 (Greene & Schafer, 2003). The National Academy of Sciences estimated that, in the absence of these improvements, vehicle fuel consumption would require an additional 2.8 million barrels of crude oil per day (Greene & Schafer, 2003). However, light-duty trucks fall under a different (less stringent) standard. Due to increases in household light-duty truck (including SUV) purchases, the average fuel economy of the light-duty fleet as a whole has decreased since the CAFÉ standards were imposed. The CAFÉ standards were recently updated and call for an increase in the fleet average fuel economy for automobiles to 35 miles per gallon by 2020 (NRC, 2008).

The CAFÉ standards have not been the only policy effort aimed at lowering vehicle emissions. National government policy to promote lower carbon dioxide (and other pollutant) emissions has involved funding research and development for alternative fuel vehicles, but most programs have started too recently to gauge performance. Moreover, the effects of any breakthroughs on the composition of the fleet would not be seen for many years. At the state level, California's Zero Emission Vehicle regulation is perhaps the most prominent example of a policy aimed at promoting lower-emissions vehicles, with the primary goal of reducing urban air pollution. First adopted in 1990, the regulation required two percent of all new vehicles sold to be zero-emissions vehicles by 1998, and called for incremental increases in that percentage in subsequent years. The regulation has been revised over the years, and its final form has not yet been established (ARB, 2008).

In the future, the United States government may enact legislation that constrains greenhouse gas emissions relative to their expected business-as-usual growth path. Although the United States did not sign on to the Kyoto Protocol, the first global treaty aimed at reducing global emissions, consensus that the U.S. should act to reduce emissions has been growing ever since. Proposals thus far have primarily involved implementation of a cap-and-trade system, although taxes on carbon-equivalent emissions have also been proposed. Both systems would have the effect of making carbon-intensive economic activity more costly. As a result, significant adjustment in the way energy is produced and used would have to take place.

In addition to growing concern about climate change, a second goal of reducing gasoline consumption in U.S. transportation has been concern about dependence on foreign oil imports. Current upward trends in vehicle ownership and usage suggest that petroleum consumption in the transportation sector will increase from 13.7 million barrels per day in 2003 to 19.9 million barrels per day in 2020, accounting for 90 percent of the projected total increase in U.S. petroleum consumption over the same period (Greene & Schafer, 2003). Much of this expanded consumption would be expected to rely on supplies from the Middle East, Africa, and South America, much of which is under the jurisdiction of regimes thought to be unstable or unreliable. As a result, some U.S. policymakers have interpreted continued reliance on petroleum-based fuels to be a national security issue as much as an environmental problem.

1.5 Modeling Strategy and Contribution

Few methods are available to study systematically the impact of regulation, technological evolution, and market dynamics on the prospects for a pre-commercial technology. The choice of the general equilibrium methodology was based on its ability to represent the most important elements of the system within a single modeling framework. In the case of the PHEV, technology-specific elements included the vehicle (and battery) technology, the interface with the electric grid, upstream capacity for refining liquid fuels, and vehicle usage patterns. Since no historical information on the adoption of the PHEV is available, and experience with other electric-drive vehicles (such as the electric-only vehicle and conventional hybrid) is very limited, a scenario-based modeling approach that captured the relevant dimensions of the system seemed to be the most appropriate research approach.

In this work, I employed a computable general equilibrium model, the MIT Emissions Prediction and Policy Analysis (EPPA) model, which is developed specifically for the evaluation of the impact of environmental policies on the global energy system and broader economy throughout the twenty-first century. The framework is particularly appropriate for evaluating the impact of a technology like the PHEV, because it allows for simultaneous observation of the impact of powering transportation with both electricity and refined fuel, two sectors with previously quite distinct markets. Relative reliance on each of these inputs is in turn a function of vehicle battery all-electric range, which is specified in the model by fixing the fraction of miles that are driven on electricity versus on refined oil. Similarly, vehicle cost, alternative vehicle and emissions control technologies, and policy constraints can all be specified in the model. The effect of altering these sources of uncertainty is reflected in the impact of PHEV technology, both in terms of its timing of market entry and its effects on energy use and emissions as compared with the corresponding counterfactual scenarios. The details of the modeling strategy are included in Chapter 3.

This study builds on past work that evaluates the expected impact of the PHEV in the U.S. market. Previous studies of PHEV prospects have focused on the transportation sector (Kromer & Heywood, 2007), or coupled independent models of the fuel, vehicle, and electricity sectors in order to evaluate environmental outcomes of interest (for example, see Duvall & Knipping, 2007a). Although some degree of technical detail is sacrificed in the EPPA framework, the main technology-related drivers of cost are represented. The general equilibrium framework in particular has the advantage of capturing interactions among markets, including electricity, refined oil, and various alternative vehicle technologies, as they evolve over time, lending insight into the economic drivers of PHEV adoption in the presence and absence of a climate policy constraint. This work begins with a description of PHEV technology in the next chapter, which forms the basis for the model development and analysis that follows.

2. The Plug-in Hybrid Electric Vehicle: Technology and Economics

This chapter develops the technical foundation for the structure of a new PHEV sector in the EPPA model, which is then described in detail in Chapter 3. Section 2.1 summarizes the history of electric transportation and early barriers to its adoption. Section 2.2 provides an overview of the main sources of flexibility in PHEV system design, which in turn depends on advances in battery technology and other important PHEV components described in Section 2.3. In Section 2.4, the cost of PHEV vehicles is then compared against several alternative vehicle designs. Section 2.5 concludes by summarizing future directions for PHEV research, and how PHEV advances dovetail with broader trends in alternative vehicle development.

2.1 History of Electric-drive Vehicles

The concept of the plug-in hybrid grew out of longstanding efforts to develop all-electric vehicles and later, conventional (off-grid) hybrid vehicles that used a battery to assist the ICE, improving fuel economy. The idea to use electricity as a transportation fuel originated around the turn of the twentieth century. The first electric vehicles in the United States entered municipal transportation fleets with the growth of for-hire services such as the Electric Vehicle Company in New York City (Kirsch, 2000). The early failures of electric vehicles have been attributed to a combination of technological and institutional factors. On the technological side, the battery technology of the day could not compete with the internal combustion engine in terms of its range and convenience. The Electric Vehicle Association of America (created in 1909 by Boston Edison) encouraged local power suppliers to promote the adoption of electric vehicles but it was unable to establish a system that could compete effectively with the internal combustion engine (ICE) (Kirsch, 2000). By the start of World War I, the ICE had already gained a strong foothold in the U.S. market. For the rest of the century, hybrid (and plug-in) electric vehicles remained mostly relegated to niche markets or hobbyists' garages. Interest in electric vehicles once again surfaced in the 1970s, as California pushed for technological advances that would reduce the emissions responsible for smog formation and related health problems. However, these vehicles, which were only available for lease, were not adopted outside a relatively small number of customers willing to pay a premium for them.

Despite decades of research, battery technology still falls far short of achieving ranges for electric-only vehicles that are on par with ICE-only vehicles, providing impetus for the development vehicle designs that combined elements of both. Over the past several years, several types of off-grid hybrid vehicles have gained popularity against a backdrop of rising gas prices and growing interest in addressing environmental issues. These vehicles, referred to here as “conventional” hybrids or simply “hybrids,” use a small on-board battery and electric motor to reduce efficiency losses associated with braking and idling.[2] In parallel with the development of conventional hybrids, renewed interest in developing a rechargeable (plug-in) version of the hybrid vehicle surfaced. Over the past several years, the idea has attracted intense interest among U.S. government agencies seeking to promote both environmental and energy security goals, as well as electric utilities interested market expansion (NRC, 2005; Sanna, 2005). However, today, the only plug-in hybrids on the road are part of demonstration fleets, or retrofitted versions of conventional hybrids. Still, with gasoline prices rising in recent years, the technology has gained the renewed interest of automakers, with GM and Toyota publicly declaring their intentions to accelerate development of PHEV models over the next several years (Reed, 2008).

2.2 PHEV Architecture, Fuel Usage, and Driving Patterns

As mentioned, PHEV is capable of running on both refined fuels and electricity. It is an electric-drive vehicle (to the extent that it uses electricity via an electric motor to drive the wheels) as well as a hybrid vehicle (because it relies on two fuel sources, refined fuels and electricity).[3] Exactly how this fuel switching is accomplished depends on the vehicle architecture, on-board energy storage capacity, and driver usage patterns. Here, I outline the major sources of design and use flexibility embedded in the PHEV. A technical discussion of the components involved is saved for Section 2.3, although it should be noted that advances in the underlying technologies mostly determine the flexibility in the design choices described in the present section.

2.2.1 Series versus Parallel PHEV Architectures

One design choice the developer faces is whether to arrange the major components of a hybrid vehicle drive train in series, in parallel, or in a combination of the two configurations. In

[2] These vehicles are not equipped with batteries large enough to merit recharging from the electric grid, but some aftermarket retrofits are available to provide plug-in recharging capability.
[3] For PHEV configurations in which the ICE drives the wheels directly, such as the parallel hybrid, the PHEV is not technically an electric-drive vehicle.

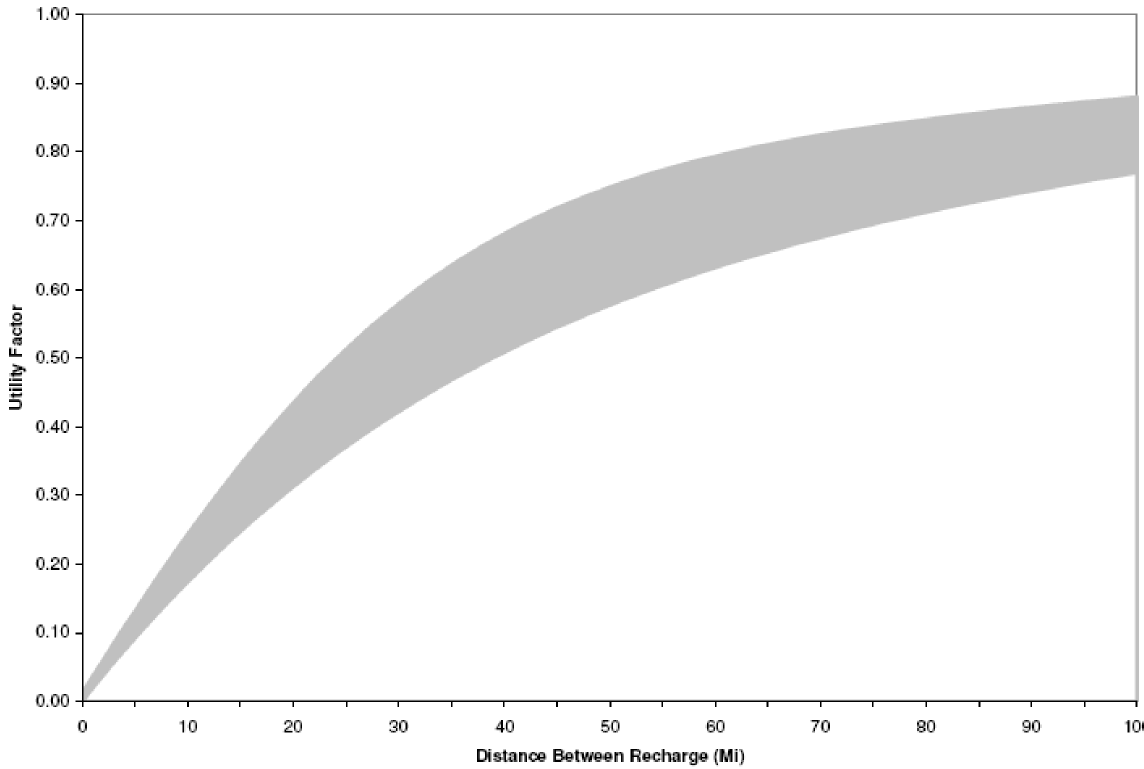
the parallel design, the engine and electric motor connect separately to the transmission, allowing each to drive the wheels directly. An advanced electronic control strategy allows the vehicle to vary how much power it draws from each source, possibly turning off the engine entirely or using it to charge the battery as needed. In the series design, by contrast, the electric motor drives the wheels at all times. The ICE is used to drive a generator that charges the battery. This configuration is typical of a battery-electric vehicle (BEV). One advantage of the series configuration is that the ICE can be run at its most efficient operating point for a much greater percentage of the time compared with the ICE-only or parallel hybrid vehicle. Series hybrids allow the most efficiency gain during stop-and-go driving but realize considerably less benefit during long-distance travel at constant speed (Friedman, 2003).

Combined hybrid designs incorporate features from both series and parallel hybrid configurations. A so-called “power-split” is used to create redundant mechanical and electrical paths for power to travel from the engine to the wheels. For instance, the Toyota Hybrid System (Hybrid Synergy Drive) uses a single power split to allow use of the optimal power path over variable driving speeds (Friedman, 2003).

2.2.2 Electricity versus Gasoline: The Utility Factor

Efforts to quantify the fuel requirements and efficiency of the PHEV have relied on a convention called the utility factor (UF), defined by the Society of Automotive Engineers (SAE) J1711 Recommended Practice (Gonder & Simpson, 1999). The UF is defined as the fraction of vehicle miles traveled on electricity, while the fraction powered by refined fuels can be expressed as 1 – UF. The value of the UF is a function of several parameters. First, the all-electric range (or AER) of the battery dictates how far a vehicle can be driven on a single charge. A PHEV with a certain all electric range is typically denoted as PHEVX, where X is equal to the vehicle’s all-electric range. Thus for a given set of driving patterns, the UF is determined solely by the all-electric range (AER) of the vehicle. Figure 2.1 shows the mapping between AER and UF in the U.S., assuming the individual driving distances observed in the 2001 National Household Transportation Survey.

Fig. 2.1 Correspondence between all-electric range and utility factor, assuming driving habits observed in the National Household Transportation Survey, 2001 (Kromer & Heywood, 2007).

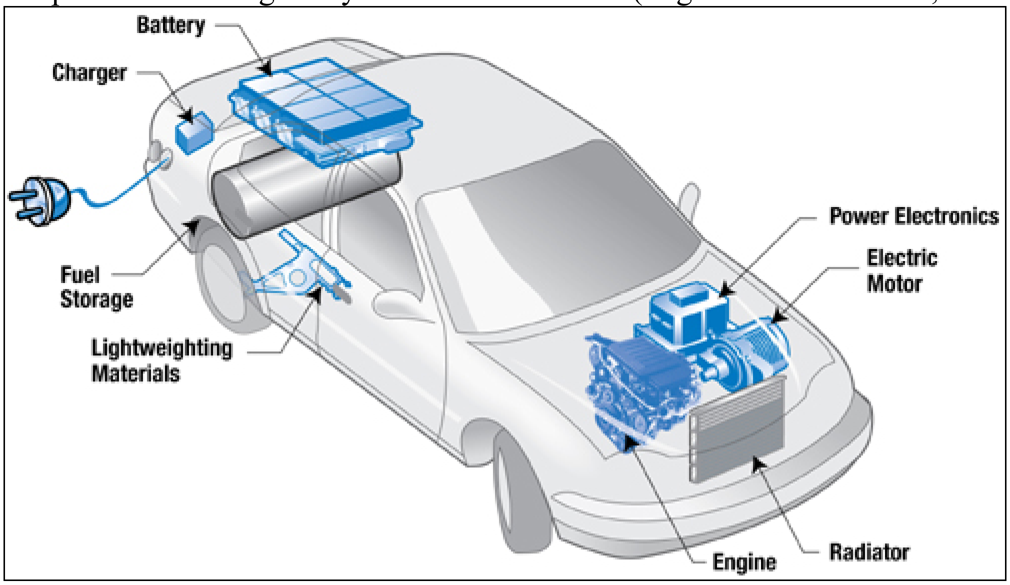


Due to the electricity cost advantage, the price of short trips relative to long trips decreases. As a result, drivers may choose to replace long trips by short trips, for instance, by moving closer to their workplace or reducing long-distance travel. As a result, the UF will also change, even if all-electric range does not increase. However, I was unable to find any quantitative evidence of how this trade-off might occur in practice.

2.3 PHEV Components

Underlying the vehicle design and usage choices mentioned above are the elements of the propulsion system responsible for the fuel flexibility of the PHEV. The drive train of the PHEV consists of a fuel tank, a small internal combustion engine, a battery, an electric motor, and if needed, a transmission (see Figure 2.2). Battery technology will be the main the focus of this section as it is the primary determinant of cost and all-electric range. As mentioned previously, I will assume that a PHEV operates first in all-electric mode, before switching to rely on the internal combustion engine.[4]

Fig. 2.2 Components of a Plug-in Hybrid Electric Vehicle (Argonne National Lab, 2007).



2.3.1 Advanced Battery Technology for the PHEV

The battery has been widely cited as the greatest barrier to development of a commercially-viable PHEV. So far, batteries with energy density and specific power adequate to propel vehicles more than a few tens of miles have proven prohibitively costly, adding a significant premium to the up-front vehicle cost (see Section 2.4). The challenge of designing batteries for electric vehicles is to increase the energy density (the energy that can be supplied by the battery over a fixed period) without compromising specific power (directly related to vehicle acceleration), cycle life, or safety of use. A number of different battery chemistries have been explored in an ongoing search for the right balance of these attributes. A brief overview of this research is presented here.

The first off-the-shelf PHEV models on the market are expected to use lithium ion based battery chemistries. Other available chemistries include the nickel metal hydride (used in the first Toyota Pruis models) or lead acid-based technology (used in the GM EV1). Lithium ion batteries offer important advantages over other alternatives. Lithium has the greatest propensity to give up

[4] An alternative PHEV configuration in which electricity is used to supplement the ICE by operating the battery operating in charge-depleting mode has also been considered as an alternative to all-electric operation, which is assumed here. The cited advantages of blended mode are that neither battery nor ICE must meet peak power requirements alone, allowing for downsizing of each (Kromer & Heywood, 2007). However, the need for intermittent engine startups carries fuel economy penalties.

its electrons (with standard electrochemical potential of -3.045V), making it well suited for battery applications. As a result, lithium batteries offer the highest energy density and therefore are very light in weight compared to other candidate chemistries, which has contributed to rapid adoption in the electronics industry (Tarascon & Armand, 2001). For vehicle applications, lithium ion chemistries have the greatest potential for reducing the battery's contribution to weight and volume of the vehicle. Additional concerns about the viability of lithium-ion chemistry for use in the PHEV include concerns about safety, durability, and cost. The recent recall of lithium ion laptop batteries found to be prone to overheating and spontaneous combustion has prompted research into the substitution of other, more stable materials in the electrodes that could rectify this problem. Durability is also a top concern, given that in a vehicle context the battery will have to endure many deep discharge cycles over its lifetime, while still maintaining the ability to assist the engine in a near charge-depleted state, allowing the vehicle to achieve the fuel economy of a conventional hybrid vehicle. At present, the NiMH batteries are less expensive and a more "proven" technology (Duvall, 2004). However, many scientists are optimistic that technological and cost barriers to the development of lithium ion batteries can be overcome, possibly making it the most promising candidate at present for PHEV applications in the long term (Kromer & Heywood, 2007; Simpson, 2006).

2.3.2 Internal Combustion Engine

The internal combustion engine design used in a PHEV is also an important consideration. Due to the battery's ability to perform an electric-assist function during ICE operation, the engine can be downsized compared with an ICE-only vehicle. The modeling work in later chapters assumes that the PHEV is able to achieve fuel economy on par with a conventional hybrid vehicle once the battery has been depleted. In today's conventional hybrids, engine power ranges from a maximum of 50 kW (Prius) up to 160kW in a Lexus LLS 600h, and electric traction motors provide about half the maximum power of the propulsion system (FCVT, 2007).

2.3.3 Other Components

Advanced electronics components are also required to coordinate power management between the ICE and the battery, and more research is required to identify an option that maintains vehicle cost-competitiveness without compromising performance. Current designs under consideration include using electronics controls similar to those in the Prius, but with the ability to mediate between charge-depleting and charge-sustaining modes. Improvements in capacitors, heat management strategies, and component configurations, as well as development of new materials for the electronics components, are also listed as targets of ongoing PHEV research (FCVT, 2007). If charging at home is to be the primary method of refueling, a standardized interface with the household electrical system will need to be developed. Advances in PHEV-sized batteries and associated technologies that enable recharging from the electric grid may improve the efficiency of energy transfer and shorten recharging times, improving the convenience of PHEV use.

