Transportation Research Part A 44 (2010) 620–641

Contents lists available at ScienceDirect

Transportation Research Part A

journal homepage: www.elsevier.com/locate/tra

Prospects for plug-in hybrid electric vehicles in the United States and Japan: A general equilibrium analysis

Valerie J. Karplus, Sergey Paltsev, John M. Reilly *

MIT Joint Program on the Science and Policy of Global Change, Cambridge, MA, USA

ARTICLE INFO

Article history:
Received 27 March 2009
Received in revised form 19 March 2010
Accepted 24 April 2010

Keywords:
Alternative fuel vehicles
Plug-in hybrid electric vehicles
Environmental policy
Emissions

ABSTRACT

The plug-in hybrid electric vehicle (PHEV) may offer a potential near term, low-carbon alternative to today's gasoline- and diesel-powered vehicles. A representative vehicle technology that runs on electricity in addition to conventional fuels was introduced into the MIT Emissions Prediction and Policy Analysis (EPPA) model as a perfect substitute for internal combustion engine (ICE-only) vehicles in two likely early-adopting markets, the United States and Japan. We investigate the effect of relative vehicle cost and all-electric range on the timing of PHEV market entry in the presence and absence of an advanced cellulosic biofuels technology and a strong (450 ppm) economy-wide carbon constraint. Vehicle cost could be a significant barrier to PHEV entry unless fairly aggressive goals for reducing battery costs are met. If a low-cost PHEV is available we find that its adoption has the potential to reduce CO_2 emissions, refined oil demand, and under a carbon policy the required CO_2 price in both the United States and Japan. The emissions reduction potential of PHEV adoption depends on the carbon intensity of electric power generation. Thus, the technology is much more effective in reducing CO_2 emissions if adoption occurs under an economy-wide cap and trade system that also encourages low-carbon electricity generation.

1. Introduction

The large and growing fraction of greenhouse gas (GHG) emissions from the transportation sector present a major challenge to global climate change mitigation efforts. Worldwide, transportation ranks second after electric power as the largest source of emissions, contributing about 20% of the total in recent trends and future projections (IEA, 2006). GHG emissions from transportation, mostly in the form of carbon dioxide (CO_2), are expected to increase with the projected growth of personal vehicle fleets in both developed and rapidly developing countries. At present, transportation accounts for more than one-third of end-use sector CO_2 emissions in the United States (US) and more than one-fifth in Japan (EIA, 2006; MOE, 2007). Personal vehicles contribute 62% and 50% of transportation emissions in the US and Japan, respectively (EPA, 2006; GGIOJ, 2008).

The plug-in hybrid electric vehicle (PHEV) has recently been suggested as a low-carbon alternative to conventional transportation that could enter the personal vehicle market within the next decade. Among the other alternatives to conventionally-fueled internal combustion engine (ICE) vehicles are flex-fuel, hydrogen fuel cell, and compressed natural gas (CNG) vehicles. Each of these alternatives, including the PHEV, requires at least some technological advancement to bring down the cost or offer other advantages that enable them to substantially replace the existing fleet of vehicles. Vehicles with flexibility to use high-percentage biofuel blends (flex-fuel vehicles) involve relatively low-cost modifications to existing engine

---

* Corresponding author.
E-mail address: jreilly@mit.edu (J.M. Reilly).

0965-8564/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tra.2010.04.004

and fuel system designs, but few refueling stations carry these fuels at present. Hydrogen fuel-cell vehicles still have large technological hurdles to overcome to bring them near to commercial viability (NRC, 2004; Sandoval et al., 2009). The reduction in GHG emissions from CNG vehicles may not be substantial, especially if the natural gas is imported as LNG (Brinkman et al., 2005). Comparing the environmental impact of alternative fuel vehicles requires careful accounting of all emissions related to vehicle manufacturing as well as fuel production and use (Hackney and de Neufville, 2001).

We use a computable general equilibrium model to investigate the prospects for PHEV market entry in the US and Japan, and to evaluate the potential associated impact on the energy system and environment. A PHEV is defined by its ability to run on battery-stored electricity supplied from the grid as well as gasoline or diesel in a downsized on-board internal combustion engine (ICE). Our modeling strategy is designed to identify conditions under which the PHEV could most contribute to reductions in greenhouse gas emissions. We examine factors specific to the PHEV technology as well as external market and policy conditions expected to affect its prospects. We then replicate parts of the analysis for the Japanese case. In Japan the private vehicle fleet is smaller, newer, and generally more fuel efficient, fuel taxes are higher, and electricity generation relies much less on coal. Japan is already a leading source of electric-drive vehicles (for example, the Toyota Prius) and related technology, including advanced batteries. By considering both the US and Japanese markets we hope to understand better how these different market conditions could affect the economic competitiveness of PHEVs.

Transportation – and the growing fleet of private household vehicles in particular – is one of the most difficult and costly parts of the US economy to achieve emissions reductions. Even a cost-competitive low carbon technology would take several decades to make a significant impact on total emissions due to the slow fleet turnover rate. Concerns about reliability, cost, and ease of use may further prevent rapid increases in PHEV sales. Alternative fuel vehicles have received growing attention over the past decade, and discussion of whether and how to support their introduction through policy has been a matter of considerable debate in the US and abroad (Liu and Helfand, 2009). The ICE has remained the dominant transportation technology since it was first marketed in the early 1900s, and an extensive infrastructure has developed to support it. However, continued reliance on the ICE, even with improvements in fuel economy, is unlikely to be consistent with a climate policy goal of stabilizing atmospheric GHG concentrations within the next century.

The article is organized as follows. Section 2 describes the main features of the PHEV technology and its anticipated costs, and compares them to today's ICE-only vehicles. Section 3 explains how a PHEV sector was implemented in the Emissions Prediction and Policy Analysis (EPPA) model in both the United States and Japan. In Section 4, this modified version of the EPPA model is used to evaluate how two important properties of the PHEV, the vehicle cost and all-electric range, affect the timing of PHEV market entry. We then test the sensitivity of these results to the implementation of a climate policy and the availability of a low carbon fuel substitute, advanced cellulosic biofuels (referred to here as "biofuels"). Section 5 evaluates the impact of PHEV adoption on electricity output, refined oil consumption, carbon emissions in total and by sector, and consumption losses due to the implementation of a climate policy. Section 6 summarizes the conclusions.

2. The plug-in hybrid electric vehicle: Technology and costs

2.1. Description of PHEV technology

The PHEV is a vehicle capable of running on both grid-supplied electricity stored in an on-board battery and refined liquid fuel(s) in an internal combustion engine. The PHEV differs from today's hybrid vehicles (such as the Toyota Prius) in that the PHEV typically relies entirely on battery power over a fixed distance and can be recharged from the electric grid.[1] Beyond this fixed distance, or "all-electric range," the vehicle operates as an off-grid (or conventional) hybrid, with the fuel economy benefits that result from relying on the battery and electric motor to reduce efficiency losses. However, PHEVs require higher power and energy from the battery than do conventional hybrids because they rely more extensively or entirely on battery-stored electricity for propulsion.

The most often-cited barriers to commercialization of the PHEV are battery performance and cost (Duvall, 2004). Although battery power and energy per unit volume has steadily improved over the last ten years, battery packs for vehicles remain costly and large in size, while on-road durability and safety remain unproven. Batteries for the PHEV are expected to employ the lithium-ion chemistry, which offers more power and energy per unit volume than nickel metal hydride or other common battery types. Recently announced PHEV models are expected to use lithium-ion batteries. Commonly used in personal electronics, the lithium-ion battery still faces hurdles to its application in vehicles. In addition to concerns about safety, durability, and performance, achieving these targets at reasonable cost remains a major challenge (Kromer and Heywood, 2007). Although many analysts believe production at scale will drive down battery cost, it is unclear if and on what time frame these costs will allow the PHEV to become competitive with conventional vehicles.

An important aspect of analyzing the environmental and economic benefits of PHEVs is the proportion of vehicle-miles driven in all-electric mode. We denote this fraction as the utility factor, UF, which can take on values $0 < \mathrm{UF} < 1$ (Simpson, 2006). The value $1 - \mathrm{UF}$ is then the fraction of miles powered by the internal combustion engine. The main factors determining the UF are the vehicle's all-electric range and user driving and recharging habits. The all-electric range is denoted in miles with, for example, the shorthand PHEVX, where X is the range in miles. Given the cost and performance issues with batteries

---

[1] Some PHEV designs have been proposed in which the battery and internal combustion engine are operated simultaneously in a so-called "blended" mode, allowing for further battery and ICE downsizing (Kromer and Heywood, 2007).

as discussed above, the main trade-off in offering a longer all-electric range is the increased battery cost against the additional savings in avoided fuel costs. With regard to users habits, households could reduce trip length or take other measures to increase driving on battery power alone, thereby raising the UF.

2.2. The economics of the PHEV

Past studies have taken a variety of approaches to estimating the up-front and recurring costs of PHEV ownership. Some studies identify and sum current estimated component costs to determine total PHEV cost (Simpson, 2006; Anderman et al., 2000; Graham, 2001; Duvall, 2004), while other studies have assumed advances in battery technology and production at scale to forecast how costs are likely to have evolved by some specified future point (Kromer and Heywood, 2007; Simpson, 2006). A brief summary of PHEV cost estimates from the literature is presented below.

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 magnitude of these reductions will depend on production volume. The extent of cost reductions possible at scale has been estimated for nickel metal-hydride batteries in the 2000 BTAP Report (Anderman et al., 2000). Analysts have expressed confidence that cost reductions with scale will occur for lithium-ion battery chemistries as well (Duvall, 2004; Simpson, 2006). Third, battery production costs are sensitive to the prices of constituent commodity metals, which introduce additional uncertainty into longer term projections (Gaines and Cuernca, 2000).

While the battery is the main driver of PHEV cost, translating battery cost into vehicle cost involves adding the cost of the battery management system and other battery-related components. Two studies offer detailed estimates of the cost of a PHEV, based on engineering cost information, which are summarized in Table 1. One study, by Simpson (2006) of 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. 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 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 $2500 to $3500. The discrepancy in the estimates appears to be due primarily to differences in assumptions about battery requirements. Overall, these estimates suggest that the PHEV is likely to be more expensive than a conventional vehicle by 22–66% for a PHEV20 (PHEV with 20-mile all-electric range), whereas the markup could be as high as 41–114% for a PHEV60.

Fuel costs for the PHEV can be calculated directly using the prevailing prices of refined oil and electricity, weighted by the utility factor, which reflects the fraction of total miles traveled on electricity (versus conventional hydrocarbon fuels). Included in Table 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 current estimates for the United States. From Table 2, it can be seen that despite the higher up-front cost, improved fuel economy of both the hybrid and PHEV models translates into savings within the lifetime of the vehicle due to the avoided fuel cost. However, it should be noted that the recurring savings are not discounted. Standard economic analysis would discount future cost savings based on the consumer's opportunity cost of money. For example, a consumer financing a new car purchase might pay a nominal interest rate of 6–8% if expected inflation is 3–4% and the real interest rate is 3–4%. Thus, if the extra cost of the vehicle is financed, any future fuel savings should be discounted at this rate to determine whether they cover the extra cost of the vehicle and the real cost of financing. On the other hand, consumers with credit card debt may pay nominal interest rates of 20% or more. Studies often find that the discount rate implied by consumers' choices on energy-saving investment are quite high (Hausman, 1979; Gately, 1980). There are a number of possible reasons for this observation

Table 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[a]	$23,392	$23,392
Conventional hybrid	+$5381	+$3266
PHEV20[b]	+$15,543	+$8436
PHEV60	+$26,792	+$13,289
Graham (2001)		
ICE-only	$18,000	
Conventional hybrid	+$2500–$4000	
PHEV20	+$4000–$6000	
PHEV60	+$7400–$10,000	

[a] ICE-only – a vehicle powered solely by an internal combustion engine.

[b] PHEV*X* – plug-in hybrid electric vehicle with all-electric range equal to *X*.

Table 2
Estimated costs for ICE-only and plug-in hybrid electric vehicles.

Cost estimates for a mid-size sedan	ICE-only	PHEV, 30-mile range
Vehicle cost (MSRP)[a]	\$20,000	+\$10,000
All-electric range	N/A	30 miles
Miles per gallon (ICE)	20 mpg	43 mpg
Annual amount of fuel (gal, kWh)	650 gal	121 gal 2430 kWh
Annual cost of fuel[b]	\$1937	\$555
Payback period (undiscounted)	N/A	∼8 years

[a] Manufacturer's suggested retail price as estimated from ICE-only 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 vehicle-miles traveled are assumed to be 13,000 in the United States.

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

including high actual opportunity cost of funds to consumers (i.e., credit card rates), use of other decision rules, different expectations about future prices, skepticism or lack of information on potential energy savings, or real or perceived differences in the quality of the service delivered by the energy-saving investment. Table 3 shows the payback period for a variety of fuel and electricity prices and discount rates under simple assumptions that these prices remain constant over the life of the vehicle. A payback period of greater than 10 or 15 years likely exceeds the lifetime of the vehicle and thus would represent a choice that was non-economic under conventional economic accounting. In general, it takes a gasoline price of \$4 per gallon or more before there is a strong economic case for the PHEV as specified in this example.

The PHEV derives a cost advantage compared with the ICE-only vehicle due to its ability to use electricity combined with the fuel economy benefits of the more efficient ICE. The evolution of the relative prices of electricity and gasoline, as well as the emergence of additional alternative vehicle designs, will influence the trade-off the consumer faces between up-front vehicle costs and recurring fuel cost savings.

2.3. Environmental impact of the PHEV

The environmental impact of a PHEV stems primarily from two sources: combustion of refined fuel in the on-board ICE and the generation of electricity from a portfolio of 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 all of these sources when estimating emissions due to the miles driven using the ICE. Since the per-barrel emissions associated with extraction and production of refined oil may increase in the future, even limited usage of the internal combustion engine in a PHEV could have a sizable environmental footprint.

Emissions associated with PHEV use of battery-stored energy 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 calculated per mile equivalent emissions for the PHEV running on electricity, which correspond to emissions from the production of the electricity needed to charge it. Other studies report the average per mile emissions of the PHEV due to both electricity and refined oil usage, which requires an estimate of the proportion of miles the vehicle will operate on battery power (the UF). Such estimates, along with their assumptions, have been summarized in Table 4.