2.4 The Economics of the PHEV

Past studies have taken a variety of approaches to estimating the vehicle and fuel costs of the PHEV. Some studies are based on a simple inventory and summation of up-front and recurring costs to estimate PHEV life cycle costs (Anderman et al., 2000; EPRI, 2001; Duvall, 2004), while other studies have assumed advances in battery technology and production at scale to estimate how costs will have evolved by some specified future point (Kromer & Heywood, 2007; Simpson, 2006). Here I present a brief summary of the literature estimates for PHEV vehicle and fuel costs.

In all cases, the battery is the primary driver of the incremental PHEV vehicle cost, compared with the ICE-only vehicle. Several factors are expected to affect the cost of batteries for electric-drive vehicles. First, major breakthroughs in battery technology are needed to deliver required performance in terms of specific energy, specific power, durability, and safety in a single low-cost vehicle battery pack. Second, manufacturing at scale is likely to result in cost reductions, but the extent of these reductions will depend on production volume. The extent of cost reductions possible at scale has been estimated for NiMH batteries in the 2000 BTAP Report (Anderman et al., 2000). Analysts have expressed confidence that similar cost reductions with scale will occur for lithium ion battery chemistries (Duvall, 2004; Simpson et al., 2006). Third, battery production costs are sensitive to the prices of constituent commodity metals, which introduce additional uncertainty into longer term projections (Gaines & Cuernca, 2000).

Translating battery markups into vehicle markups involves adding the cost of safety systems and other required components. Two studies offer detailed estimates of the cost of a PHEV, based on engineering cost information, which are summarized in Table 2.1. One study, by Simpson (2006) for the National Renewable Energy Laboratory, takes outputs from a series of engineering models that size vehicle components accordingly and uses them as inputs to an overall vehicle cost model to estimate the retail price of the vehicle based on the underlying component costs. The main discrepancy between the near and long term projections in the Simpson (2006) study are that the lithium ion battery replaces the nickel metal hydride battery in the long term scenario. Another study by Graham (2001) similarly employed a combination of vehicle engineering cost models to estimate the retail price of different HEV and PHEV configurations. The Simpson (2006) estimates of long term PHEV20 and PHEV60 vehicle costs are consistently higher than the upper bound estimates in the Graham (2001) study by approximately $2,500 to $3,500. The discrepancy in the estimates appears to be due primarily to differences in assumptions about battery technology requirements. Overall, these estimates suggest that plug-in hybrid vehicles are likely to be more expensive than conventional vehicles by 22 to 66 percent for a plug-in hybrid vehicle with a 20-mile AER, whereas the markup could be as high as 41 to 114 percent for a PHEV60.

Table 2.1 Estimates of plug-in hybrid vehicle retail costs from Simpson (2006) and Graham (2001).

Study and Vehicle Type	Near Term	Long Term
Simpson, 2006		
ICE-only	$23,392	$23,392
Conventional Hybrid	+ $5,381	+ $3,266
PHEV20	+ $15,543	+ $8,436
PHEV60	+ $26,792	+ $13,289
Graham, 2001		
ICE-only	$18,000	
Conventional Hybrid	+ $2,500-$4,000	
PHEV20	+ $4,000-$6,000	
PHEV60	+ $7,400-$10,000	

ICE-only – internal combustion engine vehicle
PHEVX – plug-in hybrid electric vehicle with all-electric range equal to X

Fuel costs for the PHEV can be calculated directly using the prevailing prices of refined oil and electricity, weighted to account for the utility factor (described above), which reflects the fraction of total miles traveled on each fuel. Included in Table 2.2 is a sample comparison of the ICE-only, conventional hybrid, and PHEV30 vehicles based on long term estimates from the

Simpson (2006) study. Assumptions about fuel costs and annual miles traveled are based on recent trends, but could be easily updated to reflect ongoing fluctuations. From Table 2.2, it can be seen that despite the higher up-front cost, improved fuel economy translates into savings within the lifetime of the vehicle due to the avoided high fuel cost. However, it should be noted that the recurring savings are not discounted. The cost advantage due to fuel savings may not be fully considered by consumers at the time of vehicle purchase.

Table 2.2 Example of costs for ICE-only, conventional hybrid, and plug-in hybrid electric vehicles. The MSRP is the manufacturer's suggested retail price.

Cost estimates by type of mid-size sedan	ICE-only	Hybrid	PHEV, 30-mile range
Vehicle cost (MSRP)*	$20,000	+$3,000	+$10,000
All-electric range	N/A	N/A	30 miles
Miles per gallon (ICE)	20mpg*	43mpg*	43mpg*
Annual amount of fuel (gal, kWh, kg per year)	543 gal	340 gal	136 gal 1,200 kWh
Annual cost of fuel**	$1,618	$1,013	$501
Payback period (undiscounted)	N/A	~5 years	~9 years

*Estimated from CV, HEV, and PHEV long term scenarios in Simpson, 2006. For the PHEV, 60% of miles driven are assumed to be supplied by electricity, while the remaining 40% are supplied by gasoline. Total annual miles traveled are assumed to be 13,000**.**

**Assumes January 2008 price of gasoline of $2.98 per gallon (EIA, 2008) and wholesale price of electricity of $0.08/kWh.

The above comparison also illustrates how the PHEV derives its cost advantage from the ability to use electricity, combined with the fuel economy benefits of the conventional hybrid technology. The evolution of the relative prices of electricity and gasoline, as well as the emergence of other alternative vehicle designs, will influence the magnitude of the trade-off the consumer faces between up-front vehicle costs and recurring savings. Our modeling strategy is designed to test the sensitivity of the vehicle market to changes in the cost of PHEV ownership and operation, and Table 2.2 captures many of the key parameters that determine its cost competitiveness.

2.5 Environmental Impact of the PHEV

The environmental impact of a PHEV stems primarily from two sources: refined fuel combustion in the on-board ICE and the generation of electricity from various primary energy sources. In the case of refined fuels, emissions occur both in the upstream process of extracting, refining, and transporting the fuel (well-to-tank) and combustion emissions released from the tailpipe (tank-to-wheels). It is important to consider each of these sources explicitly when estimating energy use and emissions due to the miles driven using the internal combustion engine. Since the per-barrel emissions associated with extraction and production of refined oil are increasing, even limited usage of the internal combustion engine in a PHEV could potentially have a sizable emissions footprint.

Emissions associated with plug-in hybrid vehicle electricity use must be traced back to the fuel sources used to generate grid-supplied electricity. When the vehicle is running in all-electric mode, there are no tailpipe emissions. However, several studies have noted the importance of examining how the output of the electricity sector changes with the addition of a plug-in hybrid electric vehicle fleet. The estimates of well-to-wheels emissions on a per mile basis for various vehicle technologies assuming different sources of primary electricity generation have been summarized in Table 2.3 below (Duvall & Knipping, 2007a; Parks et al., 2007; Kromer & Heywood, 2007).

Table 2.3 Summary of several studies that have compared PHEV emissions under different electricity generation assumptions with the ICE-only and conventional hybrid vehicle.
a) Comparison of carbon dioxide equivalent GHG emissions on a per mile basis.
Electric Power Research Institute (Year 2010)

	ICE-only	Hybrid	PHEV – Old Coal*	PHEV – New Coal*	PHEV – Nuclear*	PHEV – Renewables*
Duvall & Knipping, 2007a.	450 g	295 g	325 g	305 g	150 g	150 g

*Emissions for travel on both electricity and refined fuels. Emissions from refining and combustion of gasoline, as well as electricity generation, were included.

b) Carbon dioxide emissions only on a per mile basis.
National Renewable Energy Laboratory

	ICE-only	Hybrid	PHEV20 – Off-peak charging	PHEV20 – Continuous charging
Parks et al., 2007.	410 g	299 g	247 g	221 g

*Emissions from refining and combustion of gasoline, as well as electricity generation, were included. Off-peak charging refers to vehicle charging between 10 p.m. and early a.m., while continuous charging refers to allowing vehicle charging at any time. Units were converted from short tons CO_2 released annually per vehicle, based on 13,900 miles traveled per year.

c) GHG emissions expressed in grams of carbon dioxide equivalent on a per mile basis.

MIT Sloan Automotive Laboratory

	ICE-only (present)	Hybrid	PHEV30	Electric-only
Kromer & Heywood, 2007.	403 g	140 g	138 g	185 g

* Emissions from refining and combustion of gasoline, as well as electricity generation, were included. Units were converted from grams of CO_2 per kilometer to grams per mile.

Several observations about the projections made here are worth noting. First of all, there is some variability in the estimate of the per mile emissions from an ICE-only vehicle. Although assumptions about vehicle fuel economy, size, and weight class were not often stated, discrepancies among them may be at least partially responsible for differences in the stated emissions estimates. It is perhaps more useful to compare estimates made by the same study, rather than try to draw comparisons among them. However, even in terms of the relative emissions of the different technologies, the studies are not always consistent. For example, conventional hybrid vehicle emissions were approximately identical to PHEV emissions in the Kromer and Heywood (2007) study. In the Duvall and Knipping (2007) study, the conventional hybrid showed lower emissions only compared to the PHEV fueled with coal-fired electric power, while other sources of electricity gave a more favorable impression of the PHEV. This discrepancy highlights a need for transparent estimates differentiated by region and time of day of current and projected per mile emissions for the PHEV. Estimates of PHEV emissions based on the average generation mix assumed in the EPPA model, as well as coal-fired electric power, are presented in Chapter 5.

2.6 Trends in Electric-drive Vehicle Technology Development

Over the past few years, several major U.S. automotive companies and a few entrepreneurial developers have announced plans to develop PHEV models. Despite this flurry of recent activity, the future of electric vehicle technology faces many unknowns. The main barriers to increasing the electric-only range and reducing cost at present include limitations of the prevailing battery chemistries. Overcoming these barriers is likely to require further breakthroughs in materials research. In particular, reducing vehicle weight could significantly improve the range of a PHEV or electric-only vehicle. However, the limitations of electricity since it was first used to power transportation have proven difficult to overcome thus far, and the range of hybrid electric vehicles (both conventional and plug-in models) that are now becoming available are in part the result of a search for interim or second-best solutions. In comparing the potential technological alternatives, it is important to consider the desirability of each from both a cost and emissions standpoint, and the extent to which these criteria produce a consistent ranking of the favorability of possible vehicle configurations.

3. Representing Plug-in Hybrid Electric Vehicle Transportation in the EPPA Model

In order to observe the timing of entry and potential impact of a plug-in hybrid electric vehicle, a new sector representing PHEV transportation was introduced into the MIT Emissions Prediction and Policy Analysis (EPPA) model. This chapter first provides background on the model itself. It then describes how information from the literature reviewed in Chapter 2 was used to implement the PHEV and related electric-drive vehicle sectors in the model. Although the focus on this thesis is on the United States, a similar approach could be used to evaluate the impact of the technology in other regions of the world as well.

3.1 Background on the MIT EPPA Model

An overview of our modeling strategy provides the background for a more detailed technical description of the model and newly added PHEV sector later in this chapter. Although many PHEV designs have been put forward and several prototypes built, significant technical and cost barriers remain to the manufacture and adoption of the PHEV on a large scale. The first objective is to understand to what extent these barriers would have to change in order for the technology to become cost-competitive with prevailing ICE-only vehicles. Second, I investigate how an economically viable PHEV would affect refined oil consumption, carbon dioxide (CO_2) emissions, and the costs of meeting aggressive climate policy targets over the next century. By introducing the PHEV as an alternative to ICE-only transportation within a modeling framework that includes the electricity, transportation, and refining (fuel) sectors, I simulate how the PHEV might fare against a backdrop of endogenously changing technologies as well as fuel and electricity prices.

As part of the market entry analysis, I further develop two additional sectors that compete with the PHEV, a conventional hybrid vehicle and an electric-only vehicle, both of which are based on the structure of the original PHEV sector. In the model, climate policies, such as a tax on carbon equivalent emissions or a cap-and-trade system, can be selectively imposed on one or several regions in order to examine the effects of an emissions constraint on the resulting equilibrium allocation of goods and services in the global economy. The imposition of a policy constraint results in a price for CO_2 that is reflected in the cost of carbon-intensive fuels. It also affects the cost of final goods where CO_2 was emitted in the production process. By pricing carbon-intensive activities, a climate policy could thus change the attractiveness of otherwise uncompetitive technologies if they offer significant emissions reductions, compared with their incumbent counterparts.

Table 3.1 Sectors and regions in the EPPA model.

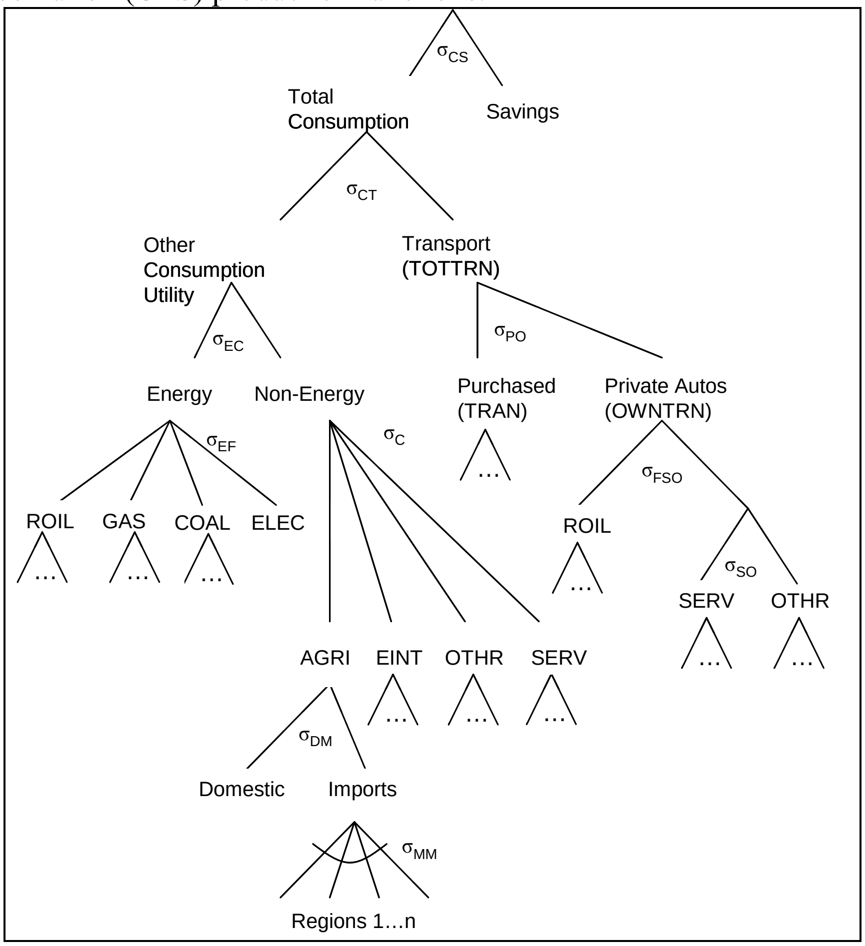
Sectors:	***Regions:***
Non-Energy	***Developed***
Agriculture	USA
Services	Canada
Energy-Intensive Products	Japan
Other Industries Products	European Union+
Industrial Transportation	Australia & New Zealand
Household Transportation: Internal Combustion Vehicles	Former Soviet Union
Household Transportation: Plug-in Hybrid Electric Vehicles	Eastern Europe
Household Transportation: Conventional Hybrid Vehicles*	
Household Transportation: Electric-only Vehicles*	
Energy	***Developing***
Coal	India
Crude Oil	China
Refined Oil	Indonesia
Natural Gas	East Asia
Electric: Fossil	Mexico
Electric: Hydro	Central & South America
Electric: Nuclear	Middle East
Electric: Solar and Wind	Africa
Electric: Biomass	Rest of World
Electric: Natural Gas Combined Cycle	
Electric: Natural Gas Combined Cycle with CO2 Capture and Storage	
Electric: Integrated Coal Gasification with CO2 Capture and Storage	
Synthetic Gas from Coal	
Hydrogen from Coal	
Hydrogen from Gas	
Oil from Shale	
Liquid Fuel from Biomass	

Note: Agriculture, services, energy-intensive products, other-industries products, coal, crude oil, refined oil, and natural gas sectors are aggregated from GTAP data; industrial transportation and household transportation sectors are disaggregated as documented in Paltsev et al. (2004); hydropower, nuclear power and fossil-fuel electricity are disaggregated from the electricity sector (ELY) of the GTAP dataset; electric-drive vehicles, solar and wind power, biomass electricity, natural gas combined cycle, natural gas combined cycle with CO2 capture and storage, integrated coal gasification with CO2 capture and storage, synthetic gas from coal, hydrogen from gas, hydrogen from coal, oil from shale, and liquid fuel from biomass sectors are advanced technology sectors that do not exist explicitly in the GTAP dataset; advanced technology sectors are modeled as described in Paltsev *et al*. (2005); specific detail on regional grouping is provided in Paltsev *et al.* (2005).
*Included in only in selected model runs.

The EPPA model is a recursive-dynamic general equilibrium model of the world economy developed by the MIT Joint Program on the Science and Policy of Global Change (Paltsev et al., 2005). The EPPA model is built on the GTAP dataset (Hertel, 1997; Dimaranan and McDougall, 2002), which accommodates a consistent representation of energy markets in physical units as well as detailed data on regional production, consumption, and bilateral trade flows. Besides the GTAP dataset, EPPA uses additional data for greenhouse gases (carbon dioxide, CO2; methane, CH4; nitrous oxide, N2O; hydrofluorocarbons, HFCs; perfluorocarbons, PFCs; and sulphur hexafluoride, SF6) and air pollutants (sulphur dioxide, SO2; nitrogen oxides, NOx; black carbon, BC; organic carbon, OC; ammonia, NH3; carbon monoxide, CO; and non-methane volatile organic compounds, VOC) emissions based on United States Environmental Protection Agency inventory data. For use in EPPA, the GTAP dataset is aggregated into 16 regions and 24 sectors with several advanced technology sectors that are not explicitly represented in the GTAP data (see Table 3.1).

The model is calibrated based upon data organized into social accounting matrices (SAM) that include quantities demanded and trade flows in a base year denominated in both physical and value terms. A SAM quantifies the inputs and outputs of each sector, which allow for the calculation of input shares, or the fraction of total sector expenditures represented by each input. Much of the sector detail in the EPPA model is focused on providing a more accurate representation of energy production and use as it may change over time or under policies that would limit greenhouse gas emissions. The base year of the EPPA model is 1997. From 2000 the model solves recursively at five-year intervals. Sectors are modeled using nested constant elasticity of substitution (CES) production functions (with Cobb-Douglass or Leontief forms). The consumer's production function is shown in Figure 3.1. The degree to which one input can be substituted for another in response to changes in their relative prices in the model is specified by an elasticity of substitution (Paltsev et al., 2005). The model is solved in the Mathematical Programming System for General Equilibrium (MPSGE) language as a mixed complementarity problem (Mathiesen, 1985; Rutherford, 1995). The resulting equilibrium in each period must satisfy three inequalities, the zero profit, market clearance, and income balance conditions (for more information, see Paltsev et al., 2005).

Fig. 3.1 The structure of the MIT EPPA model is comprised of sectors described by constant elasticity of substitution (CES) production functions.



In the model, technological change can influence the energy and emissions intensity of the economy, and is incorporated into the structure of the model in three main respects (Paltsev et al., 2005):

- Exogenous increases in the supplies of labor and natural resources.
- A decrease in energy use per unit output (called the Autonomous Energy Efficiency Improvement or AEEI).
- "Backstop" technologies that are currently uneconomic but may prove competitive at some future time if prevailing vehicle technologies grow too costly. These technologies become available in specified future periods.

The first two representations include general trends based on improvements in existing technology and resource use efficiency. Backstop technologies embody tangible technological options that are either available today or expected to become available in the future, but are currently not cost competitive. The PHEV falls into this category, as do both conventional hybrid and electric-only vehicles, which are added in several scenarios to compete with the PHEV. The conventional hybrid sector uses refined fuel at roughly double the fuel economy (requires half of the refined fuel input) of an ICE-only vehicle, while the electric-only vehicle relies entirely on grid-supplied electricity. All three technologies—the PHEV, conventional hybrid, and electric-only vehicles—are assumed to be available starting in the year 2010.