Regarding the estimates in Table 4, there are differences among the studies in per mile emissions even for an ICE-only vehicle. These reflect in part varying coverage of emissions but also likely reflect different assumptions about vehicle fuel economy, size, weight, and drive cycle. While such differences create some issues in comparing across studies, the within study differences highlight how the primary source of electricity generation affects emissions. For example, the Electric Power Research Institute (EPRI) study finds that emissions from a PHEV using electricity generated with coal (even if from

Table 3
Sensitivity of PHEV payback period (in years) to gasoline and electricity prices and the annual discount rate.

		Discount rate		
		0%	4%	10%
Gasoline price[a]	\$2/gal	14	>15	>15
	\$3/gal	8	10	>15
	\$4/gal	6	7	9
Electricity price[b]	\$0.08/kWh	8	9	14
	\$0.12/kWh	8	10	>15
	\$0.16/kWh	9	10	>15

[a] Assumes electricity price remains constant at \$0.12/kWh.

[b] Assumes gasoline price remains constant at \$3/gal.

Table 4
Estimated CO_2-e emissions in grams per mile for the ICE only vehicle, conventional hybrid, and PHEV.

Electric Power Research Institute (Duvall and Knipping, 2007)					
ICE-only[a]	Hybrid	PHEV20 – 2010 coal	PHEV20 – 2035 coal	PHEV20 – nuclear	PHEV20 – renewables
450	295	325	305	150	150
National Renewable Energy Laboratory (Parks et al., 2007)					
ICE-only[a]	Hybrid	PHEV20 – off-peak charging		PHEV20 – continuous charging	
410	299	247		221	
MIT Sloan Automotive Laboratory (Kromer and Heywood, 2007)					
ICE-only[a]	Hybrid	PHEV30		Electric-only	
477	140	138		185	

[a] ICE emissions correspond to the average for current (2007) new vehicles sold in the US (except for the Electric Power Research Institute study, which estimates improvements likely to occur by 2010).

a new high efficiency plant) would be more than the conventional hybrid but considerably less if the electricity was generated from nuclear or renewable energy (Duvall and Knipping, 2007). The National Renewable Energy Laboratory (NREL) study shows that the time-of-day of recharging can affect emissions owing to the fact that in some regions baseload generation capacity that would be operating at night is more likely coal, whereas daytime recharging would require peaking capacity that is more likely natural gas-based generation (Parks et al., 2007).

3. PHEV transportation in the MIT EPPA model

3.1. Background on the MIT EPPA model

We begin by describing our modeling strategy, then follow with a more detailed technical description of the model and the newly added PHEV sector. Although many PHEV designs have been put forward and several prototypes built, technical and cost barriers remain to the manufacture and adoption of PHEVs on a large scale. Our first objective is to understand under what combinations of cost and technology conditions the PHEV could become economically viable. Second, we are interested in how, under optimistic cost assumptions, a PHEV could affect refined oil consumption, CO_2 emissions, and the costs of meeting aggressive climate policy targets over the next century. By introducing the PHEV as an alternative to conventional transportation within a modeling framework that includes the electricity, transportation, and refining (fuel) sectors, we simulate how the PHEV might fare against a backdrop of changing technologies as well as fuel and electricity prices. 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 such constraints on the allocation of goods and services in the economy through the year 2100. The imposition of a policy constraint on CO_2 emissions results in a price for CO_2 that is reflected in the cost of carbon-intensive fuels, which in turn affects the relative prices of energy-intensive goods and services. As a result, a climate policy could change the economics of otherwise uncompetitive technologies that offer significant emissions reductions compared with existing in-use technologies.

To examine the issues discussed above we use the EPPA model, 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 using the GTAP dataset (Hertel, 1997; Dimaranan and McDougall, 2002). 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 (Table 5). Additional data for greenhouse gas (carbon dioxide, CO_2; methane, CH_4; nitrous oxide, N_2O; hydrofluorocarbons, HFCs; perfluorocarbons, PFCs; and sulphur hexafluoride, SF_6) and air pollutant (sulphur dioxide, SO_2; nitrogen oxides, NO_x; black carbon, BC; organic carbon, OC; ammonia, NH_3; carbon monoxide, CO; and non-methane volatile organic compounds, VOC) emissions is based on United States Environmental Protection Agency inventory data and projects.

Much of the sectoral 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, and the model is solved recursively in 5-year intervals starting with the year 2000. The EPPA model represents production and consumption sectors as nested Constant Elasticity of Substitution (CES) production functions (or the Cobb-Douglas and Leontief special cases of the CES). The model is written in the GAMS software system and solved using the MPSGE modeling language (Rutherford, 1995). The EPPA model has been used in a wide variety of policy applications (e.g., US CCSP, 2007).

The EPPA model also includes many low carbon technologies that were either not developed or pre-competitive in 1997, but could enter the market in the future under favorable cost conditions. For example, these technologies may be too expensive relative to pre-existing technologies. Bottom-up engineering detail is used to specify these so-called “backstop” technologies (Jacoby et al., 2004; McFarland et al., 2004). The competitiveness of these technologies depends on the evolution of endogenously determined prices for all inputs. These input prices in turn depend on the depletion of resources, policy, and other forces driving economic growth such as savings, investment, and productivity of labor. In the model, the PHEV is specified as one such “backstop” technology, and is described in detail in the next few sections.

Table 5
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 and New Zealand
Household transportation: internal combustion engine vehicles	Former Soviet Union
Household transportation: plug-in hybrid electric vehicles	Eastern Europe
Energy	*Developing*
Coal	India
Crude oil	China
Refined oil	Indonesia
Natural gas	East Asia
Electricity generation technologies	Mexico
Fossil	Central and South America
Hydro	Middle East
Nuclear	Africa
Solar and wind	Rest of World
Biomass	
Natural Gas Combined Cycle (NGCC)	
NGCC with CO_2 Capture and Storage (CCS)	
Advanced Coal with CCS	
Synthetic gas from coal	
Hydrogen from coal	
Hydrogen from gas	
Oil from shale	
Liquid fuel from biomass	

Note: Detail on aggregation of sectors from the GTAP sectors and the addition of advanced technologies are provided in Paltsev et al. (2005). Details on the disaggregation of industrial and household transportation sectors are documented in Paltsev et al. (2004).

The electricity sector in EPPA is modeled according to the share of each generation type in the total US or Japanese electricity production in the base year. The version of the EPPA model used here does not capture dispatch dynamics (baseload, peaking, and shoulder electricity generation). Rather each generation type is characterized by the per kilowatt hour cost of providing electricity and an average emissions rate. The share of electricity generation by primary source evolves in response to changes in the relative costs of underlying fuels. In all cases, the electricity generation mix is assumed to grow more efficient with time, consistent with historical trends, at a rate of about 0.4% per year. Household electricity use (including usage by PHEVs) is modeled as demand for a "grid-average" kilowatt hour. Additional electricity required to supply PHEVs is assumed to result in an increase in electricity generation (and its associated emissions) according to the lowest marginal cost source available. Under a policy, carbon-intensive electricity sources grow relatively more expensive due to the cost of meeting the GHG emissions constraint.

3.2. The household transport sector in the EPPA model

Previous work augmented the GTAP data set to create a household transportation sector in the EPPA model that supplied the transportation needs of individual households (Paltsev et al., 2004). Spending on transportation is assumed to be a constant fraction of the household budget, based on work by Schafer (1998) and Schafer and Victor (2000). In this version of the EPPA model, the household chooses between purchased transport and the services of household-owned vehicles as shown in Fig. 1.