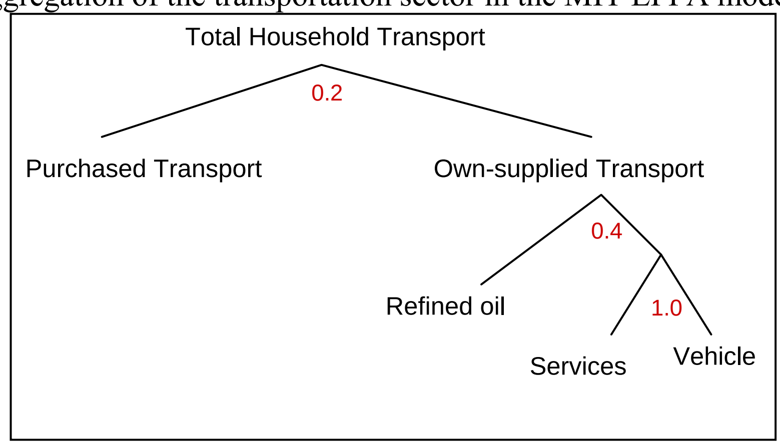
Two additional backstop technologies (already implemented in the model) that will be used in this analysis include advanced lignocellulosic biofuels and carbon capture and storage. Advanced lignocellulosic biofuels (referred to here simply as biofuels) provide a low carbon substitute for refined oil beginning in mid-century. In the version of the model used in this analysis, land availability for biofuel crops is constrained by land prices, which rise as economic activity and the demand for biofuels increases. In reality, additional constraints, such as conservation mandates, may limit the expansion of cropland. In that case, the substitution potential of biofuels may be overestimated in this analysis. Carbon capture and storage (CCS), which removes carbon dioxide from the emissions stream of power plants, is available starting in 2020 in the model. CCS initially captures 90 percent of emissions from power plants built or retrofitted with CCS capability, and this percentage captured is allowed to grow as the carbon price increases. Under a carbon constraint, the availability of CCS is expected to favor the PHEV because a decrease in electricity sector emissions translates directly into a reduction in the per mile CO_2 emissions of the PHEV. However, implementing CCS technology is costly, and therefore the carbon price must be high enough to make investment in carbon control technology economically viable. This technology only becomes available when an economy-wide constraint on carbon emissions is imposed.

The EPPA model allows for the imposition of economy-wide emissions constraints at varying levels of stringency. In this analysis, I explore the effects of imposing a policy that constrain carbon emissions in the United States only. The constraint caps U.S. emissions at levels consistent with a global target of stabilizing atmospheric concentrations at 450 parts per million (denoted 450ppm Policy Case) (for more information on the 450ppm emissions trajectory assumed for the U.S., see CCSP, 2007). The analysis included here assumes the more stringent (450ppm) emissions constraint. The policy considered is imposed as a cap on emissions in the U.S. only; trading of emissions permits with regions outside of the U.S. does not occur because no cap is assumed in these regions.

3.2 The Household Transport Sector in the EPPA Model

The underlying base year data used in the EPPA model is derived from the GTAP data set, which does not disaggregate household transportation from total household consumption. Previous work in the Joint Program augmented the GTAP data to create a household transportation sector, which supplied the transportation needs of individual households (Paltsev et al., 2005). This sector is comprised of inputs from purchased transport and household-owned automobiles (hereafter referred to as own-supplied transport). The nested structure of the CES production function for this sector is shown in Figure 3.2.

Fig. 3.2 The disaggregation of the transportation sector in the MIT EPPA model.



The low elasticity of substitution (0.2) between the purchased and own-supplied transportation alternatives suggests that drivers are reluctant to shift toward purchased transportation (initially a small share of total household transport) in response to relative increases in the cost of own-supplied transportation. Refined oil, services (including operations and maintenance costs), and the vehicle itself comprise the inputs to the household transport sector. The elasticity of substitution between refined oil and the vehicle-services branch indicates a limited ability to save fuel by spending more on maintenance or purchasing a vehicle with better fuel economy. This specification is based on econometric estimates as described in Paltsev et al. (2004). The trade-off between vehicles and services is more elastic, suggesting that one could reduce recurring service costs by purchasing a more expensive, higher quality vehicle.

3.3 Implementing a PHEV Sector in the MIT EPPA Model

The goal of the modeling work was to implement a vehicle technology in the own-supplied transport sector that would use both refined oil and grid-supplied electricity, and compete directly with ICE-only transportation. The structure of the new PHEV sector is shown in Figure 3.4, and is based on the original ICE-only vehicle sector. Both the PHEV and ICE-only vehicle sectors are specified as perfect substitutes (with infinite elasticity of substitution), which forces the two technologies to compete on a pure cost basis. Once the total cost of PHEV transportation drops below the cost of ICE-only transportation, the PHEV enters the market.

3.3.1 Defining Input Shares to the PHEV Sector

The inputs to the PHEV sector include electricity and refined oil as energy inputs, as well as services, the vehicle itself, and a fixed factor. In the model, each of these inputs is defined by its expenditure share, which is determined by its fraction of the total cost of producing a particular good or service (in this case, it is household transportation by PHEV). The calculation of the share of each input to PHEV transportation was based on similar calculations for the pre-existing disaggregated household transportation sector (ICE-only vehicles). I began by identifying the values of ICE-only transportation inputs for a single year, 1997 (which are based on a disaggregation of the underlying GTAP dataset as mentioned above).[5] These values are shown in Table 3.2a for the United States. I considered the vehicle and services contributions to the sector to be constant for purposes of the expenditure shares calculation. I took the fuel input value (in this case refined hydrocarbon-based fuels) and divided it by the 1997 average price of gasoline, $1.24 (EIA, 2008), to get the total gallons of fuel consumed to supply U.S. household transportation in that year. Assuming a fleet average fuel economy of 20 miles per gallon, the total vehicle miles traveled in 1997 (as assumed by the model) were found. Using the utility factor, a measure of the fraction of miles driven on electricity, the miles a PHEV would have driven using either electricity or refined oil were calculated. I then determined the electricity and fuel required to power the PHEV for these distances, in kilowatt-hours and gallons, respectively.

[5] Vehicle cost is expressed in terms of annualized expenditures.

The PHEV ICE was assumed to achieve a fuel economy of 43 miles to the gallon, making it slightly more than twice as efficient as its counterpart in the 1997 ICE-only vehicle. I then computed the cost of each of total kilowatt-hours of electricity and total gallons of fuel required by the PHEV as inputs to the PHEV sector, and combined them with the pre-existing annualized vehicle and services costs to calculate the sector's expenditure shares (Table 3.2b).

Table 3.2 Calculating PHEV Sector Input Shares

a)

ICE-only Vehicle	Fuel	Vehicle	Services
USA ($10 billion, 1997)	4.595	13.907	38.871
Shares	0.080	0.242	0.678

b)

PHEV	Electricity	Fuel	Vehicle	Services
USA ($10 billion, 1997)	0.734	0.855	13.907	38.871
Shares	0.013	0.016	0.256	0.715

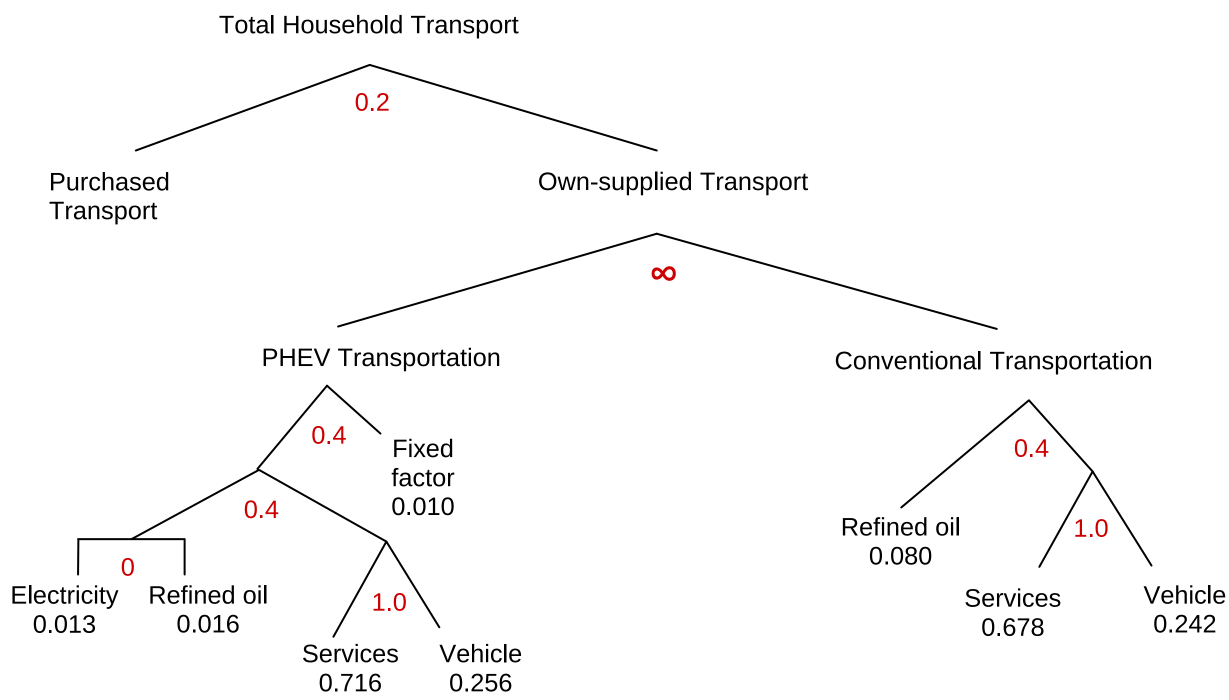
3.3.2 Modeling the Trade-off in Refined Oil and Electricity Use

The electricity and refined oil inputs to the PHEV sector are represented as a Leontief production function (i.e. with substitution elasticity equal to zero).[6] This relationship derives from the fact that the PHEV is assumed to operate only in all-electric mode before switching to rely on the internal combustion engine. Since drivers are likely to purchase a PHEV for the cost advantage of using electricity as a transportation fuel, the vehicle is assumed to be operated first in all-electric mode, beyond which the only option available is the ICE.

Expenditure shares for PHEV transportation in the United States are shown under each of the inputs in Figure 3.3. Throughout this analysis, I assume that the PHEV is available in the United States only, and that the 450ppm Policy is applied in the United States only. The Leontief structure of the electricity-refined oil nest could be relaxed to represent changes in behavior (favoring shorter driving distances) as fuel prices rise, but there is not good evidence at this point as to how users would respond.

[6] The substitution elasticity between electricity and refined oil is modified to 1.0 in the version of the model in which the three electric-drive vehicles are allowed to compete, because otherwise the model does not reach a solution in the 450ppm Policy, No Biofuels case. This modification does not make a significant difference in the outcomes observed for the scenarios in which the model was able to reach a solution (compared with the Leontief case).

Fig. 3.3 The addition of the PHEV as a perfect substitute for the ICE-only vehicle that uses both electricity and refined oil as fuel. The fixed factor slows the rate of entry.



3.3.3 Vehicle Markup

Since the PHEV is expected to be more expensive compared with ICE-only vehicles when it becomes available, a representative parameter, the vehicle markup, was specified in the model. The vehicle markup is simply the cost of the PHEV divided by the cost of its ICE-only counterpart (multiplied by 100 when expressed as a percentage). Based on the estimates given in Chapter 2, 30 to 80 percent is expected to be a reasonable window for the long-term estimate of vehicle markup for a PHEV with 20 to 60 mile all-electric range cited in Chapter 2. The markup is only applied to the expenditure share in PHEV transport that corresponds to the purchase of a vehicle. Services costs for the PHEV are assumed to be similar to an ICE-only vehicle.

3.3.4 Modeling Growth of the PHEV Sector

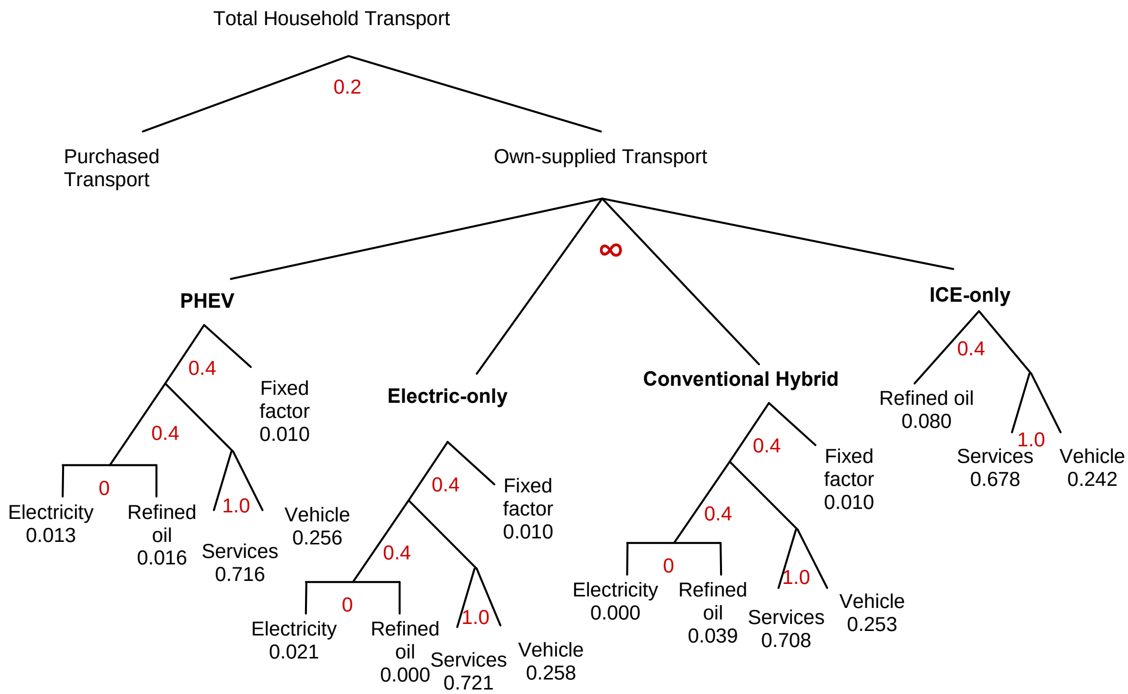
As part of the modeling strategy, I considered how to represent the rate of PHEV entry once the technology becomes cost competitive. Without a constraint on the rate of PHEV sector growth, the technology would immediately take over the vehicle fleet in the first period in which total cost of PHEV transportation drops below the total cost of ICE-only vehicle use. In order to restrain PHEV sector growth, I specify a fixed factor, or additional resource requirement for sector growth. The fixed factor in this case is calibrated to grow as the fraction of plug-in hybrid vehicles in the total fleet increases. This representation approximates the combined influences of fleet turnover, consumer acceptance, and time needed to scale up mass production.

More important that the actual value of the fixed factor is the fact that all scenarios use the same fixed factor, and as a result the effects are consistent across the scenarios compared. In addition, the chosen fixed factor does not allow the technology to enter faster than the rate of fleet turnover. The vehicle fleet has a half life of approximately 15 years, and thus I assume that in the most optimistic case, complete fleet turnover could occur in not less than 30 years (Bullis, 2006). Therefore, 30 years is taken as an upper bound estimate of the smallest time frame over which the PHEV could fully penetrate the fleet. (For more information on the specification of the fixed factor for the new electric-drive vehicle sectors, see Appendix A.)

3.3.5 Modeling Competition from Electric-only and Conventional Hybrid Vehicles

In addition to the PHEV sector, I included both conventional hybrid and electric-only vehicles in the model to evaluate their impact on PHEV entry, as shown in Figure 3.4. Each of these technologies was specified as a separate sector, but based directly on the structure of the PHEV sector described previously (i.e. perfect substitution with ICE-only vehicles and the PHEV). The markup for each of these technologies is specified exogenously in the same manner as for the PHEV. The main distinction among the three electric-drive vehicle alternatives is in the all-electric range (captured in the utility factor, or fraction of miles driven on electricity), as well as the associated cost markup. The all-electric range is reflected in the input shares of electricity and refined oil. In the case of the electric-only vehicle, the UF was 1.0, with the result that all vehicle-miles traveled were assumed to be provided by electricity, using the electricity requirement of 0.3 kWh per mile (Duvall & Knipping, 2007a). For the conventional hybrid vehicle, all miles traveled were supplied by the internal combustion engine, and thus utility factor was effectively zero. However, expenditures on refined fuel were roughly halved compared to the ICE-only vehicle due to the higher efficiency of the conventional hybrid, with the result that the shares of services and vehicle expenditures increased proportionately to account for the remainder of the personal transportation budget.

Fig. 3.4 Structure of the household transportation sector with competing technologies (electric-only and conventional hybrid vehicles) in direct competition with PHEV and ICE-only vehicles.



By representing all three potential electric-drive vehicle technologies in the EPPA model, it is possible to observe how they compete relative to each other and to the ICE-only vehicle under various policy and technology scenarios. The contribution of this work is thus to improve the resolution of the EPPA model in terms of the electric-drive vehicle alternatives, so that their prospects for entry and impact can be rigorously explored in a general equilibrium context.

4. Prospects for PHEV Market Entry in the United States Through 2100

Using the MIT EPPA model, I perform a detailed scenario analysis to investigate how several factors could potentially affect the timing and pace of plug-in hybrid electric vehicle entry over the next century. In particular, I ask how the timing of PHEV market entry could be affected by:

- Vehicle technology-specific attributes, such as vehicle price or all-electric range (specified by the utility factor);
- The availability of technologies beyond the vehicle itself, including the availability of advanced lignocellulosic biofuels technology (here referred to simply as "biofuels");
- Competition with other electric-drive vehicle technologies, including the conventional hybrid and battery electric vehicle.

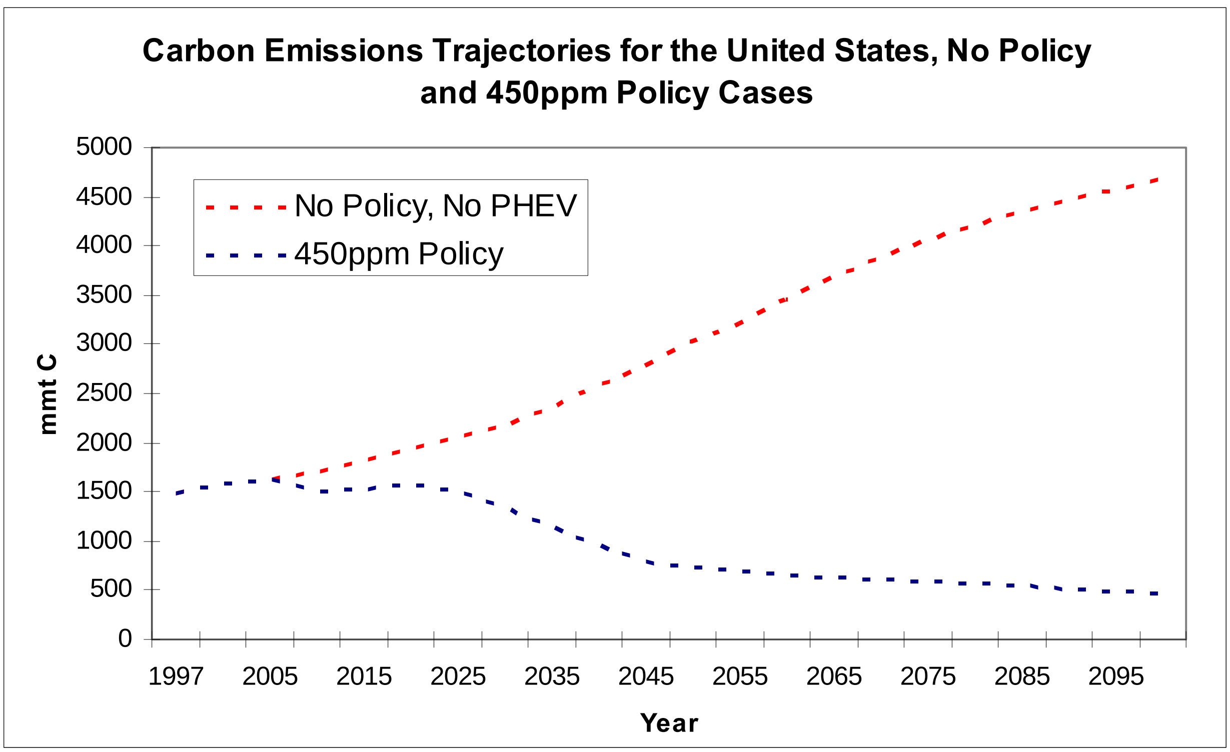
To investigate the role of these factors, I have developed the following series of scenarios, summarized in the table below. The scenarios listed below are a subset of a comprehensive analysis that was conducted to explore a broad range of possible technology and climate policy combinations.