Elasticities of substitution reflect a combination of consumer preferences as well as physical and technical limits to substitutability. The most crucial elasticities given our interests in the effect of carbon policy are those that determine substitution away from fuels or away from own-supplied transportation. The main evidence for these elasticities comes from econometric studies, which often estimate the price elasticity of fuel demand. The price elasticity of demand is closely related to the substitution elasticity between fuel and other inputs as described in Paltsev et al. (2004). That paper also reviews the econometric evidence for values of this key elasticity.

3.3. Implementing a PHEV sector in the MIT EPPA model

To investigate PHEVs, we implement a vehicle technology in the own-supplied transport sector that uses both refined oil and grid-supplied electricity and competes directly with ICE-only transportation. We represent PHEVs with a production structure similar to that for conventional vehicles but with electricity added as an input. The ICE-only vehicle sector utilizes existing expenditure data and must be consistent with the national income and product account data that is the basis for the

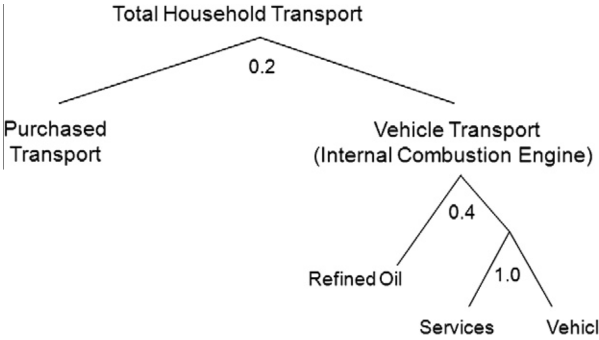

Fig. 1. The disaggregation of the household transportation sector in the MIT EPPA model.

model. The PHEV sector does not yet exist and so there we rely on engineering cost data. The key components of the production structure are (1) cost share parameters for each input that across all inputs sum to 1 and that given base year prices are consistent with technical efficiencies expected of PHEVs, (2) the production structure and elasticities of substitution, and (3) markup factors that are multiplied times input shares and capture how the cost of the technology differs from ICE-only vehicles represented in the base year data.

3.3.1. Defining input shares to the PHEV sector

The inputs to the PHEV sector in the EPPA model 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 supplied by a PHEV). The calculation of the share of each input to PHEV transportation is based on similar calculations for the pre-existing disaggregated household transportation sector (ICE-only vehicles). We first identify the values of ICE-only transportation inputs for the base year 1997 with vehicle cost expressed as an annualized cost. Starting with motor gasoline consumption in 1997 and assuming a fleet average fuel economy of 20 miles per gallon, the implied vehicle-miles traveled is calculated. We then estimate fuel and electricity requirements if the fleet had instead been PHEVs and driven the same mileage. The ICE in the PHEV is assumed to achieve a fuel economy of 43 miles to the gallon, slightly more than twice its counterpart in the average 1997 ICE-only light-duty vehicle, which supplies 40% of total vehicle-miles driven. The PHEV is assumed to require 0.3 kWh per mile, consistent with previous estimates (Duvall and Knipping, 2007). Given these assumptions on technical efficiency, the electricity and fuel required for the hypothetical 1997 fleet of PHEVs is determined. We then calculate the electricity and fuel share, assuming fuel and electricity prices in 1997 US dollars. The values of these share parameters are shown in Table 6 for the United States and Japan.

3.3.2. The PHEV production structure

Fig. 2 illustrates the production structure for the PHEV sector with cost share parameters for the United States and Japan shown under each input and elasticities shown between input branches. The share parameters of the CES production structure remain unchanged in simulations but actual cost shares will vary as the prices of inputs change. In the production structure, electricity and refined oil inputs to the PHEV sector are represented as a Leontief production function (i.e. with substitution elasticity equal to zero). This relationship assumes the PHEV fleet consists of vehicles with identical all-electric range and that driving patterns are unchanged from the present by the existence of the PHEV and do not respond to changing relative prices of fuels and electricity.[2] For the remaining substitution elasticities (i.e. at the fuel and vehicle-services branch point and at the vehicle and services branch point in the nested structure), elasticities identical to those specified for ICE-only vehicles were used. We assume PHEVs are a perfect substitute (infinite elasticity) for conventional vehicles.

There are a number of factors that may lead to a gradual market penetration of any new technology. For a new vehicle technology this includes fleet turnover, scaling up production, retooling of vehicle manufacturing plants, and the development of infrastructure to service the new vehicle fleet. For PHEVs in particular, households may have varying access to a convenient electrical outlet and driving habits (e.g. typical daily trip lengths) vary in ways that make PHEV more or less attractive. In a manner similar to other new technology sectors in the EPPA model we introduce a fixed factor input to the PHEV sector that is initially available in limited supply. Growth of the PHEV fleet is then limited by the availability of the fixed factor. The fixed factor grows as a function of the share of PHEVs in the total household vehicle sector,

$$FPHEV_{t+1,r} = FPHEV_{t,r} + A_r \times \left(\frac{YPHEV_{t,r}}{YHOSTRN_{t,r}}\right)^b \qquad (1)$$

$$FPHEV_{t_0,r} = 0.00001 \qquad (2)$$

---

[2] The possibility of a mix of available PHEVs with different ranges and costs as well as consumer willingness to shift driving patterns to increase all-electric use in response to a gasoline price increase could be represented by a non-zero elasticity.

Table 6
ICE-only vehicle and PHEV ownership costs (US $10 billion, 1997) and input shares in the US and Japan.

	Electricity	Fuel	Vehicle	Services
ICE-only, USA	N.A.	4.595	13.907	38.871
Input shares	N.A.	0.080	0.242	0.678
PHEV, USA	0.734	0.855	13.907	38.871
Input shares	0.013	0.016	0.256	0.715
ICE-only, Japan	N.A.	1.319	5.375	7.346
Input shares	N.A.	0.094	0.383	0.523
PHEV, Japan	0.210	0.245	5.375	7.346
Input shares	0.016	0.019	0.407	0.557

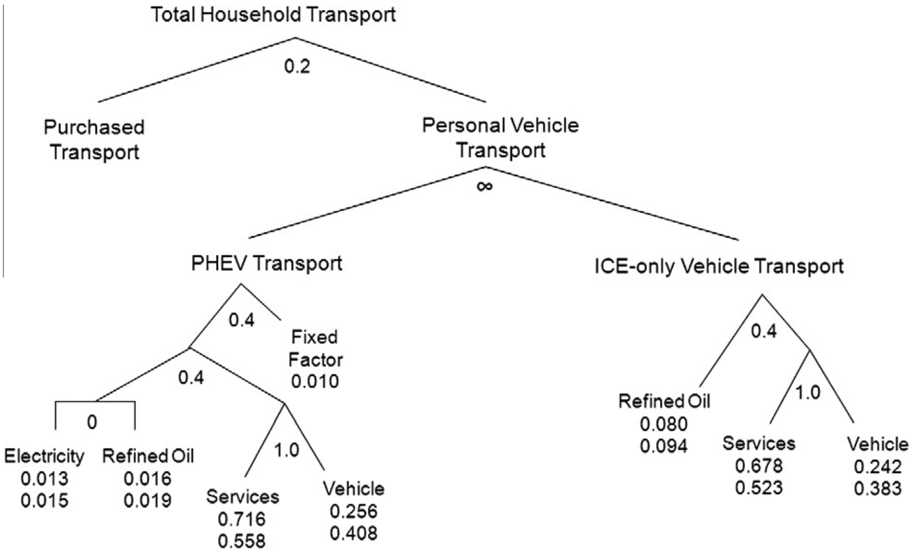

Fig. 2. Nested structure of the household transportation sector showing the addition of the PHEV as a perfect substitute for the ICE-only vehicle. The fixed factor affects the rate of technology turnover. Cost shares for the U.S. (upper number) and Japan (lower number) are given for each input.