Table 4.1 Scenarios for analysis of factors affecting PHEV market entry

Section 4.1	**Role of PHEV Technology Attributes (No Biofuels)**
	PHEV Markup – 0%, 30%, 80%, No Policy
	PHEV Markup – 0%, 30%, 80%, 450ppm Policy
	PHEV Utility Factor – 0.3, 0.6, 0.8, No Policy
	PHEV Utility Factor – 0.3, 0.6, 0.8, 450ppm Policy
Section 4.2	**Role of Biofuels**
	PHEV Markup, Biofuels – 0%, 30%, 80%, No Policy
	PHEV Markup, Biofuels – 0%, 30%, 80%, 450ppm Policy
	PHEV Utility Factor, Biofuels – 0.3, 0.6, 0.8, No Policy
	PHEV Utility Factor, Biofuels – 0.3, 0.6, 0.8, 450ppm Policy
Section 4.3	**Role of Conventional Hybrid Vehicle (Hybrid) and Electric-only Vehicle (Electric-only)**
	Hybrid Markup = 0%, PHEV Markup = 30%, Electric-only Markup = 40%, No Biofuels, No Policy
	Hybrid Markup = 0%, PHEV Markup = 30%, Electric-only Markup = 40%, No Biofuels, 450ppm Policy
	Hybrid Markup = 0%, PHEV Markup = 30%, Electric-only Markup = 40%, Biofuels, No Policy
	Hybrid Markup = 0%, PHEV Markup = 30%, Electric-only Markup = 40%, Biofuels, 450ppm Policy

The choice of scenarios can be justified briefly as follows. In Section 4.1, I first investigated how variability in markup and utility factor affects the timing and pace of PHEV entry under both No Policy and 450ppm Policy scenarios (the baseline emissions trajectories without the PHEV are shown in Figure 4.1). The 450ppm Policy scenario was chosen because, by imposing a strict carbon constraint, it requires deep cuts in transportation emissions (in addition to other sectors). In these scenarios, I assumed that biofuels were not available. However, carbon capture and storage is available as a low carbon backstop technology for power plants that utilize coal and natural gas, and becomes active (economically viable) only in the 450ppm Policy case (for more information see McFarland et al., 2004). Second, I varied the PHEV utility factor, holding vehicle markup constant. Since the utility factor is the fraction of miles a vehicle travels on electricity, these scenarios lend insight into the impact of relative fuel costs on the economic viability of the PHEV. Since electricity is cheaper than refined oil on a gallon-equivalent basis, my initial hypothesis was that the more a PHEV can take advantage of electricity as an energy source, the sooner it will enter the market.

Fig. 4.1 Carbon emissions paths for both No Policy and 450ppm Policy Cases in EPPA model.



In Section 4.2, I repeat the vehicle markup and utility factor scenarios assuming that biofuels are available. As a low carbon substitute for refined oil, biofuels make vehicle technologies that use refined fuels look more favorable, especially in a carbon constrained world. In all scenarios, carbon capture and storage is available and has the ability to substantially reduce the carbon intensity of electricity production when it becomes economically viable, which occurs only when a climate policy is imposed.

Section 4.3 evaluates the impact of making available two electric-drive vehicle technologies on the entry of a PHEV, in both the presence and absence of biofuels and a 450ppm carbon constraint. The PHEV assumed in these scenarios is the same as above, with a markup of 30% and an all-electric range equivalent to about 40 miles. The first technology, the conventional hybrid vehicle, attains approximately double the fuel economy of the ICE-only vehicle. Since the conventional hybrid vehicle is assumed to have no markup (a potentially realistic assumption over the long term), it is immediately competitive with the ICE-only vehicle when it becomes available in the model in 2010. The second technology, the battery electric vehicle, is assumed to have a markup of 40% over the ICE-only vehicle, which is very optimistic given the long term estimates cited by Simpson (2006).

4.1 Role of PHEV Technology Attributes

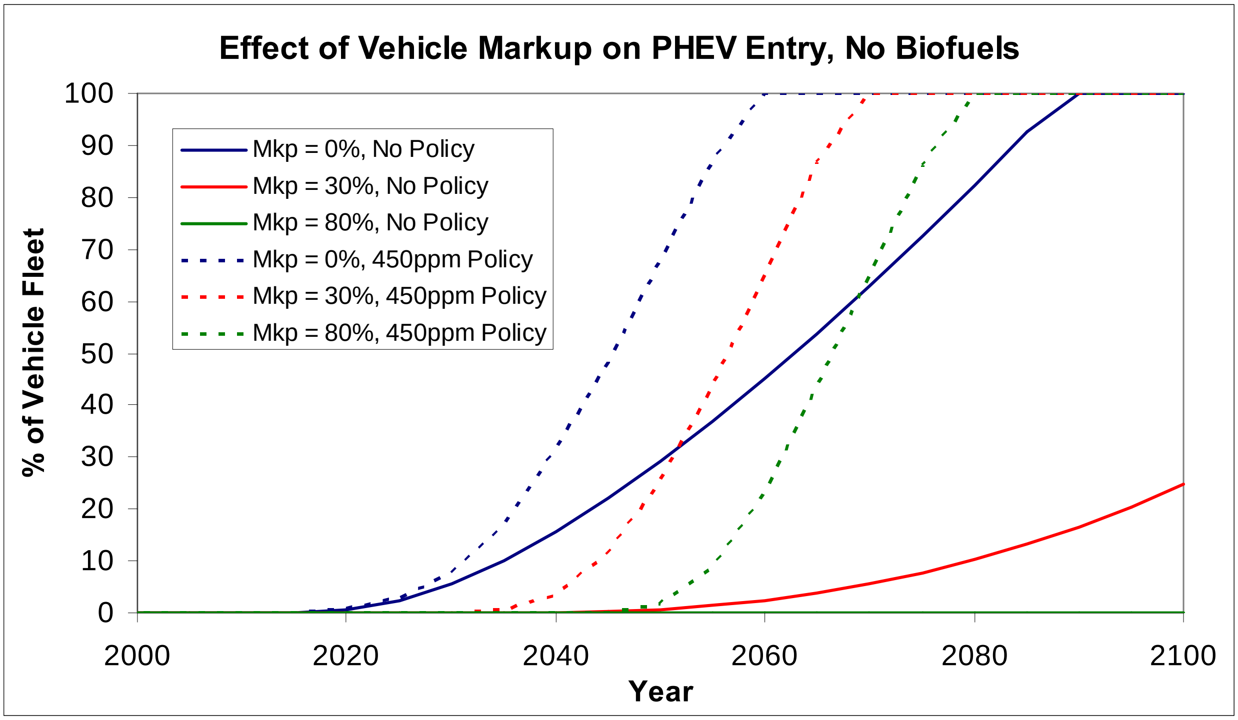
4.1.1 Role of Vehicle Markup

First, I investigated the impact of vehicle markup on PHEV entry in the presence and absence of a climate policy. Vehicle markup has a strong effect on timing of PHEV entry, although this effect is less pronounced in the 450ppm Policy case compared with the No Policy case. Figure 4.2 shows how larger vehicle markups delay market entry in both the No Policy and 450ppm Policy cases when biofuels are not available. Even with a modest markup of 30%, the initial date of entry and percentage of the PHEV in the vehicle fleet in 2100 drop dramatically compared with the 0% markup case when no carbon constraint is imposed. However, the implementation of a 450ppm policy dramatically hastens the entry of the PHEV, with full fleet penetration occurring sometime between 2050 and 2070, for a markup range of 0 to 80%. Carbon capture and storage is assumed to be available in the 450ppm policy scenarios.[7] It should be noted that the first electric vehicles are likely to have a markup of 30 to 50%, which, if assumptions in our model prove correct, could substantially delay or prevent PHEV market entry compared with the 0% markup case. In the No Policy case, a prohibitive markup is around 40%,

[7] Scenarios without carbon capture and storage (CCS) were not considered, because the behavior of the model under such a severe carbon constraint produced a highly distorted picture of total electricity generation enabled by unrealistically high levels of input substitution that is not meaningful in a real world context. All scenarios considered here thus have CCS available to the electricity sector under both the No Policy and policy cases, but CCS only becomes economically viable in the policy cases due to its high cost.

while in the 450ppm Policy case, the PHEV enters the market under much higher markups (100% or more) by the end of the century.

Fig. 4.2 Impact of vehicle markup on PHEV sector entry in the absence of biofuels. Policy indicates a stabilization path aimed at 450ppm adopted in the U.S. only.

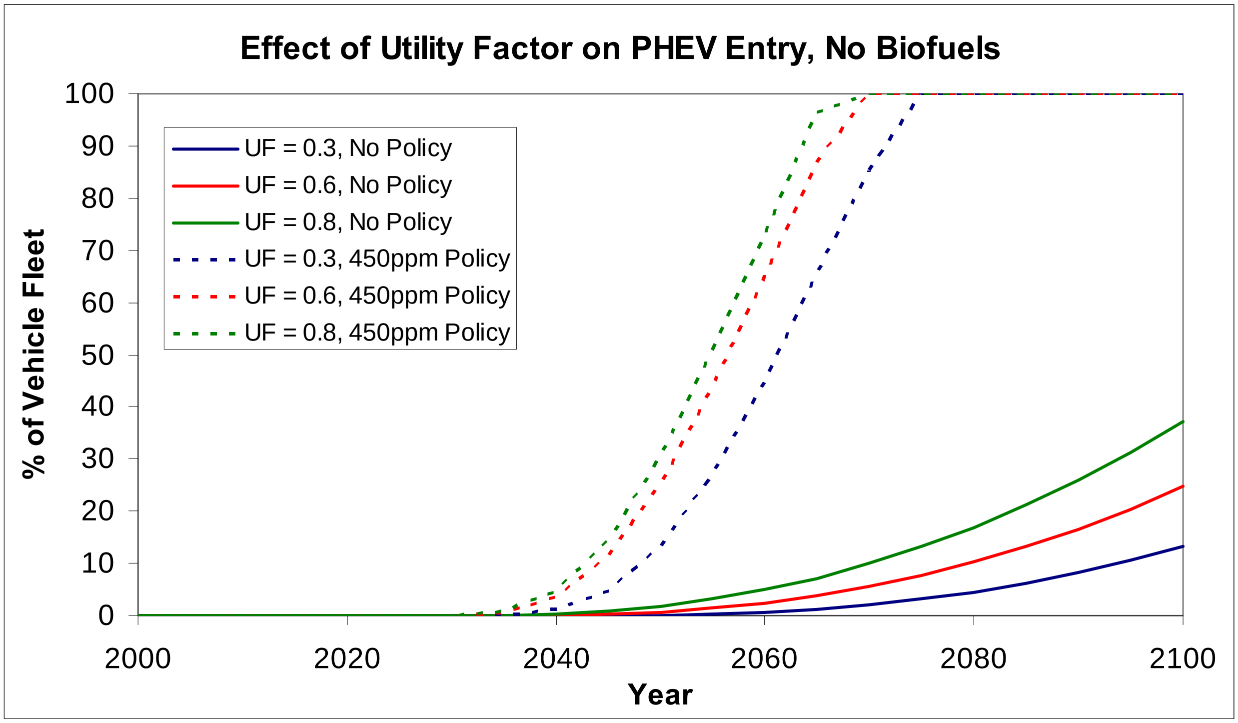


4.1.2 The Role of Utility Factor

The utility factor (UF) is a function of both the vehicle's all-electric range and individual driving habits. Given that electricity is cheaper than gasoline on a per mile basis, it is logical that changing either vehicle all-electric range or driving patterns in a way that increases the fraction of miles driven on electricity would be favorable for PHEV market entry. It is worthwhile to note here that a markup of 30% is assumed for all of the UF scenarios. In reality, this markup assumption is unlikely to be fixed across the spectrum of utility factors considered, especially in the near term, because vehicle cost is closely correlated with battery all-electric range. This analysis should therefore be thought of as an experiment to gauge how market entry might occur if a target of 30% for the cost markup were achieved for a vehicle with a specified all-electric range.

In the absence of a climate policy, and assuming current driving patterns, increasing the PHEV all-electric range while holding vehicle cost constant hastens PHEV market entry (Figure 4.3). In the 450ppm Policy case, the impact of the utility factor on the timing of entry seems to be somewhat muted, with changes in utility factor having less of an effect on rate of fleet penetration. The exogenous changes in utility factor examined could be interpreted as differences in all-electric range, or instead as changes in driving habits. Over the long term, it is plausible that for a given vehicle all-electric range, individuals may alter their driving behavior in response to the cost advantage of electricity as a fuel, effectively increasing the utility factor with no change in vehicle cost.

Fig. 4.3 Impact of utility factor given household transport usage patterns in the U.S. on PHEV market entry, assuming a vehicle markup of 30%.



4.2 The Role of Biofuels

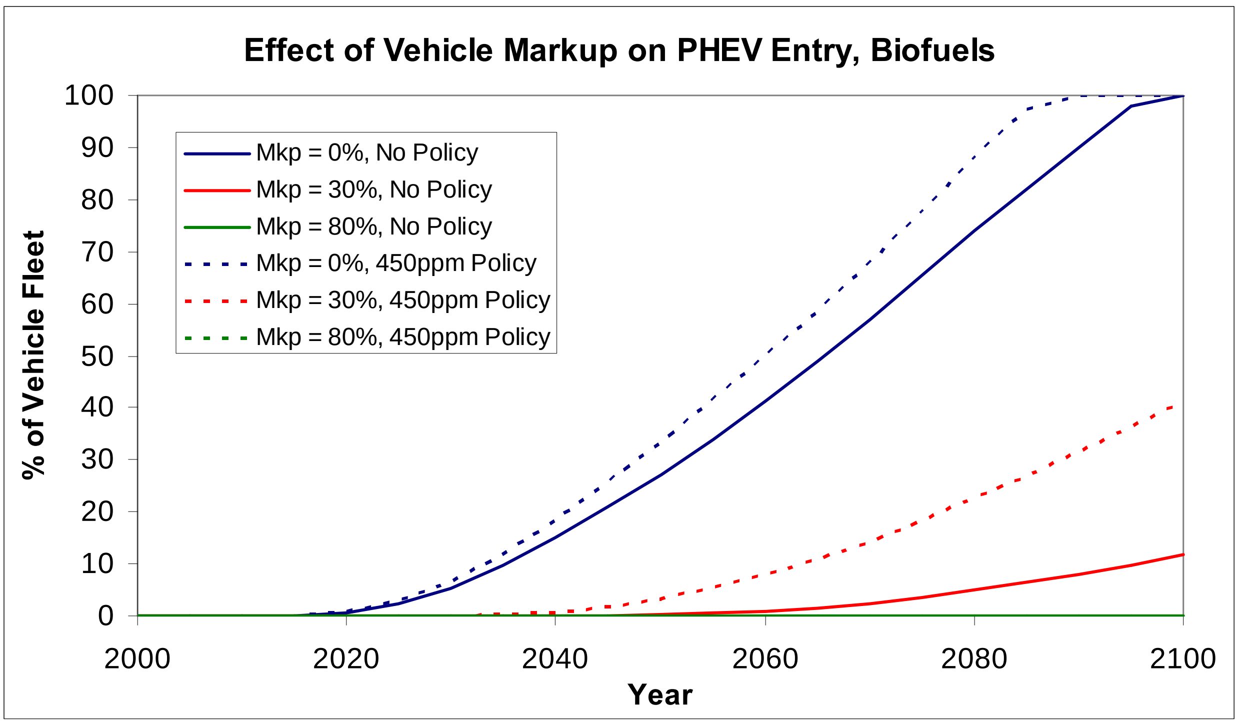
The availability of biofuels can have a strong impact on rate of PHEV market entry. When available in the No Policy case, biofuels account for 25% of all refined fuels used in the economy by the end of the century, but their role is limited due to the absence of a carbon constraint. When a 450ppm Policy is imposed, biofuels account for all refined fuel use by the end of the century, since they provide a carbon neutral alternative. Here I investigate how biofuels affect the competitiveness of the PHEV. To the extent that biofuels as represented in the model allow the reduction of the carbon footprint of vehicles that rely on the ICE (including the ICE-only and hybrid vehicles), biofuel availability may have the effect of slowing PHEV entry.

However, biofuels also have the potential to eliminate the residual carbon emissions of the PHEV due to the ICE contribution. In this sense, the two technologies could also prove complementary.

4.2.1 Impact of Biofuels on PHEV Entry in Markup Scenarios

Using the scenarios in Section 4.1 as a starting point, I ask how the results would change if advanced biofuels as specified in the EPPA model became available and provided a carbon neutral substitute for refined fuel. The effect of biofuels on PHEV entry turns out to be relatively minor in the absence of a climate policy, but pronounced if a 450ppm Policy is imposed. In the No Policy case (shown in Figure 4.4), a PHEV with a 30% markup is economically viable approximately one to two decades later than it would have been in the absence of biofuels.

Fig. 4.4 Impact of vehicle markup on PHEV sector entry when biofuels are available. Policy indicates a stabilization path aimed at 450ppm adopted in the U.S. only

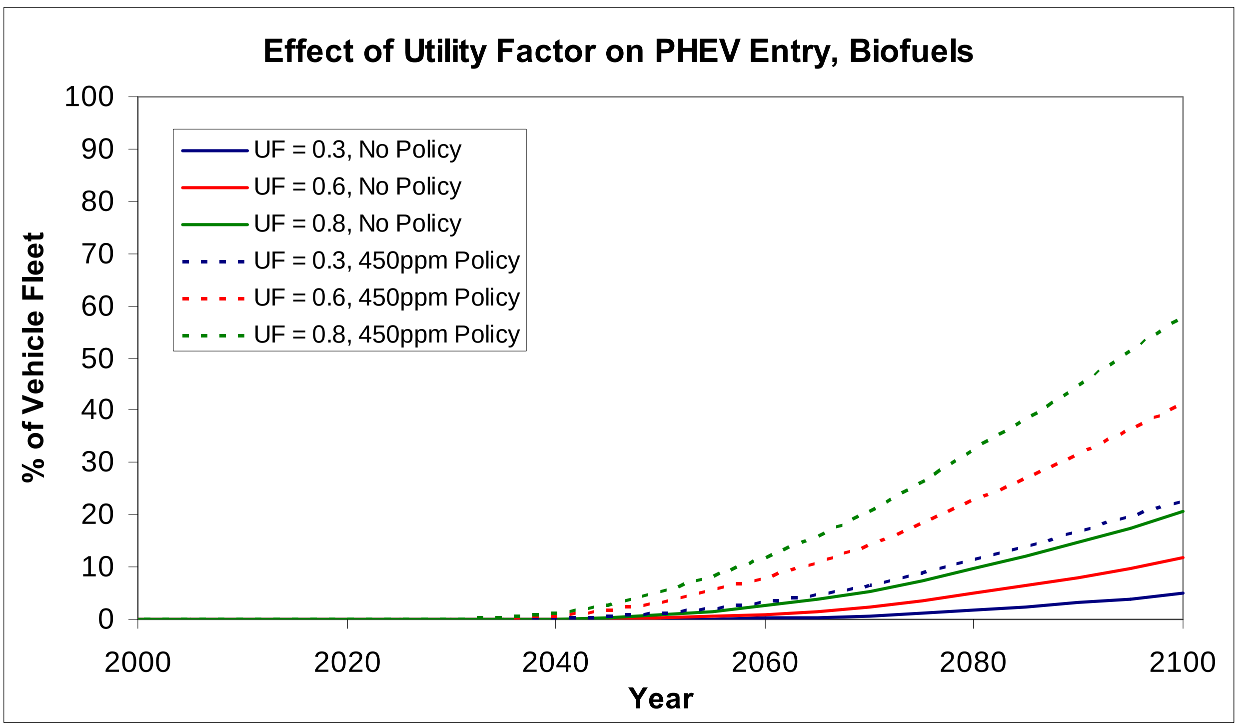


This pattern is consistent with the role of biofuels as a low carbon substitute for refined oil, which would decrease the attractiveness of the PHEV as a means of reducing refined oil consumption. The main driver of PHEV adoption in all No Policy cases is savings due to electricity as a substitute for refined fuels. This advantage is somewhat muted when biofuels are available. The PHEV enters at a relatively steady pace with a pattern similar to the No Biofuels case above, and fully takes over the market approximately a decade before the end of the century. However, in the 450ppm Policy Case, PHEV entry slows dramatically for all markups compared with the no biofuels case shown above, and a PHEV with 80% markup does not enter at all before the end of the century, whereas it completely took over the vehicle fleet by 2070 in the least optimistic case when biofuels were not available. This result follows from the fact that as carbon emissions become expensive, biofuels provide a more cost-competitive, readily available substitute for emissions-intensive fuel use than the PHEV.

4.2.2 Impact of Biofuels on PHEV Entry in Utility Factor Scenarios

A similar trend is evident when biofuels are available in the previous UF scenarios. As discussed earlier, it is assumed that all PHEV designs have a markup of 30%. The presence of biofuels can again be seen to handicap the PHEV and favor the ICE-only vehicle (see Figure 4.5). This trend is most pronounced in the 450ppm Policy case.

Fig. 4.5 Impact of utility factor on PHEV market entry when biofuels are available.



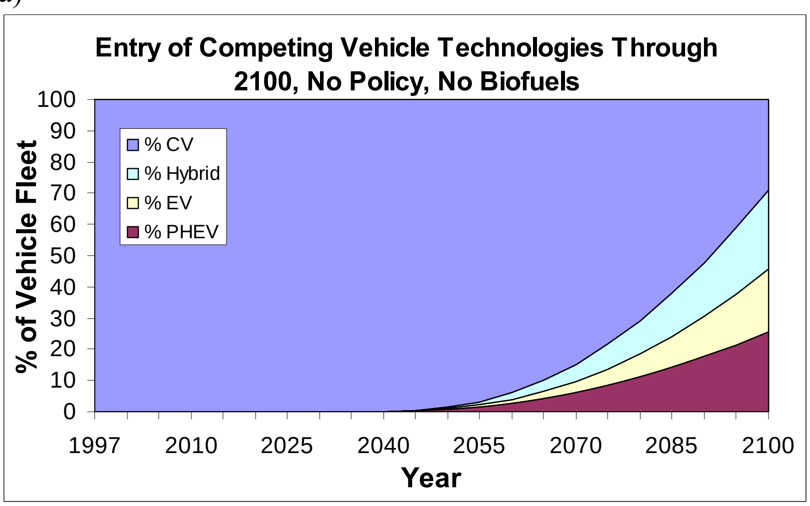
However, even in the No Policy case, total end-of-century fleet penetration is reduced by almost half compared to the No Policy/No Biofuels scenario considered above (see Figure 4.3). In the No Policy case, end-of-century fleet penetration with biofuels is around 23% of the fleet, considerably less than in the corresponding No Biofuels scenarios (39%). In the 450ppm Policy case, fleet penetration is reduced from 100% to a range from 24% to 60% by the end of the century, a significant decrease.

4.3 The Role of Competing Technologies: The Conventional Hybrid Vehicle and the Electric-only Vehicle

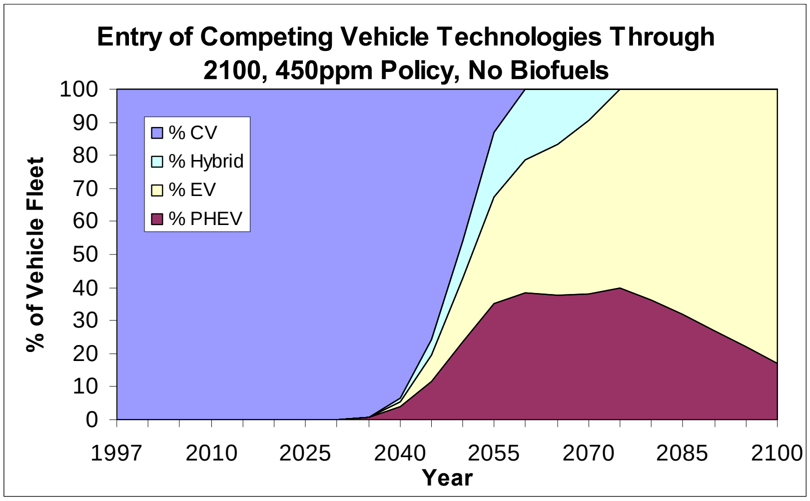
In order to create a more realistic representation of the future vehicle market, competition from existing or expected alternative electric-drive vehicles was simulated using the EPPA model. In addition to the PHEV, an electric-only vehicle and a conventional hybrid vehicle (referred to in the text and figure legends as simply a "hybrid") were added to the model. These designs were chosen because they represent the two ends of the electricity-gasoline spectrum for electric-drive vehicles. I add both of these alternative electric-drive vehicle specifications to the model and observe the outcomes in four scenarios with either No Policy/450ppm Policy or Biofuels/No Biofuels. It should be noted that CCS is available in all scenarios considered here.

Fig. 4.6 Effect of competing vehicle technologies on the entry of the PHEV in four scenarios: a) No Policy and No Biofuels, b) 450ppm Policy and No Biofuels, c) No Policy and Biofuels, and d) 450ppm Policy and Biofuels.

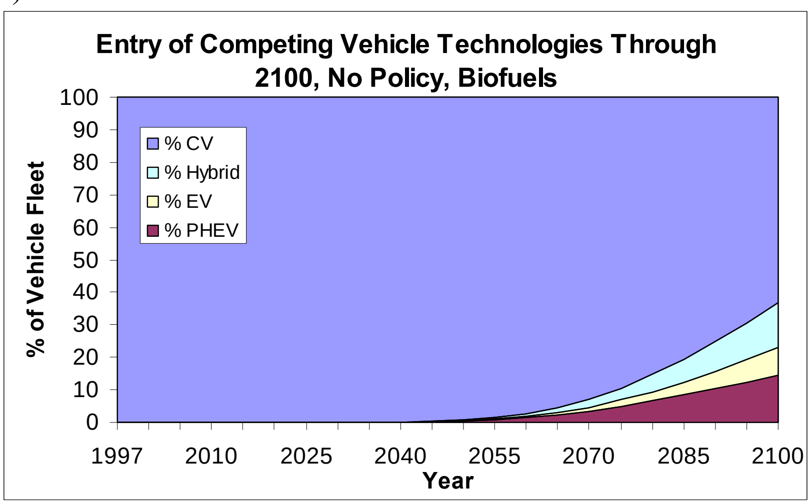
a)



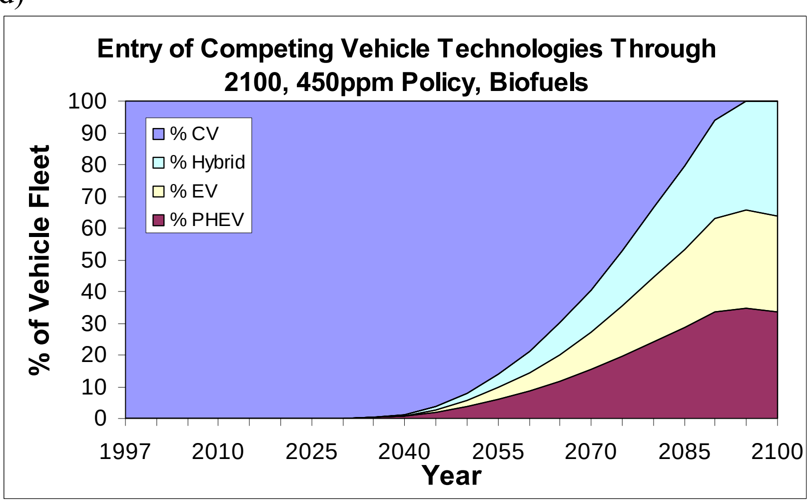
b)


Entry of Competing Vehicle Technologies Through 2100, 450ppm Policy, No Biofuels
% CV
% Hybrid
% EV
% PHEV
% of Vehicle Fleet
100
90
80
70
60
50
40
30
20
10
0
1997
2010
2025
2040
2055
2070
2085
2100
Year

c)


Entry of Competing Vehicle Technologies Through 2100, No Policy, Biofuels
% CV
% Hybrid
% EV
% PHEV
% of Vehicle Fleet
100
90
80
70
60
50
40
30
20
10
0
1997
2010
2025
2040
2055
2070
2085
2100
Year

d)


Entry of Competing Vehicle Technologies Through 2100, 450ppm Policy, Biofuels
% CV
% Hybrid
% EV
% PHEV
% of Vehicle Fleet
100
90
80
70
60
50
40
30
20
10
0
1997
2010
2025
2040
2055
2070
2085
2100
Year

In all competing technology scenarios, PHEV market penetration changes only when the economics of the PHEV are less favorable than other competing technologies (Figure 4.6). For instance, in both No Policy cases, the end-of-century market share of the PHEV does not change noticeably compared to the no-competition cases presented in Section 4.1 and 4.2. However, in the 450ppm Policy/No Biofuels case, the electric-only vehicle dominates the fleet by the end of the century, while the hybrid and PHEV are only viable over finite periods before they lose out to the electric-only vehicle (Figure 4.6b). By contrast, in the 450ppm Policy/Biofuels case (Figure 4.6d) both the PHEV and electric-only vehicle begin to lose out to the conventional hybrid vehicle by the end of the century.

4.4 Summary of Findings: PHEV Market Entry

The scenarios presented in this chapter demonstrate the effects of vehicle markup, utility factor, and competing technologies under the assumptions of the EPPA model. Vehicle markup has a strong effect on the viability of the PHEV, which is particularly pronounced in the 450ppm Policy case. In general, a higher utility factor allows for earlier PHEV entry, although this effect is somewhat muted when a 450ppm Policy is imposed. Finally, competing technologies affect the economics of the PHEV to the extent that each can take advantage of low carbon opportunities in the electricity and fuels sectors. In particular, when a policy is imposed and biofuels are not available, the electric-only vehicle dominates, while in the presence of biofuels, a strict policy slightly favors the conventional hybrid vehicle by the end of the century.

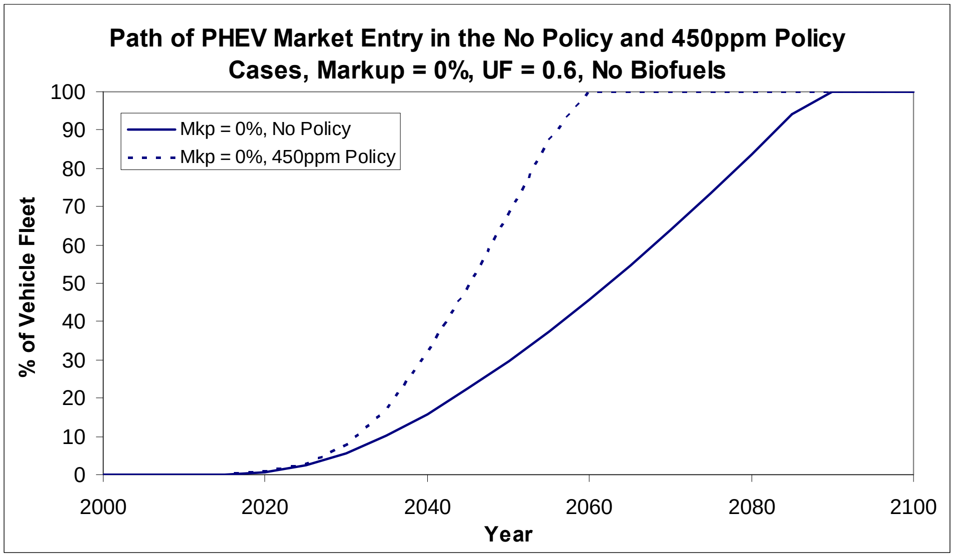
5. Potential Impact of the PHEV in the United States

The second part of this analysis explores the impact that the plug-in hybrid electric vehicle would be expected to have on several environmental and economic outcomes of interest. In particular, I evaluate the impact of the following PHEV entry scenarios on:

- Total electricity output
- Refined oil consumption
- Total and per mile carbon dioxide emissions
- Consumption losses due to climate policy

In this section, I develop a detailed comparison of the case in which the PHEV is not available and the case in which it has a low cost (0% markup) with a utility factor of 0.6. The rationale behind this choice of markup and utility factor is to obtain an estimate of the potential impact of the PHEV under conditions that favor its market penetration. In the scenarios in which the PHEV is available, the assumed path of entry is shown in Figure 5.1. Biofuels are not available in the cases considered here unless specified otherwise. The choice of markup for the PHEV cases represents the most optimistic conditions for PHEV market entry in the presence and absence of a climate policy constraint out of all the scenarios considered in Chapter 4.

Fig. 5.1 The assumed path of market entry used for impact analysis of an inexpensive PHEV in the United States in the presence and absence of a climate policy. CCS technology is assumed to be available. Biofuels are not available.

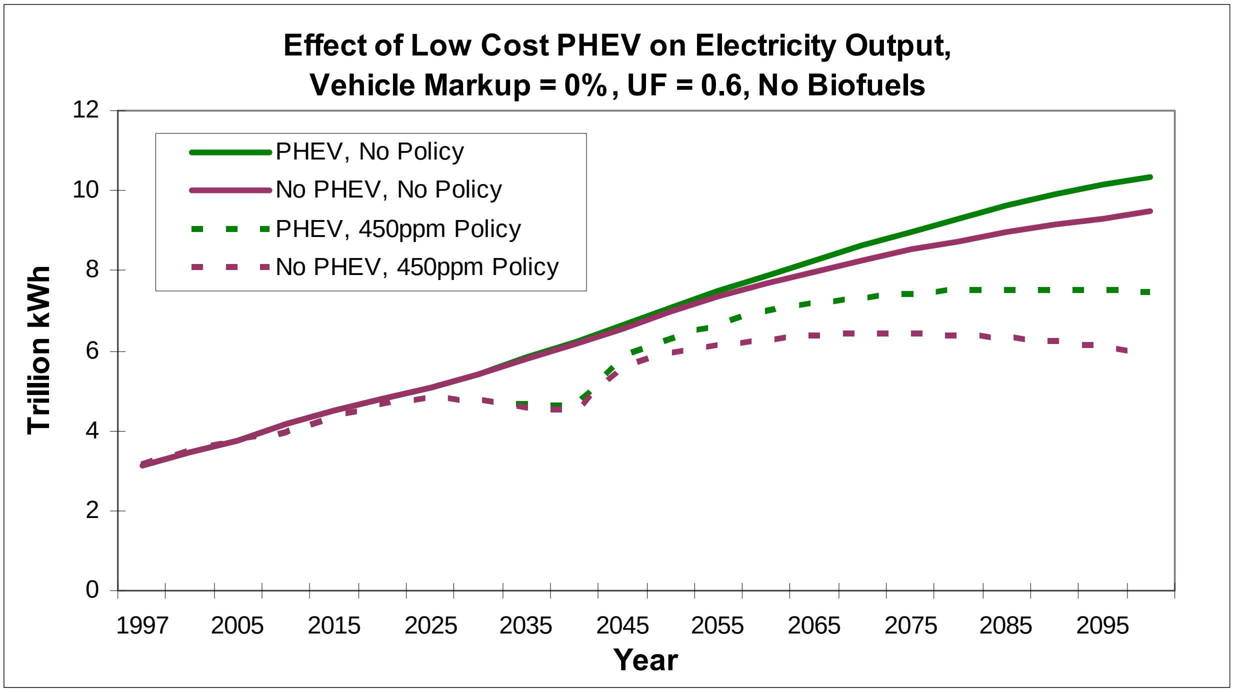


5.1 Electricity Sector Output

The shift to a form of transportation that runs on grid-supplied electricity would be expected to increase electricity output in proportion to the technology's adoption. From the model results, it can be seen that the gradual entry of a PHEV with markup of 0% and UF of 0.6 results in an increase in electricity output of around 10% over the baseline No PHEV case by 2100 when no climate policy is imposed (Figure 5.2).

The percentage increase in electricity output in the year 2100 is much larger in the 450ppm Policy case compared with the No Policy case, around 26%. The larger percentage difference is due at least in part to the comparison to a lower level of total output in the No PHEV case, as carbon intensive sources of electricity become more expensive, resulting in a transition to more expensive, less carbon intensive sources. Increases in prices also induce budget-constrained consumers to use less electricity. However, since the PHEV provides a low carbon cost-competitive substitute for the ICE-only vehicle, the model permits an increase in electricity output for the purpose of charging a PHEV fleet.

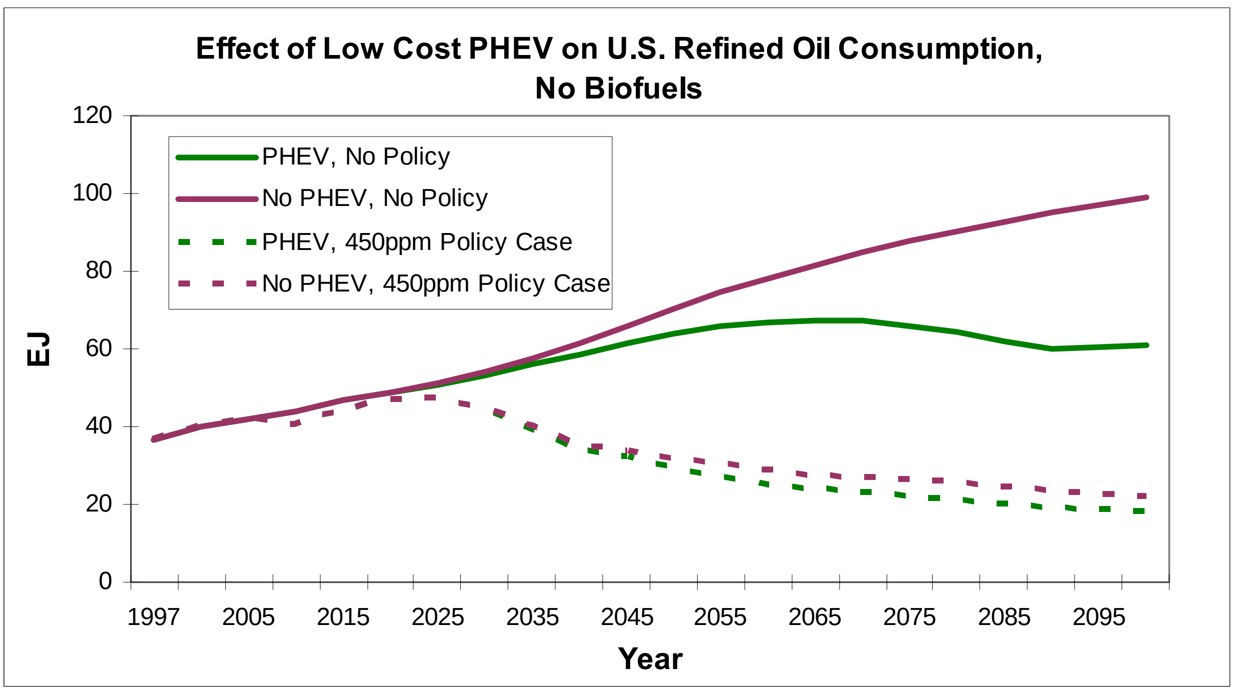
Fig. 5.2 Impact of inexpensive PHEV entry on total electricity output in the United States in the presence and absence of a climate policy. Biofuels are not available.



5.2 Refined Oil Consumption

Full fleet penetration of the PHEV results in a significant decrease in refined oil consumption. Refined oil consumption as simulated by the model is shown in Figure 5.3. In the No Policy case, the percentage decrease in refined oil consumption is substantial (around 40%). This reduction is due to the displacement of refined oil by electricity. However, refined oil is not completely displaced, due both to the modest requirement of the PHEV and its usage in other parts of the economy. In the 450ppm Policy Case, the PHEV allows only a very modest reduction in refined oil consumption in both relative and absolute terms, since the basis for comparison is a carbon-constrained world without biofuels in which refined oil commands high prices, inducing conservation.