where $FPHEV_{t,r}$ is the level of fixed factor in region r at time t (Eq. (1)), $YPHEV_{t,r}$ is the PHEV transportation output, $YHOSTRN_{t,r}$ is total household vehicle transportation output, and $FPHEV_{t_0,r}$ is the initial endowment of the fixed factor (Eq. (2)). All input and output levels are expressed in tens of billions of 1997 US dollars. We base the fixed factor parameters in the US on data for conventional hybrid vehicle penetration over the period 1998 to 2008 from DOE (2008). In the absence of price pressure to substitute for the fixed factor, and given the input share parameter in the production function, the initial year production of the PHEV would be 4500 vehicles. If there were greater demand for PHEVs, the initial production could be greater as governed by the elasticity of substitution between the fixed factor and other inputs. The parameter A, set to 0.1 in the US, is scaled so that the fleet would increase to just over a million vehicles with no additional demand pressure. The parameter b is set at 0.25. With $b < 1.0$, growth of the fixed factor slows as the share of PHEVs increases. The intuition is that expansion into market niches for which PHEVs are not well suited would require greater cost advantage and/or improvements in the range of the vehicle. Slower fixed factor growth results in less rapid expansion of the PHEV fleet. For Japan, the value of A, 0.032, is obtained by scaling the value of the A parameter for the U.S. by the ratio of the size of the household vehicle sector in Japan to that in the US. This specification allows full fleet penetration of PHEVs within 20 years, which would be consistent with estimates of fleet turnover where there is significant economic advantage for PHEVs but more gradual penetration with less demand pressure.

3.3.3. Vehicle markup

We retain the convention that the CES cost share parameters sum to 1 and that implies the same vehicle cost as ICEs, making the PHEV cost-competitive with ICEs in 1997. To represent different PHEV vehicle costs we introduce a markup parameter that is multiplied times the relevant input share(s). We estimate the vehicle markup as a projected cost of the PHEV divided by the cost of an equivalent performance ICE-only vehicle (multiplied by 100 when expressed as a percentage). In simulations we vary this markup parameter to evaluate the impact of the PHEV vehicle cost on its commercial viability. 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.

4. Scenario analysis: Factors affecting PHEV market entry

We use scenario analysis to investigate the potential for commercialization of PHEVs under different assumptions about the vehicle technology, the existence of climate policy, and the availability of biofuels as an alternative low-CO_2 option in transportation. We consider many different combinations of these various assumptions as detailed in Table 7. The PHEV technology characteristics considered are the utility factor and vehicle markup. The policy scenario for the US is drawn from the US CCSP (2007). We take the US emissions constraints for the 450 ppm scenario and impose them in the US without emissions trading among regions (Fig. 3a). The US CCSP (2007) specified a global policy but did not provide details for other regions. We extend a comparable policy for Japan, requiring the same percentage reductions from reference as in the US (Fig. 3b). We refer to the climate policy as a 450 ppm scenario because these paths in the US and Japan are nominally consistent with the world achieving such a target but we do not actually impose a constraint in other regions.

We consider scenarios where biofuels are or are not available. The specification of biofuels assumes a second generation technology that is CO_2 neutral – all process energy is supplied by biomass and the biomass used for conversion and for processing is assumed to be grown without an increase in land use emissions. The parameterization of the technology is such that it would be roughly competitive (in the US) with gasoline at a retail price range of \$4.00–\$5.00 (2005 US \$) per gallon accounting for the differential energy content, state and federal excise taxes, and retail markups. The actual price in any period depends on other prices, especially the price of land for which traditional agricultural products compete (Reilly and Paltsev, 2007). One aspect of this scenario design, with climate policy implemented only in the US and Japan, is that only their demand for biofuels is augmented by the CO_2 constraint and so they face less competition than if other regions of the world were also CO_2-constrained.

4.1. Effect of vehicle markup

We first examine the impact of varying vehicle markup on PHEV entry with and without the 450 ppm climate policy and assuming biofuels are not available. As mentioned, the PHEV is expected to be at least somewhat more expensive than an ICE-only vehicle of equivalent performance when it first reaches the market, as indicated in Table 1. To capture the range of possibilities for the technology we simulate PHEV penetration with markups of 15%, 30%, and 80% for a vehicle with a utility factor of 0.6. The 30–80% range is consistent with current estimates of the technology potential as reviewed in Section 2.2. Achieving a 15% markup would require greater advance in the technology to bring down the cost of a battery designed to support a UF of 0.6. Assuming current driving habits in the US, a utility factor of 0.6 corresponds roughly to a PHEV with a 30-mile all-electric range. A comparison of the impact of vehicle markup on timing of market entry is shown in Fig. 4.

Higher markups slow the rate of PHEV market entry. Even in the absence of climate policy, a PHEV with 15% markup begins to enter the market starting in 2010 when it becomes available (the initial market share is small and we only begin to see a significant effect on overall fleet composition by 2020). Essentially at this vehicle cost markup the fuel cost savings makes the PHEV immediately economically viable, and penetration is limited by the fixed factor growth that simulates fleet turnover and other factors. By the end of the century, around 70% of personal vehicles are PHEVs in this scenario. With a markup of 30%, significant PHEV entry is delayed by several decades, with the end-of-century fleet composed of around 35% PHEVs. The reference oil prices rise faster than electricity prices and thus fuel cost savings are eventually sufficient to make the PHEV economic in the 30% markup case. At a markup of 80%, the PHEV does not enter the vehicle fleet in the period to 2100. Thus, if PHEVs can be produced at the optimistic end of what analysts think is possible they may be commercially viable even without climate policy. Immediate viability would require breakthroughs in the technology that reduce vehicle cost below what experts currently project.

Table 7
A list of scenarios with variation in the percent retail price markup (15%, 30%, 80%) over a conventional ICE vehicle with similar characteristics as well as variation in the utility factor (fraction of miles driven on electricity).

4.1	**Role of PHEV markup** PHEV markup – 15%, 30%, 80%, (UF = 0.6)
4.2	**Role of PHEV utility factor** PHEV utility factor – 0.3, 0.6, 0.8, (markup = 30%)
4.3	**Sensitivity to policy and biofuels availability**
Markup	PHEV markup – 15%, 30%, 80%, 450 ppm Policy (UF = 0.6) PHEV markup, biofuels – 15%, 30%, 80%, No Policy (UF = 0.6) PHEV markup, biofuels – 15%, 30%, 80%, 450 ppm Policy (UF = 0.6)
UF	PHEV utility factor – 0.3, 0.6, 0.8, 450 ppm Policy (markup = 30%) PHEV utility factor, biofuels – 0.3, 0.6, 0.8, No Policy (markup = 30%) PHEV utility factor, biofuels – 0.3, 0.6, 0.8, 450 ppm Policy (markup = 30%)

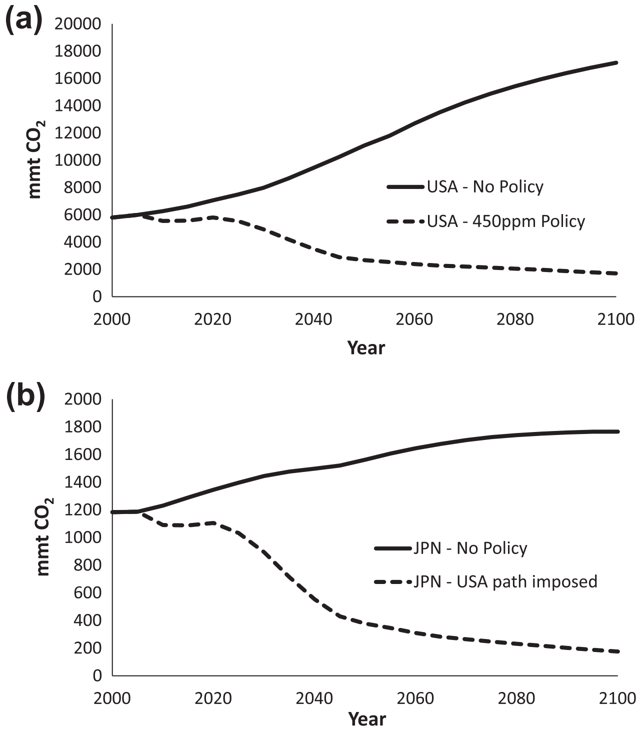

Fig. 3. CO_2 emissions paths in the reference and 450 ppm Policy cases in (a) the United States and (b) Japan.

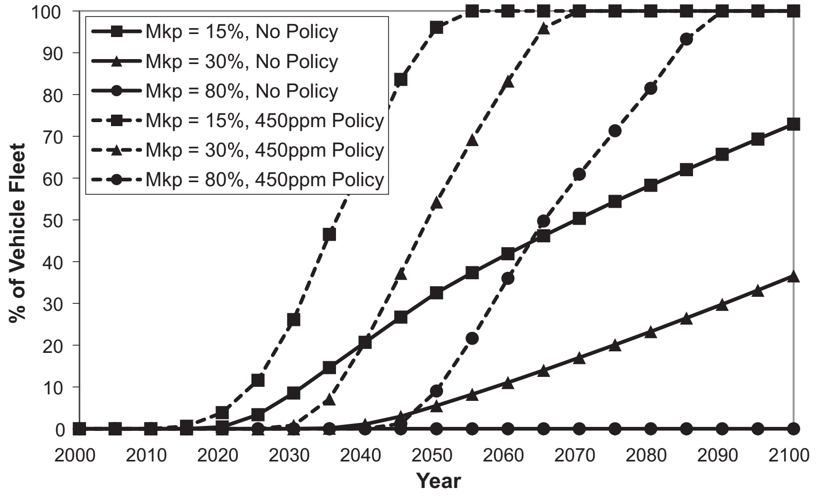

Fig. 4. Impact of vehicle markup on PHEV adoption in the United States when biofuels are not available.

The CO_2 policy changes significantly the prospects for commercial success of the PHEV. Even with a vehicle markup of as much as 80%, the fleet turns over to all PHEVs in the second half the century. Without the PHEV, the only option in this model scenario for reducing vehicle emissions is for households to reduce vehicle use.

Fig. 5 illustrates the effect of biofuels availability on PHEV adoption. In the absence of climate policy (shown in Fig. 5a), the availability of biofuels reduces somewhat the market share of PHEVs. This occurs because biofuels add to the liquid fuel supply, resulting in somewhat less upward pressure on fuel prices, and thereby reducing the incentive to adopt PHEVs. As shown in Fig. 5b, the effect of climate policy is to increase commercial viability of PHEVs compared to the case with no climate policy. However, if we compare the penetration of PHEVs under policy with and without biofuels available, we see that the presence of a CO_2-neutral biofuel alternative reduces significantly the penetration of PHEVs. Essentially, the availability of biofuels makes it possible to continue to drive conventional vehicles and still meet the carbon constraint.

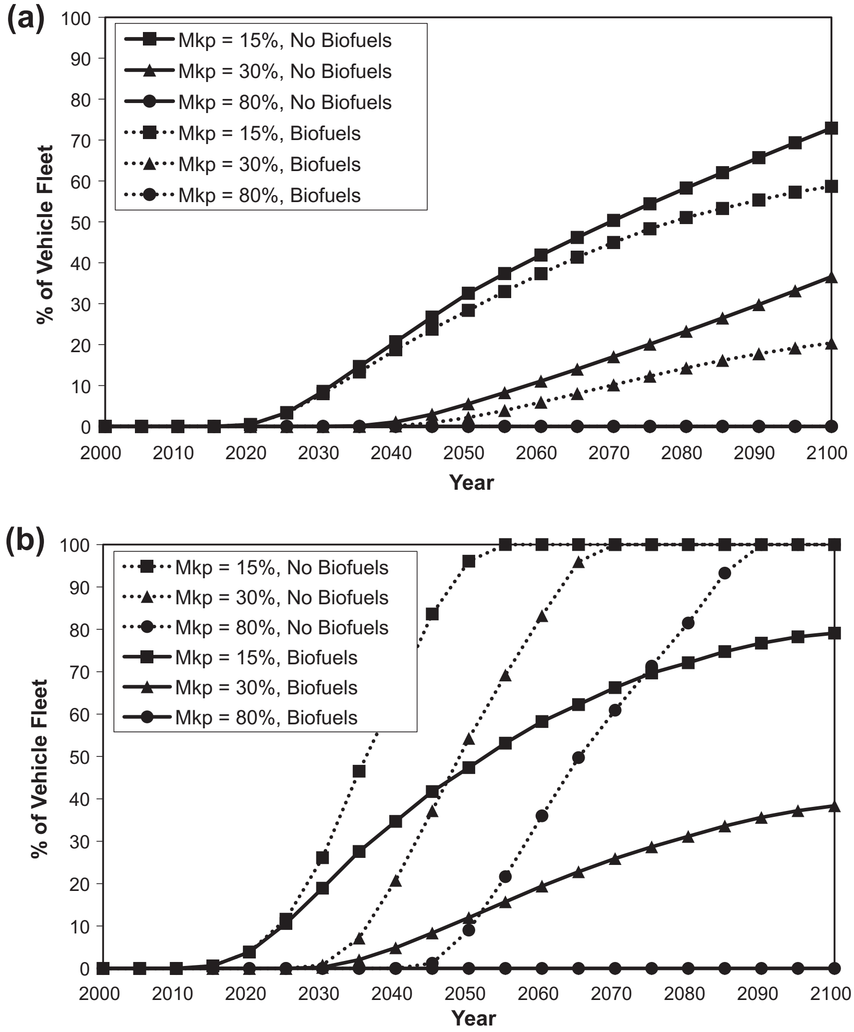

Fig. 5. The impact of biofuels availability on PHEV adoption in the United States (a) with No Policy and (b) with a 450 ppm Policy.