Fig. 5.3 Impact of PHEV entry on refined oil consumption in the United States. Biofuels are not available.



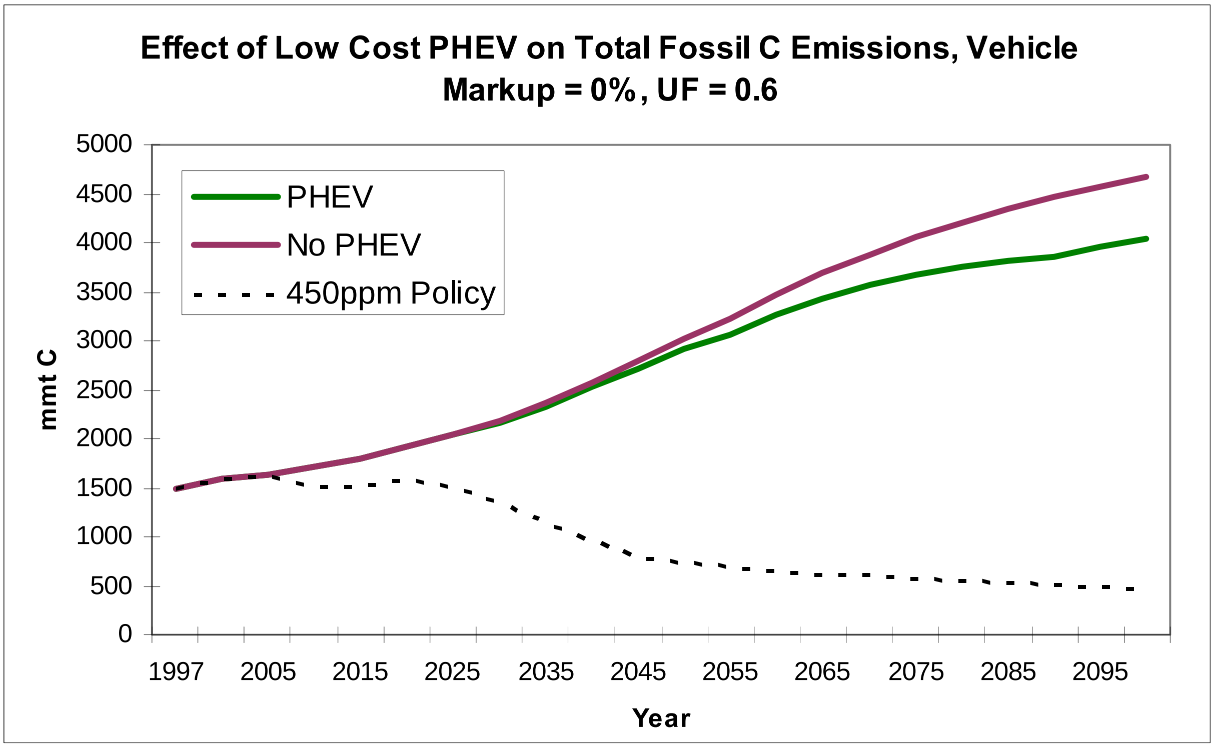
5.3 Energy Use and Carbon Dioxide Emissions

5.3.1 Total Change in Carbon Dioxide Emissions

The opposing effects of PHEV entry on coal electricity output and refined oil consumption leads us to ask how changes in the use of underlying carbon-intensive primary energy sources affect the total carbon dioxide emissions from the U.S. economy. The model outputs shown in Figure 5.4a indicate that the PHEV enables substantial reductions in carbon emissions (around 15%) in the year 2100, when the PHEV has completely taken over the fleet. The reduction stems mostly from the fact that electricity can be produced and used in the PHEV more efficiently than refined oil can be extracted, refined, and utilized by today's ICE-only vehicles.[8] While coal has higher carbon content than an energy-equivalent amount of refined oil, the greater average conversion efficiency of electricity production, combined with the fact that other sources of primary energy besides coal are used to produce the electricity, means that emissions decrease with PHEV entry into the market.

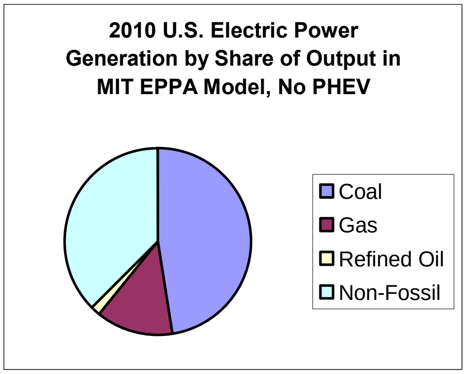
Fig. 5.4 Impact of PHEV entry on total fossil fuel carbon emissions in the United States is shown in a). The mix of primary energy sources used to produce electricity in the United States as predicted by the EPPA model in Year 2010 (in the No PHEV/No Policy case) is shown in b).

a)



[8] However, it should be noted that conventional hybrid vehicles are slightly more efficient than the PHEV and electric-only vehicle under the assumptions used here.

b)



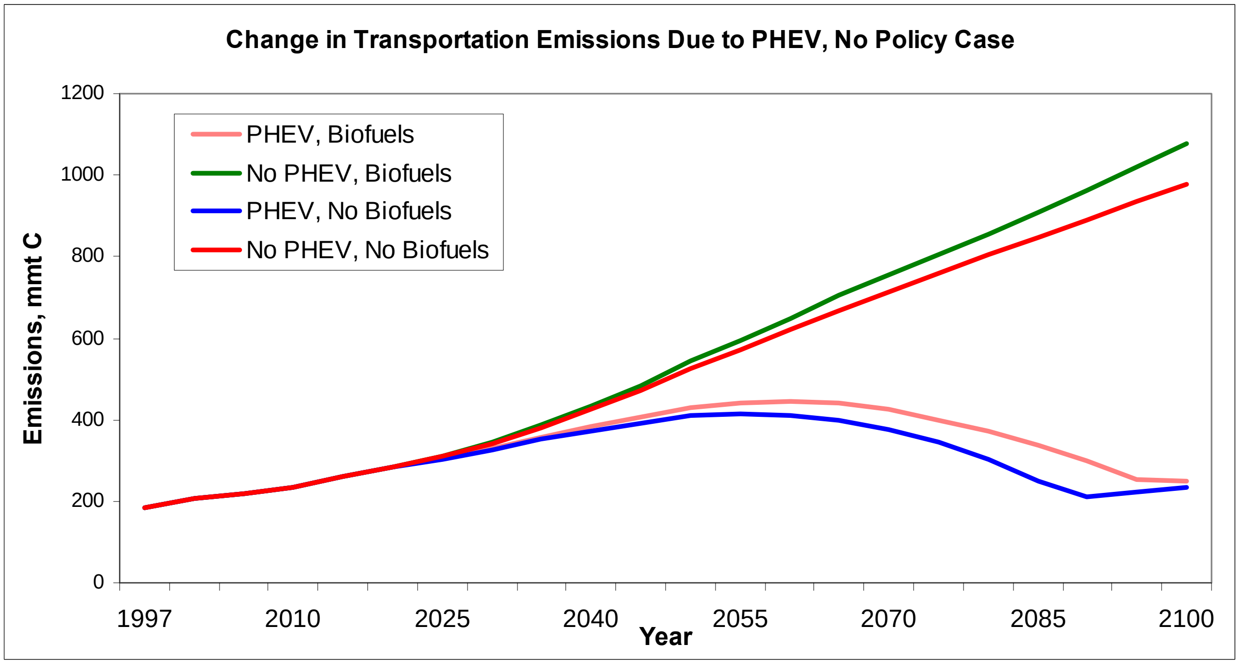
The model assumes that additional power provided to charge the PHEV fleet is sampled from the existing U.S. generation portfolio in proportion to its constituent sources (see Figure 5.4b). This portfolio changes endogenously in each successive period as the model optimizes the allocation of energy resources, and grows more efficient at a rate that approaches an efficiency of 0.5 by the end of the century in the No Policy cases (Paltsev et al., 2005). Although it is always favorable compared with the ICE-only vehicle in terms of emissions, the environmental advantage of the PHEV depends heavily on the carbon intensity of electric power generation. The 450ppm Policy case emissions trajectories are shown as a single dotted line (see Figure 5.4) because the emissions path for each policy case is by definition fixed by the policy constraint. Although the PHEV does lead to reduced emissions in the No Policy case, it does not come close to substituting for a 450ppm climate policy in terms of its impact on total emissions.

5.3.2 Changes in Transportation Emissions

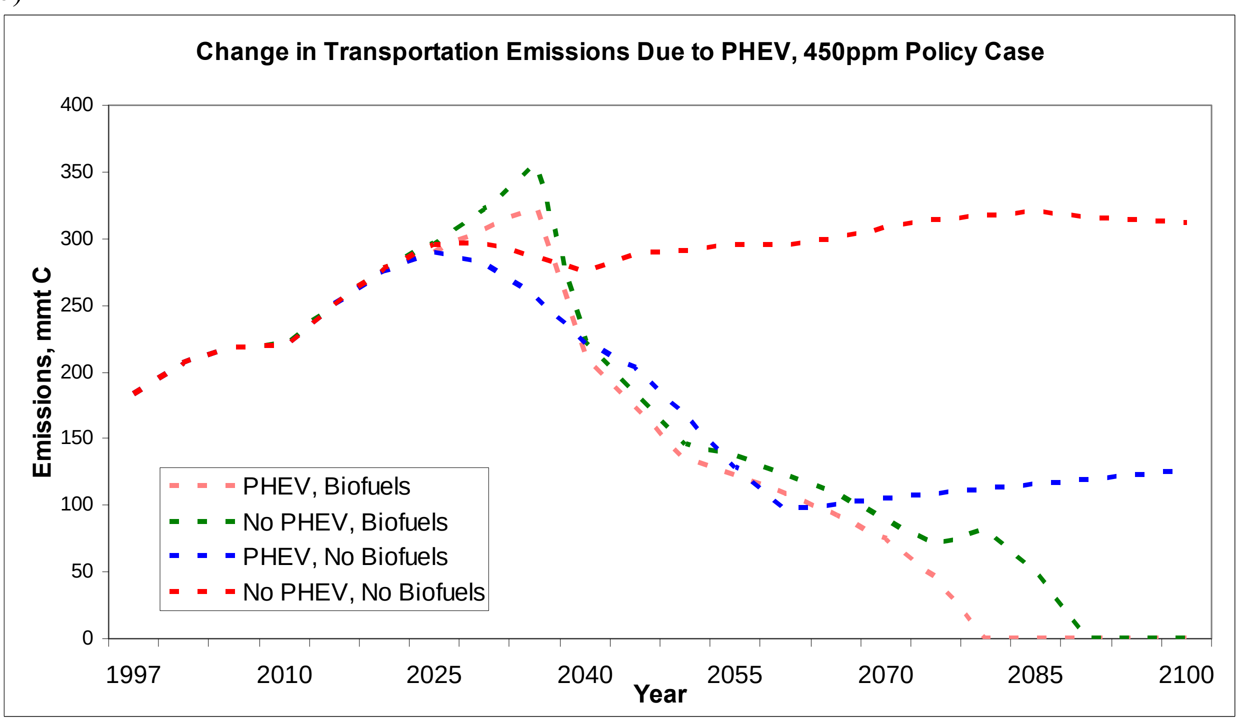
To investigate further the impact of the low cost PHEV on emissions from household transportation, I compared the emissions paths with and without the PHEV in the presence and absence of biofuels. In the No Policy case, the PHEV is responsible for a substantial decrease in emissions relative to the No PHEV/No Policy case (see Figure 5.5a). Since the availability of biofuels slightly delays the entry of the PHEV in the No Policy case, emissions reductions are achieved slightly later in the cases in which a low cost PHEV is available. However, in the No PHEV/No Policy case, biofuels availability leads to a slight increase in total transportation emissions, as total carbon emissions are not constrained. In the 450ppm Policy cases, by contrast, emissions are reduced to zero by the end of the century in both cases in which biofuels are available (Figure 5.5b). When the PHEV is available but biofuels are not available, carbon emissions level off around 130 million metric tons due to the emissions associated with partial reliance on the ICE.

Fig. 5.5 Impact of PHEV and biofuels availability on carbon emissions from household transportation in the a) No Policy case and b) 450ppm Policy case.

a)

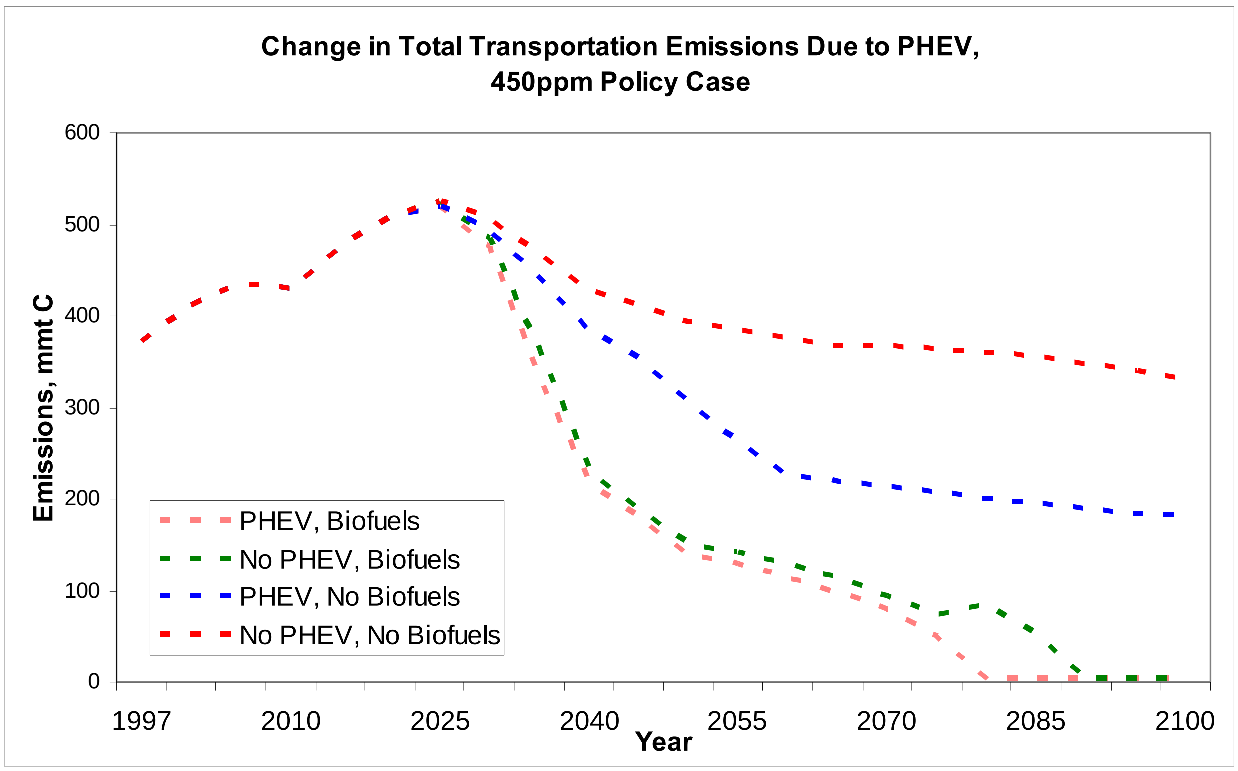


b)



In the 450ppm Policy Case, it was not immediately obvious what was causing the elevated emissions in the Biofuels cases relative to the No Biofuels cases in the years between 2025 and 2040. To investigate this apparent anomaly, I examined the breakdown of emissions from all sectors in every five year period. I observed that in cases where biofuels were available, the commercial transportation sector was the first to implement them as a low carbon substitute in the 450ppm Policy case, and as a result, emissions from household transportation increased relative to the No Biofuels case. The reduction in commercial transportation emissions compensated for continued increases in emissions from household transportation until eventually cuts in household transportation were required as well. Consistent with this explanation, the two peaks disappear when the total household plus commercial transportation emissions are compared in the Biofuels and No Biofuels cases (see Figure 5.6).

Fig. 5.6 Impact of PHEV and biofuels availability on CO_2 emissions from all types of transportation (both household and commercial) in the 450ppm Policy case.

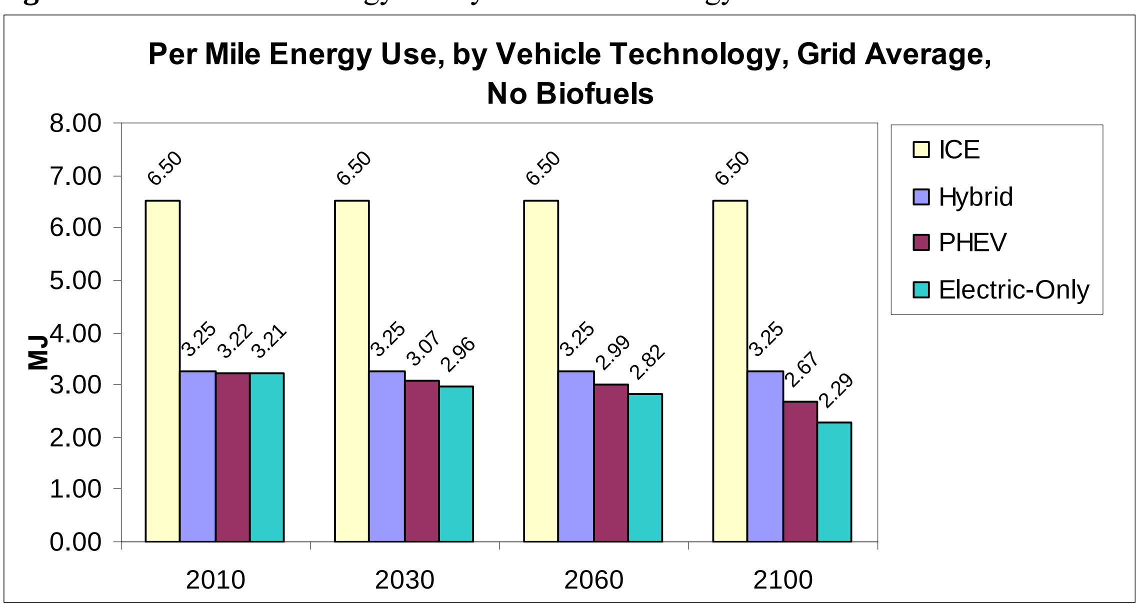


5.3.3 PHEV per Mile Energy Use and Emissions

The magnitude of the electricity advantage can be best understood by examining the performance of each alternative vehicle technology on a per mile energy use and emissions basis. Using the assumptions and outputs of the MIT EPPA model, I calculated per mile energy use and emissions from each type of vehicle technology in four years, 2010, 2030, 2060, and 2100. These calculations use the outputs from the EPPA model, which assumes that all ICE technology (used in ICE-only vehicles as well as the conventional hybrid and the PHEV) does not become more efficient with time. However, the efficiency of primary energy conversion in the electricity sector is increasing over time. The PHEV considered here is similar to that used throughout the impact scenarios, with a utility factor of 0.6.

Turning first to energy use, the energy efficiency advantage of grid-supplied electricity is apparent compared with the currently available ICE-only vehicle, but is far less pronounced when the PHEV is compared with the conventional hybrid vehicle (Figure 5.7). For the calculation of energy use from electricity, I use the assumption specified in the EPPA model that a PHEV will require 0.3 kWh per mile (Kintner-Meyer et al., 2004; Duvall & Knipping, 2007a). This figure considers both upstream primary energy inputs required to produce refined fuels or electricity as well as on-board fuel conversion efficiency. There is no assumed improvement in the efficiency of the ICE. However, an improvement could easily be included, and would increase the attractiveness of the ICE-only vehicle relative to its alternatives. The reduction in energy use by the PHEV and electric-only vehicles over time is driven by increases in the efficiency of grid-supplied electric power generation.