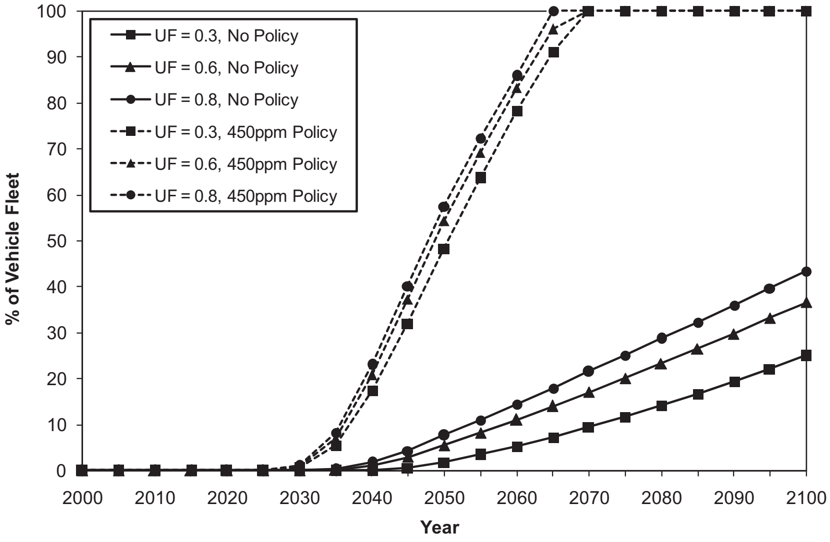

Fig. 6. Impact of UF on PHEV adoption in the United States when biofuels are not available.

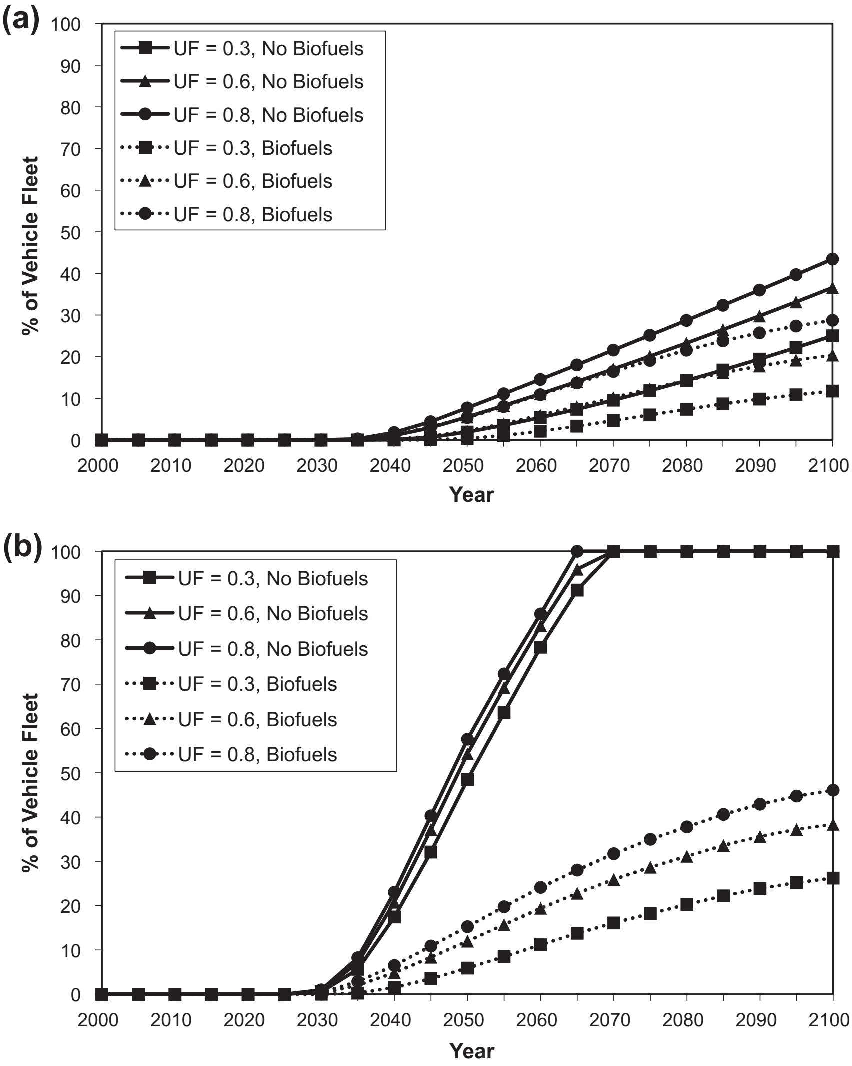

Fig. 7. The impact of UF and biofuels availability on PHEV adoption in the United States (a) with No Policy and (b) with a 450 ppm Policy.

4.2. Effect of all-electric range

The main cost advantage of a PHEV comes from its use of electricity, which is currently less costly on a per mile-equivalent basis. Holding vehicle cost constant, we expect that increasing the fraction of miles a vehicle is able to drive on electricity alone should hasten its market entry. We test this hypothesis by varying the utility factor (the fraction of vehicle-miles traveled supplied by electricity) from the 0.6 used above to 0.3 and 0.8. The PHEV markup in all cases was assumed to be 30%.

The impact of changing the UF under constant vehicle markup can be interpreted in a couple of ways. One interpretation is that these scenarios represent more or less success in advancing battery technology, which results a longer or shorter all-electric range for a given vehicle cost. Another interpretation is that driving habits could change given a viable PHEV. Drivers could adjust by using more commercial transport for long trips, moving closer to work, or choosing activities closer to home. Such changes could mean that the UF for a given all-electric range would be greater the more drivers adjusted their driving patterns. Again, no climate policy constraint was imposed and biofuels were assumed to be unavailable.

The effect of changing the UF on the timing of PHEV market entry in the United States is shown in Fig. 6. Higher UFs correspond to more rapid fleet entry and higher end-of-century percentages of PHEVs in the fleet in the No Policy case (PHEVs take over completely in the 450 ppm Policy cases). However, these effects are less pronounced than the effect of changing vehicle markup. Given that vehicles that allow higher UFs without behavioral adjustment are likely to be more expensive, the effect of markup will likely offset the influence of the utility factor on PHEV adoption in the near term.