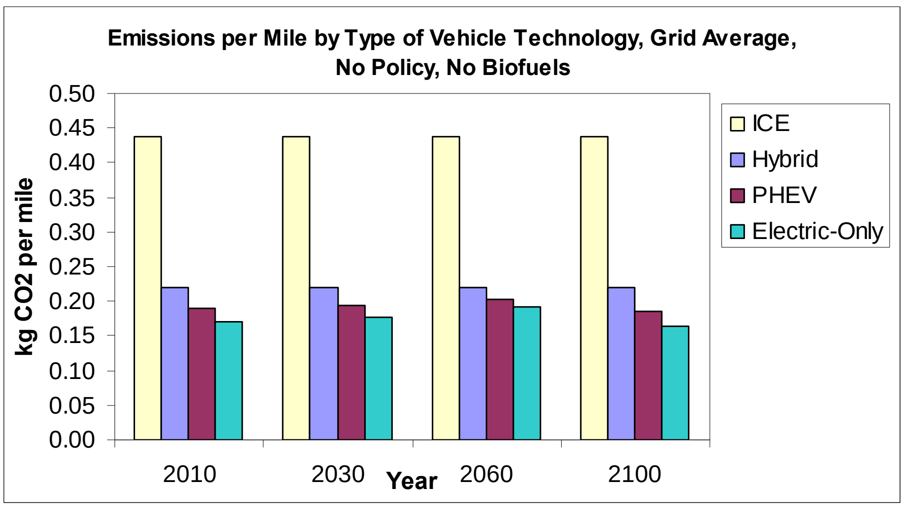
Fig. 5.7 Well-to-wheels energy use by vehicle technology. Biofuels are not available.



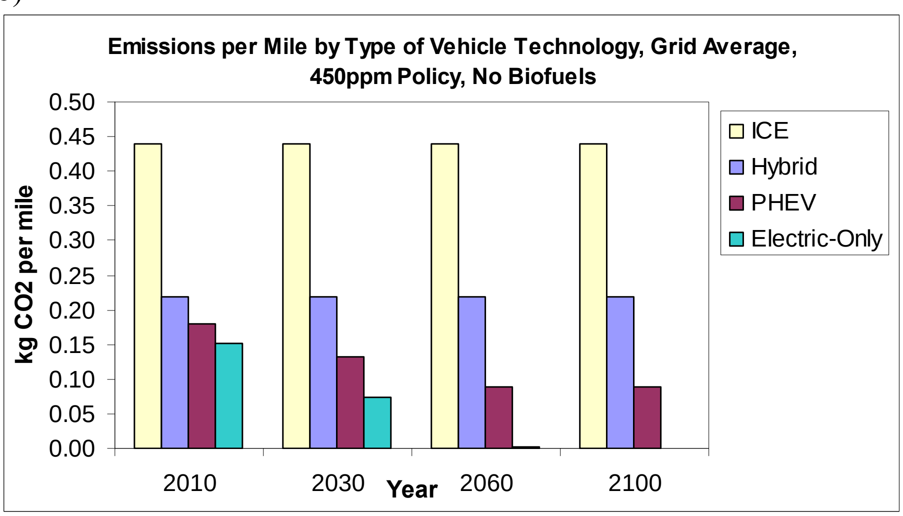
A comparison of the evolution of emissions per mile in the presence and absence of a 450ppm climate policy demonstrates impact of an economy-wide emissions constraint on the environmental performance of the various technology options. In the absence of a climate policy, the main driver behind the changing emissions per mile for vehicles powered by grid-supplied electricity is the increasing efficiency of primary energy conversion in the electricity sector. In all cases where the grid average is assumed, the PHEV is a better option than the ICE-only vehicle on both a per mile energy use and emissions basis. However, the ICE-only vehicle may not be most appropriate case for comparison; the conventional hybrid vehicle (which is already available in the market) may be the better choice.

Fig. 5.8 Evolution of emissions per mile by type of vehicle technology through 2100 in the a) No Policy and b) 450ppm Policy cases using the emissions intensity of the average grid mix in each year. Coal-fired electricity only is shown for the c) No Policy and d) 450ppm Policy cases. Biofuels are not available.

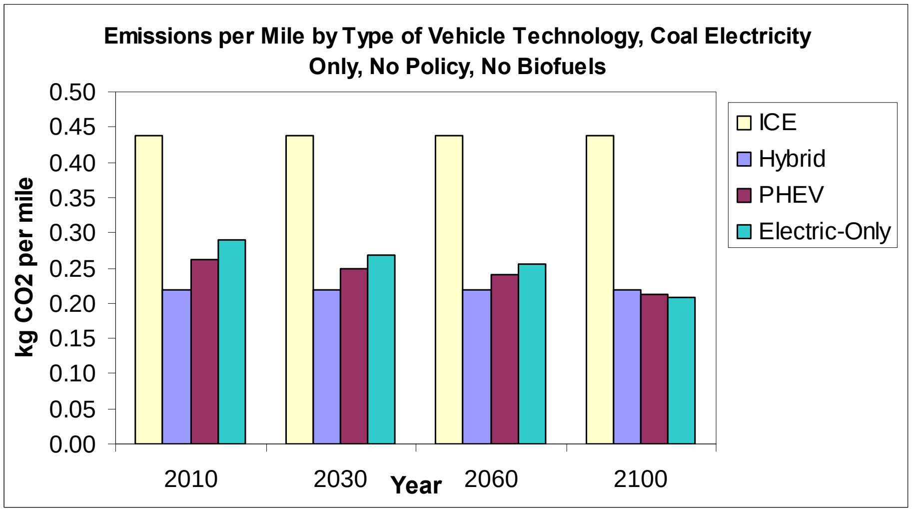
a)



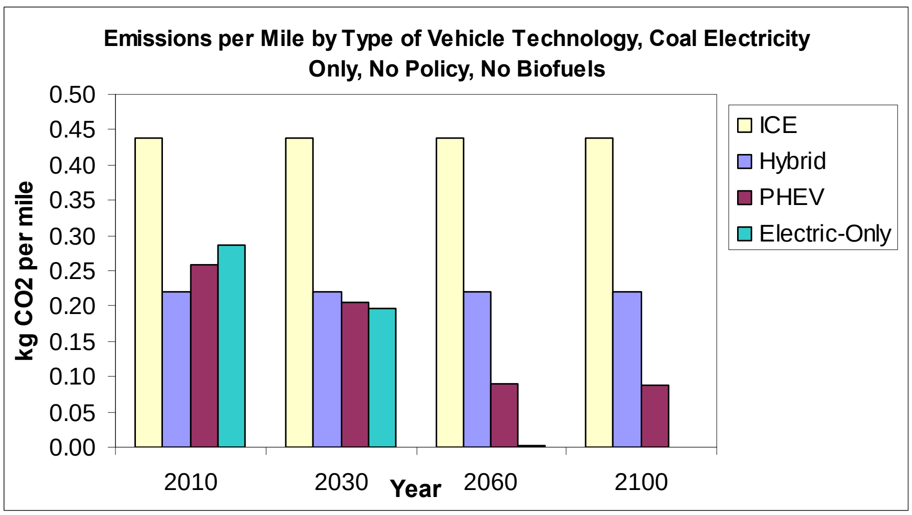
b)



c)



d)



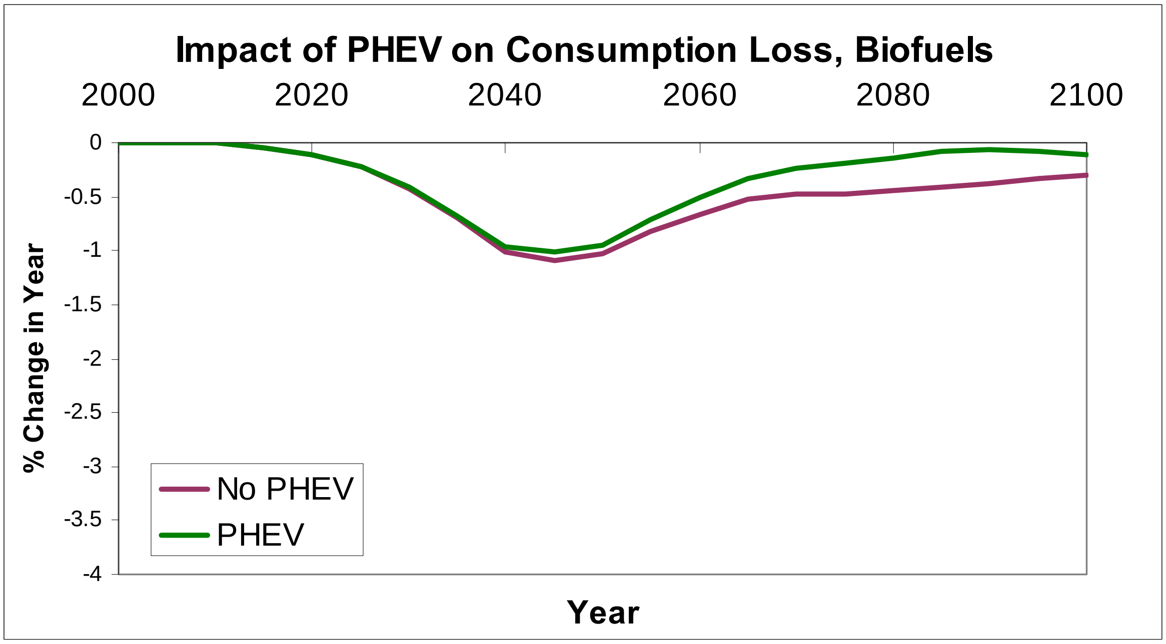
In the No Policy case, the per mile energy use and emissions of the PHEV and electric-only vehicle are only slightly lower than those of the corresponding conventional hybrid vehicle over the course of the twenty-first century (see Figure 5.8a). However, when a 450ppm Policy is implemented, the PHEV and electric-only vehicles emit substantially less carbon dioxide per mile than the corresponding conventional hybrid vehicle, as a carbon constraint results in the reduction of electricity sector carbon emissions (see Figure 5.8b).

An interesting contrast is evident when the per mile emissions based on the grid average is compared with per mile emissions based on coal-fired electricity generation. In the No Policy case for coal-fired electricity generation, the per mile emissions of both the PHEV and the electric-only vehicle are higher than for a conventional hybrid vehicle, but still lower than the ICE-only vehicle (Figures 5.8c). A 450ppm Policy allows the near-complete reduction of emissions from PHEV and electric-only vehicle transportation as CCS is added to all coal-fired power plants (see Figures 5.8b and 5.8d). The high capture efficiency is driven by the carbon price to a level higher than 90%. Therefore, when coal-fired electricity is used to charge the PHEV, it appears that an economy-wide carbon constraint is required to fully realize the environmental advantages of grid-supplied electricity in household transportation.

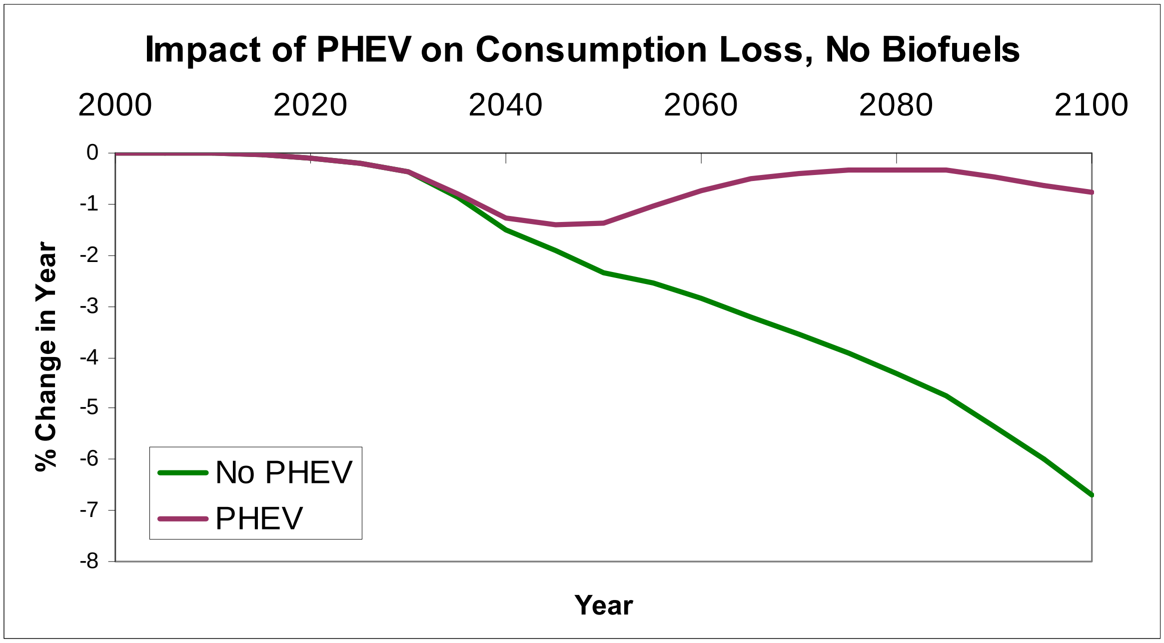
5.4 Economic Costs of Climate Policy

An important measure of the potential of the plug-in hybrid is its ability to reduce the costs (measured as loss of economic consumption or welfare) associated with climate policy adoption by providing an economical low carbon alternative to prevailing transportation technology. Climate policies are costly because they result in significant increases in the price of energy intensive goods and services, if no low carbon substitutes are available. Here, I explore potential of the PHEV to offset these adverse effects on welfare by evaluating the expected loss with and without the PHEV available in the absence of biofuels.

Fig. 5.9 Impact of the availability of a low cost PHEV on economic consumption losses due to implementation of a strict (450ppm) climate policy a) with biofuels and b) without biofuels.
a)



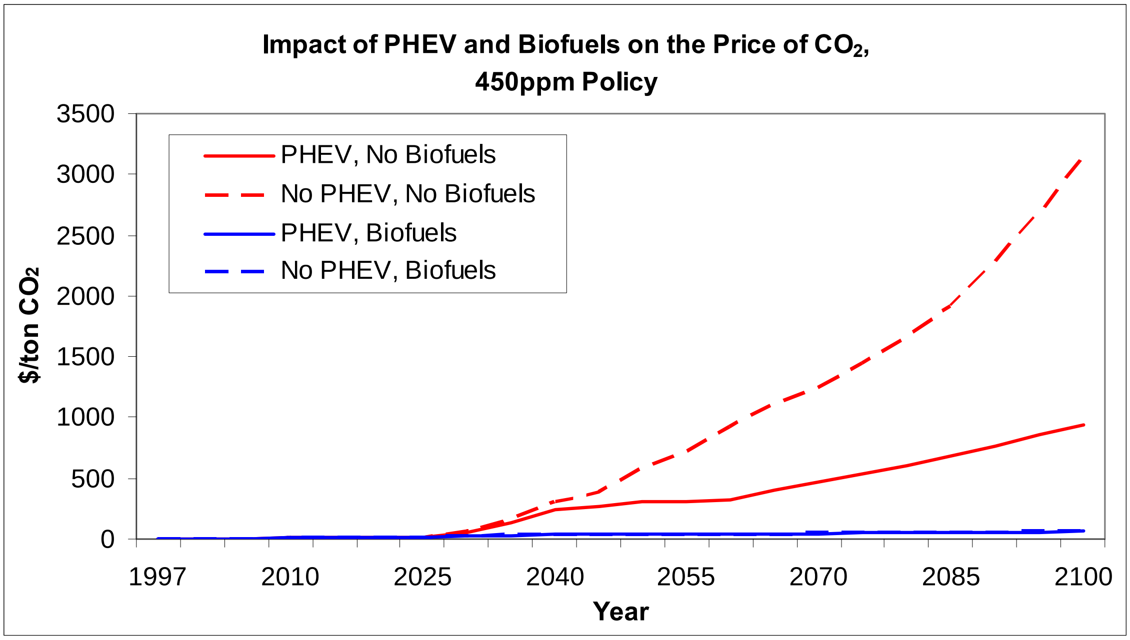
b)



The model results show that the PHEV could offset the cost of climate policy in comparison to the No PHEV case (Figure 5.9). This impact is especially pronounced in the case in which biofuels are not available (Figure 5.9b). In the case where biofuels are available, consumption losses are relatively modest in the absence of the PHEV due to the availability of biofuels as a low carbon substitute for refined oil. However, if land use issues, trade policies, or other constraints beyond those assumed in the model limit the availability of biofuels or drive up their costs, the plug-in hybrid could provide an important alternative option to reduce the cost of adjustment in the household transportation sector under a climate policy.

The mitigating effect of biofuels and the PHEV on consumption losses is driven by their effects on the CO_2 price over the course of the twenty-first century. The CO_2 price trajectories are shown in Figure 5.10. As long as biofuels are available, the CO_2 price remains below $100/ton through 2100. It should be noted that CCS is available in all scenarios considered here, reducing the carbon intensity of generating the electric power used to charge the PHEV fleet. When a PHEV is available, but biofuels are not, the PHEV has some mitigating effect on the carbon price, which reaches around $1,000/ton by the end of the century. However, if neither the PHEV nor biofuels are available, the result is a steep and steady increase in the price of CO_2, reaching over $3000/ton by the end of the century. The increase in CO_2 price drives the rapid adoption of the PHEV in the PHEV/450ppm Policy/No Biofuels case.

Fig. 5.10 The impact of availability of the PHEV and biofuels on the price of CO_2.



5.5 Summary of Findings: PHEV Impact

The results from the impact analysis suggest that a low cost PHEV would result in a modest increase in output from the electricity sector in both the No Policy and 450ppm Policy cases. Refined oil consumption, on the other hand, would be expected to decrease by up to 40% as electricity displaced refined oil. Large-scale adoption of the PHEV by the end of the century could be expected to reduce U.S. total carbon emissions by up to 15% in 2100 compared with the No PHEV/No Policy case. In the No Policy case, household transportation emissions would be offset by around 80% if a low cost PHEV were to be adopted on a large scale by the end of the century. In the 450ppm Policy case, emissions from the household transportation sector would decrease substantially, reaching zero in the case in which biofuels are available to power the PHEV. A comparison of per mile emissions for the ICE-only, conventional hybrid, PHEV, and electric-only vehicle reveals that in the No Policy case, the PHEV and electric-only vehicles are more emissions intensive relative to the conventional hybrid vehicle when coal-fired electric power is used to charge them. If the average grid mix is assumed instead, the PHEV and electric-only vehicles appear slightly more favorable compared with the ICE-only vehicle. However, if a 450ppm climate policy is imposed, both the PHEV and electric-vehicle become definitively superior on a per mile emissions basis, suggesting that a strong carbon emissions constraint is needed to maximize the environmental benefits of the PHEV.

6. Realizing the Potential of the PHEV: Challenges and Prospects

Despite several attempts over the last century, electricity has failed to make a significant contribution to personal vehicle transportation in the U.S. The challenge of developing on-board energy storage that can meet performance requirements safely over the lifetime of the vehicle has ranked among the major showstoppers. Is the plug-in hybrid electric vehicle, with its fuel flexibility, capable of overcoming these challenges? The results of this research suggest that the answer to this question may depend on a number of factors. The market entry and impact of the PHEV is likely to be driven not only by the cost and performance of the vehicle itself, but also on the availability of complimentary and competing technologies, including advanced lignocellulosic biofuels and other alternative electric-drive vehicles. Since the low carbon electric-drive vehicles considered in this work are not yet cost-competitive, their adoption is likely to further depend on the existence and strength of an economy-wide carbon constraint.

This research has applied a computable general equilibrium model to explore the dynamics of PHEV market entry and impact using a set of scenarios designed to identify the role of a number of potentially influential factors. This chapter summarizes the major findings of this research, and discusses their implications for ongoing policy and R&D efforts to maximize the emissions reductions that could be realized with large-scale adoption of the PHEV.

6.1 Summary of Factors Affecting PHEV Market Entry

Prior to undertaking the modeling work, I identified several factors that I expected would affect the rate of plug-in hybrid electric vehicle market entry: 1) incremental vehicle cost markup, 2) relative cost of the fuel and electricity inputs, 3) the availability of other electric-drive vehicles, such as the conventional hybrid and the electric-only vehicle, and 4) the availability of biofuels as a low carbon substitute for refined oil. I further hypothesized that the relative effects of these factors could change, depending on the existence and stringency of an economy-wide climate policy. The model results offered several important insights into the role of each of these factors.

First, the results indicated that increasing incremental vehicle markup has a strong effect on delaying the market entry of the PHEV, particularly in the absence of a climate policy. In the No Policy case in the absence of biofuels, the PHEV does not enter the market at all in the next century when the vehicle markup is greater than 40 percent. The cost markup for a PHEV primarily reflects the cost of the on-board battery. Thus, unless the cost of manufacturing long-range vehicle batteries can be reduced, the PHEV is likely to play a minimal role, given that the vehicle markup is expected to be at least 30 percent and perhaps as high as 50 to 100 percent for the first commercially-available PHEV models. When a strict (450ppm) climate policy is implemented and biofuels are not available, the PHEV enters the market and completely takes over the fleet under assumed markups of higher than 80%.

Second, the results of this analysis suggest that in addition to vehicle cost, the relative cost of electricity and refined fuels could have an important effect on the economic viability of the PHEV. At present, electricity is less expensive than gasoline on a per mile basis. Both the prices of refined oil and electricity are sensitive to the implementation of a climate policy. However, in the model electricity remains less expensive than refined oil on the basis of energy delivered per mile driven throughout the twenty-first century, especially in scenarios in which biofuels are not available. This trend is likely to be further exaggerated by a transition to greater reliance on non-conventional hydrocarbon fuels that are more difficult and carbon intensive to extract and refine, but become more economically viable as oil prices rise. As a result of the "electricity advantage," PHEV designs that exploit electricity as much as possible are likely to appeal most to cost-conscious consumers. However, it should be noted that in practice, many drivers may not fully consider recurring cost savings in their vehicle purchase decision, but focus instead on up-front vehicle cost.

Third, in almost every case, the availability of alternative electric-drive vehicles does not significantly affect the market entry of the PHEV for the range of markups examined here. The main exception occurs in the 450ppm Policy case when biofuels are not available, which creates conditions that strongly favor vehicles that can utilize electricity exclusively. In this case, an electric-only vehicle with cost markup of 40% will take market share from the PHEV (with a markup of 30%) by the end of the century because of the cost advantage of grid-supplied electricity. When biofuels are available and a 450ppm Policy is implemented, the conventional hybrid emerges as the most favorable technology, due to the ability of carbon neutral biofuels to completely displace refined oil in its fuel efficient propulsion system. The extent to which each of the four competing vehicle technologies—ICE-only, electric-only, hybrid, and PHEV—can take advantage of the least costly fuels available drives the timing and extent of market penetration for each, although more exhaustive analysis is needed to understand the sensitivity of observed patterns to vehicle cost markups and refined fuel cost. The fixed factor, which approximates the effects of technological learning and fleet turnover, prevents changes in the relative economics of the four technologies from instantaneously transforming the vehicle fleet.

Fourth, as noted previously, biofuels have a strong affect on the economics of the PHEV under a carbon constraint. The availability of biofuels provides an additional cost-competitive source of emissions reductions beyond the PHEV option. Without a carbon constraint, advanced cellulosic biofuels offset only a very modest amount of fuel consumption. However, under both policy scenarios, their importance as a low carbon substitute for refined oil becomes more substantial, making technologies that rely on refined oil alone look more economically viable compared with those that rely on both refined oil and electricity, or electricity alone. As a result, when biofuels are available, a stringent climate policy has only a mild effect in hastening the market penetration of the PHEV.

6.2 Summary of Factors Affecting PHEV Economic and Environmental Impact

The second part of this analysis used the EPPA model to explore both economic and environmental outcomes of interest associated with the full market penetration of the PHEV. Economic outcomes examined included the impact that the plug-in hybrid electric vehicle could have on electric sector output, refined oil consumption, and the economic welfare losses associated with the implementation of a strict (450ppm) climate policy. Environmental outcomes included quantification of changes in total emissions by the end of the century, as well as the change in per mile emissions in specified years over the course of the next century, in the presence and absence of a climate policy. In these scenarios, the PHEV is assumed to be equivalent in cost to a conventional vehicle and have a utility factor of 0.6.

6.2.1 Economic Impact

If the cost of the PHEV were to come down to that of the ICE-only vehicle, model results suggest that large-scale adoption would occur by the end of the century and have a substantial impact on the present energy system in both the No Policy and 450ppm Policy cases. First of all, in the No Policy case, electric power output will need to increase by around 10% in 2100 in order to support a fleet of plug-in hybrid electric vehicles. This fuel switch will displace around

40% of refined oil consumption in the United States in 2100, however, total usage will still remain above early twenty-first century levels. Still, fuel savings of this magnitude could reduce upward pressure on oil prices, change the economics of developing non-conventional hydrocarbon resources, and reduce the need to expand oil imports.

In the 450ppm Policy cases, the situation grows more complex. With the PHEV available, electricity demand increases more dramatically (+26%) compared to lower baseline production in the No PHEV/450ppm Policy case. The impact of adding a large PHEV charging load to a carbon-constrained electricity sector may present important energy management issues for utilities and regulators. Under the same carbon constraint, the impact of large-scale PHEV adoption on refined oil demand is less pronounced because the use of refined oil has already been reduced as a result of pricing its associated emissions.

A PHEV could also have the effect of reducing the cost of pursuing a climate policy, particularly if biofuels are not available. The existence of vehicles like the PHEV, electric-only vehicles, and hybrid vehicles (as well as other alternative fuel vehicles) becomes important when substitutes for carbon-intensive propulsion technologies are required. However, if advanced biofuels are available, the result is that even in the No PHEV case, significant consumption losses can be averted by employing biofuels on a large scale. It should be noted that carbon capture and storage for electric power generation from both coal and natural gas is available in all the 450ppm scenarios. Carbon capture and sequestration effectively sets a maximum cost at which electricity will be supplied to the grid under a carbon constraint.

6.2.2 Environmental Impact

The attractiveness of the PHEV from the standpoint of environmental performance depends on 1) the source of grid-supplied electricity, and 2) the availability of cost-competitive alternatives to refined oil. For all scenarios considered, the PHEV proved favorable to today's ICE-only vehicle on the basis of per mile emissions. However, it was not always the superior choice when compared to alternative electric-drive vehicles, depending on the carbon intensity of electricity generation. If grid-supplied electricity is primarily generated by coal-fired power plants, per mile emissions of a PHEV are higher than a conventional hybrid, and the emissions of an electric-only vehicle are higher still. Thus policies that emphasize the PHEV or electric-only vehicle as way to reduce dependence on oil imports or avoid high fuel prices may preclude the realization of their full emissions reduction potential, if these vehicles are charged primarily using carbon intensive sources of electric power.

However, if grid-supplied electricity is generated from nuclear or renewable sources, or from power plants retrofitted with carbon capture and storage, per mile emissions of the electric-only vehicle are lowest, followed by the PHEV. This only occurs when a strict climate policy is imposed. If the average U.S. grid mix is assumed, the PHEV is slightly more attractive than the conventional hybrid on a per mile emissions basis. However, the average grid mix is unlikely to represent any single region's generation profile. Thus, model results suggest that an economy-wide carbon constraint (or at least one that considers emissions from both transportation and electric power) is needed in order to ensure that the emissions externality is appropriately priced into each vehicle and electricity generation technology.

The shift to an all-PHEV fleet results in sizable reductions in total emissions in the No Policy case in 2100. Although the carbon content of coal assumed in the model is larger than the carbon content of refined oil, the high efficiency with which electricity can be used in a vehicle, combined with the sizable fraction of nuclear and large hydropower in the generation mix, results in a significant decrease in emissions. In the 450ppm Policy Case, total emissions are constrained by the economy-wide emissions cap. The PHEV enables deeper cuts in carbon emissions from household transportation than would otherwise have occurred if the PHEV were not available, mitigating economic disruption associated with pursuing a climate policy. The availability of biofuels further helps to reduce emissions from the PHEV to zero by the end of the century, as it provides a carbon neutral substitute for the residual amount of refined fuel required by the PHEV. Although the availability of biofuels slows the adoption of the PHEV in the 450ppm Policy case, biofuels also appear to provide an important complementary technology once the PHEV has fully taken over the fleet to completely reduce tailpipe carbon emissions from personal vehicle transportation.

6.3 Limitations of This Study

The goal of this study was to identify dynamic interactions among vehicle, fuel, and electricity markets that could affect both the cost-competitiveness of plug-in hybrid electric vehicles and their potential impact on important economic and environmental outcomes. The model uses a deliberately simple representation of most advanced energy technologies, which enables it to reach a solution in a reasonable period of time. The PHEV and other electric-drive vehicles are no exception, and were represented using the features primarily expected to affect the economics of each technology.

As a result of this simplification, I do not distinguish among vehicles of different size, weight, or performance, nor do I consider diesel-fueled vehicles (which in the United States are so far not widely available for household transportation use). As a result, I am unable to compare explicitly the potential emissions reductions of a PHEV with those achievable from a shift towards smaller vehicles, changes in driver behavior, or a large-scale switch to diesel fuel. These additional possibilities are unlikely to affect the validity of my conclusions related to the PHEV, although they might be considered in the choice of PHEV design. The model also does not explicitly represent vehicle fleet turnover, an important determinant of new technology uptake, but approximates it using a fixed factor. In future versions of EPPA, the ability to keep track of different fleet vintages will be added to the model.

Second, the model's assumptions about the availability of biofuels may be overly optimistic, because it assumes that advanced biofuels technologies will be carbon neutral. As a result, the contribution of biofuels may prove to be more limited than the model allows. Constraints on the production of biofuels are likely to favor earlier entry of the PHEV. Additionally, a low cost PHEV could reduce pressure for land conversion to support the expansion of biomass crops needed to meet the refined fuel demands of the vehicle fleet under a carbon constraint.

Third, as mentioned above, the electricity sector is also less detailed than is necessary to fully explore the impact of the PHEV on regional output and emissions. Our assumption that the increase in electricity use required for a large plug-in hybrid fleet will reflect the average mix of grid-supplied electricity in the United States obscures differences in carbon intensity among regional generation portfolios. Other studies have explored the effects of charging patterns on emissions, and attempted to recommend practices that optimize emissions reductions. Our model is unable to resolve time-of-day effects on pricing and emissions. Nevertheless, it allows important general insights that are based on the evolution of the carbon intensity of aggregate electricity protection and its response to the imposition of an economy-wide carbon constraint.

6.4 Directions for Future Work

This work represents an initial analysis of the impact of PHEV transportation in the United States. In addition to improving the model in ways that address the caveats mentioned in the previous section, several additional directions for future work can be identified. First, even if the United States is the first country to adopt the PHEV on a large scale (which is perhaps unlikely, given efforts to develop charging infrastructure and subsidize vehicles in other countries), it is unlikely to be the only adopting country. Therefore, it will become important to evaluate how the addition of electric-drive vehicle fleets in other large economies—particularly rapidly developing countries—could affect global emissions and the aggregate costs of pursuing a climate policy. In addition, the electricity costs, generation efficiency, and fuel mix are different in other countries (e.g., Japan and France) in ways that may affect PHEV market entry and emissions impact differently. In order to carry out this analysis, the specification and evolution of the vehicle fleet in all 16 regions of the EPPA model needs to be revisited. On the U.S. domestic front, additional economic modeling studies (perhaps at the regional level), combined with a careful examination of the regulatory process that dictates fuel economy standards and transportation-relevant climate policies, would yield a richer description of the interactions among national policy, energy markets, and technological change in the automotive sector. The modeling work and analysis presented here provides initial insights into the potential and limitations of the PHEV in the United States, and offers a foundation for future research.

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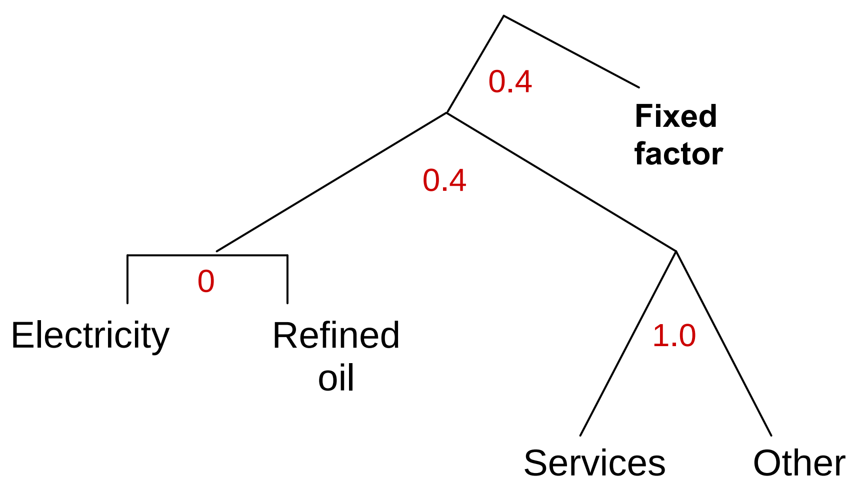
Appendix A: Specification of the Fixed Factor for New Electric-Drive Vehicle Sectors

Since the EPPA model does not explicitly account for the stock and turnover of the vehicle fleet, the novel technology would instantly take over the entire vehicle fleet in the period in which it becomes cost competitive. In order to more realistically model the process of fleet turnover, I have added a fixed factor to the nested structure of the PHEV sector. The fixed factor represents a quantity of input that is required for the production of the PHEV. The elasticity of substitution was set to be relatively low (0.4), and, more importantly, is held constant throughout all of the analysis performed. The fixed factor quantity grows as a function of the PHEV fraction of the personal vehicle fleet (or, in the cases of conventional hybrid and electric-only vehicles, it grows as fraction of these vehicles in the fleet).

The PHEV Sector



The fixed factor is initially allowed to be as large as one percent of the value of the vehicle fleet, an endowment large enough to allow the technology to enter the sector. It then grows as a function of the square root of the fraction of plug-in hybrid electric vehicles in the total fleet of household vehicles. The choice of a square root function was based on the intuition that the PHEV fleet would be expected grow more rapidly in the early decades of adoption, when gains from scaling up production in response to growing demand and learning effects would hasten the technology's market entry (see equation below). The fixed factor elasticity, 0.4, was set to ensure that the PHEV did not take over the fleet within less than 30 years in the most favorable scenarios (i.e., the 450ppm Policy Case without biofuels available), consistent with the maximum vehicle lifetime (Higgins et al., 2007). The fixed factor also slows down the rate at which the technology can be phased out once it is no longer economically viable, by preserving the value of the fixed factor in the previous period in proportion to a "surviving share" defined by the square of one minus the depreciation rate. It is expected that beyond some point the fixed factor will no longer be needed, as the early constraints on scaling up a new technology are overcome. At this point, the fixed factor price begins to decrease, as is the case in for all price trajectories for the PHEV fixed factor shown in Figure A.1.

The fixed factor is only an approximation for the actual turnover of vehicle capital stock. Ongoing work at the Joint Program is aimed at developing an explicit representation of the vehicle fleet, of which a portion would become available for replacement by a more cost-competitive technology, should one become available. However, even with explicit treatment of the vehicle fleet, considerable uncertainty persists in forecasts of market shares that novel vehicle technologies are expected to attain in the future.

Equation for Fixed Factor:

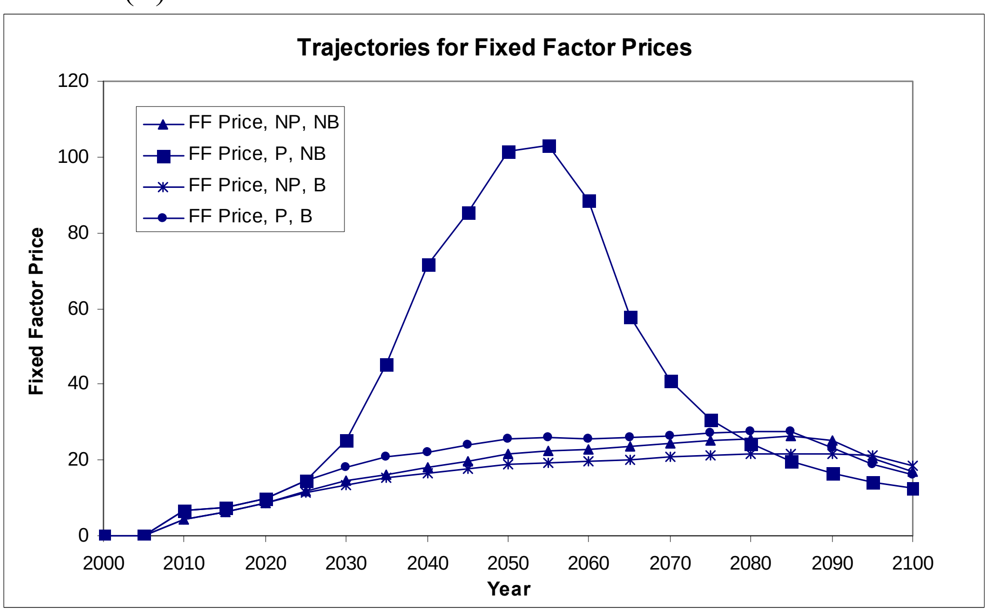
$I_0(r)$ – Initial share of fixed factor for PHEV sector
$F_0(r)$ – Value of fixed factor in the first period the PHEV is available
$F_t(r)$ – Value of fixed factor in region *r* in year *t*
$H_t(r)$ – Output of the household transport sector in region *r* in year *t*
$P_t(r)$ – Output of PHEV sector in region *r* in year *t*
$SS_t(r)$ – Surviving share, defined as $(1-d)^2$, where d is the depreciation rate

Initial magnitude of PHEV:
$$F_0(r) = 0.01 \times H_t(r)$$

Growth of PHEV sector:
$$F_t(r) = F_{t-1}(r) + I_0(r) \times \left(\frac{P_t(r)}{H_t(r)} \right)^{0.5}$$

Path of decline if PHEV stops producing:
$$F_{t+1}(r) = Max\left[F_{t=2000}(r), F_{t-1}(r) \times SS_t(r)\right]$$

Figure A.1 The trajectory for fixed factor prices in the No Policy (NP), Policy (P), No Biofuels (NB), and Biofuels (B) scenarios.



Appendix B: Assumptions for per mile Energy Use and Emissions Calculations

The total emissions and emissions per mile reported in Chapter 5 were calculated based on a combination of outputs from the EPPA model and engineering data and conversion factors. A detailed explanation of these calculations and the assumptions behind them is presented here.

CO_2 Emissions Intensity of a) coal-fired electricity generation and b) the average grid mix in the MIT EPPA Model in the various scenarios considered (PHEV markup is equal to 0% and utility factor is 0.6).

Scenarios considered:
NP – No Policy
P – Policy
NB – No Biofuels
B – Biofuels

CO_2 Emissions Intensity by Generation Type in MIT EPPA Model

U.S. Average Grid Mix
Million metric tons carbon / TkWh

Year	NP, NB*	P, NB*	NP, B	P, B
2010	155.5998	138.633	154.59	137.9351
2030	160.9302	66.4397	160.85	83.98162
2060	175.0777	1.62906	175.6	28.81421
2100	147.9339	0.58557	148.97	26.66876

*Per mile emissions for these cases are shown in the text.

Coal-fired Electricity Generation
Million metric tons carbon / TkWh

Year	NP, NB*	P, NB*	NP, B	P, B
2010	263.9535	259.6437	264.078	259.8894
2030	243.2315	178.4335	243.153	202.5775
2060	231.9382	2.134906	231.752	33.39072
2100	188.3804	0.765218	188.606	10.32716

*Per mile emissions for these cases are shown in the text.

Technology Assumptions for Emissions Calculation

	ICE-only		Hybrid		PHEV		Electric-only	
Fuel economy	20	mpg	40	mpg	40	mpg	N/A	
Grid electricity	N/A		N/A		0.3	kWh/mi	0.3	kWh/mi
UF*	0		0		0.6		1	
1-UF	1		1		0.4		0	

*UF – Utility Factor, the fraction of miles driven using grid-supplied electricity, based on the driving patterns observed in the U.S. National Household Transportation Survey (2001).

Carbon Content Assumed in MIT EPPA Model by Fuel Type

Carbon content		
C content refined oil	18.4	mmt C/EJ
C content coal	24.686	mmt C/EJ

Conversion Factors

Conversion Factors	
J/kWh	3.60E+06
g CO2/g C	3.666667
gallons/bbl ref oil	42
J/gal gasoline	1.30E+08
Elec. conv. efficiency	0.3365

In all cases, the energy efficiency of electric power generation was assumed to increase in a rate that allows efficiency of fuel conversion in electricity generation in the No Policy case to approach 0.5 by the end of the century (Paltsev et al., 2005). No such change in efficiency was assumed for energy conversion in personal vehicle transportation.