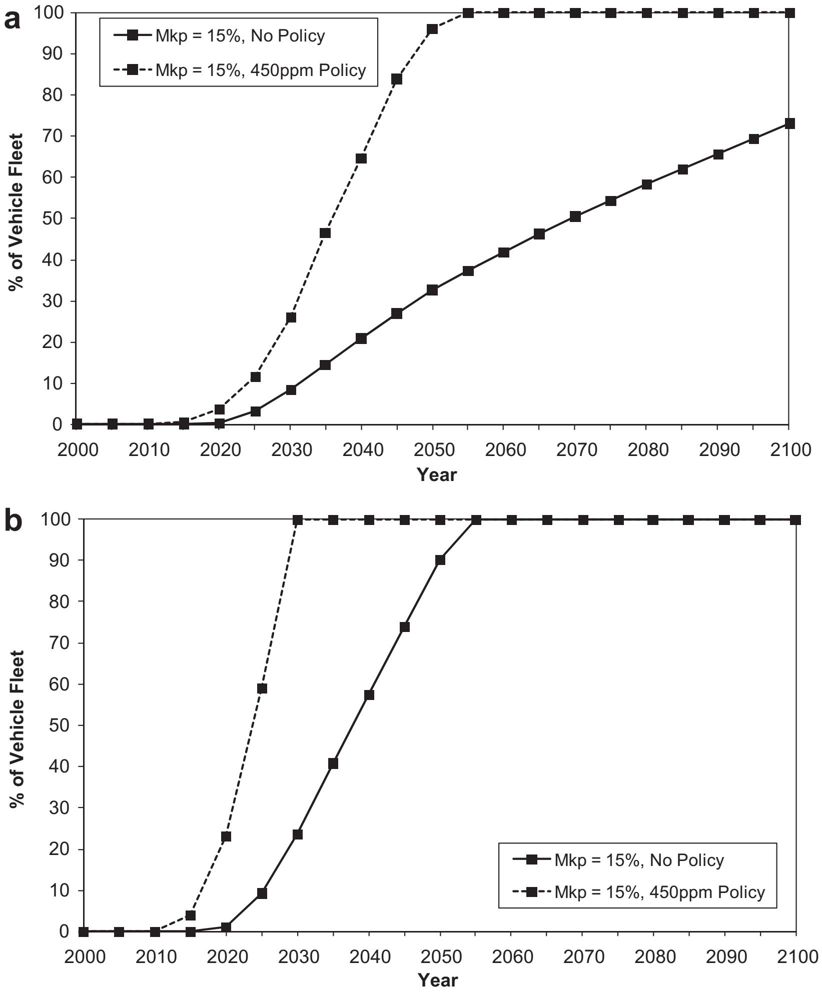

Fig. 8. PHEV adoption path assuming the vehicle markup is 15% and the utility factor is 0.6 in (a) the United States and (b) Japan.

We then consider the impact of UF in the same reference and policy scenarios with biofuels available. In the absence of a policy, the availability of biofuels has a noticeable but modest effect in reducing PHEV fleet penetration over the course of the century (see Fig. 7). For example, in the absence of biofuels, a PHEV with a UF of 0.8 reaches around 30% of the fleet by the end of the century. This percentage drops below 20% if biofuels are available. With policy, increasing the UF of the PHEV does not significantly offset the adoption of biofuels as the preferred low carbon solution. The biofuels scenario results do not change the conclusion that PHEVs with higher utility factors (for a given markup and assumption about policy) are likely to be increasingly economically competitive.

5. Scenario analysis: PHEV impact

Large-scale adoption of plug-in hybrid electric vehicles has been suggested as a way to alter current patterns of fuel use in electricity and transportation, energy-related emissions, and, over the longer term, offset the economic costs of pursuing a climate policy. In the following section, we develop comparisons between pairs of scenarios with and without an inexpensive PHEV available (15% markup compared with conventional transportation) in the United States and Japan. In particular, the impact of the PHEV on the following outcomes is evaluated:

- Total electricity output.
- Refined oil consumption.
- Total and sectoral carbon dioxide emissions.
- Carbon price under policy.

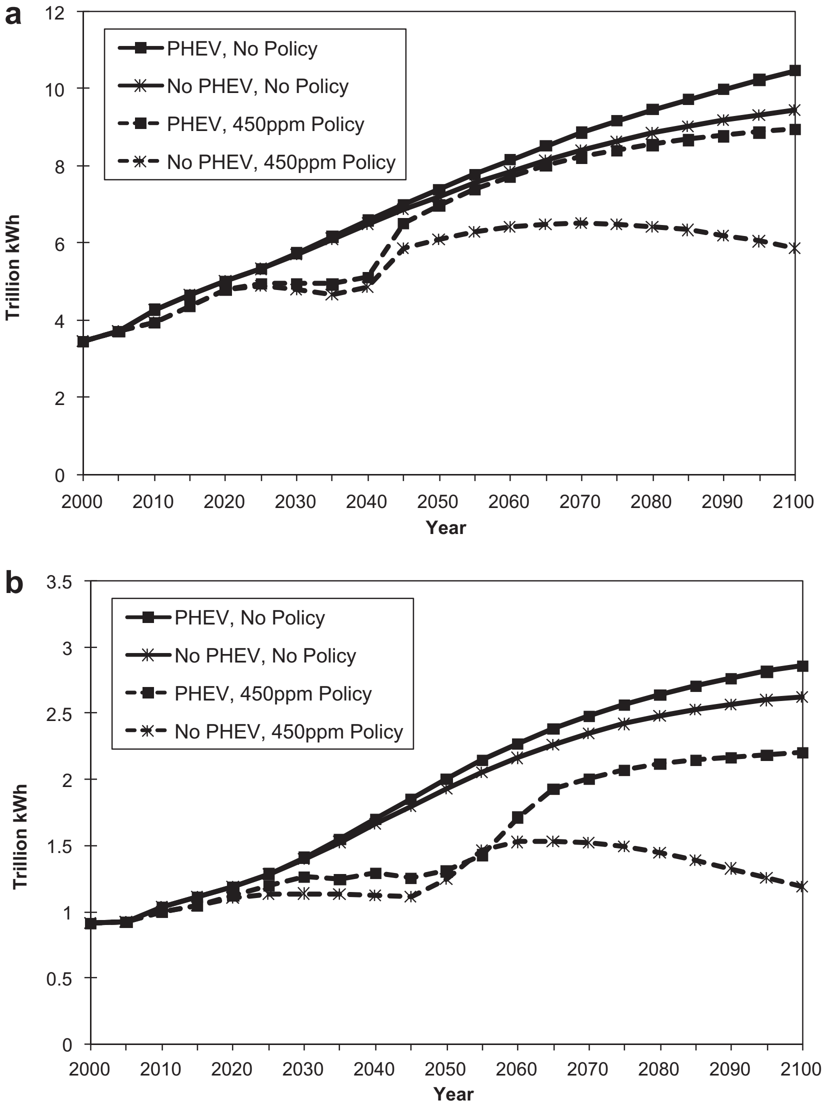

Fig. 9. Impact of PHEV adoption on electricity output in the United States in the No Policy and 450 ppm Policy cases in (a) the United States and (b) Japan.

The rationale behind the 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. Biofuels are not available in the cases considered here unless specified otherwise. In all scenarios, the vehicle markup is assumed to be 15% and the utility factor is assumed to be 0.6. Given these assumptions, the market entry paths for the PHEV in both the United States and Japan are shown in Fig. 8. Penetration in Japan is faster, even without policy. This reflects in part the higher prices, tax inclusive, in Japan that make the PHEV more economic. PHEVs under these circumstances could fully penetrate the fleet in Japan by 2050 while reaching a substantial 20% penetration of the US fleet.

5.1. Effect of PHEV on electricity output

Adoption of the PHEV in the US would result in an increase in demand for electricity. Using the model, we estimated the increase in demand needed to supply the PHEV fleet in 2100 to be around 10% (1 trillion kWh) in the No Policy case, but 52% (3.1 trillion kWh) in the 450 ppm Policy case. The difference in demand over the next century is graphed in Fig. 9a. In the 450 ppm Policy case, carbon capture and storage is available and is applied to almost all electricity production with a higher than 90% capture efficiency by the end of the century.[3] The larger percentage increase in electricity required in the 450 ppm

---

[3] The efficiency of carbon capture and storage when it first becomes available in the model is assumed to be 90%. However, in the model capture efficiency is endogenously driven to higher efficiencies as the carbon price increases.

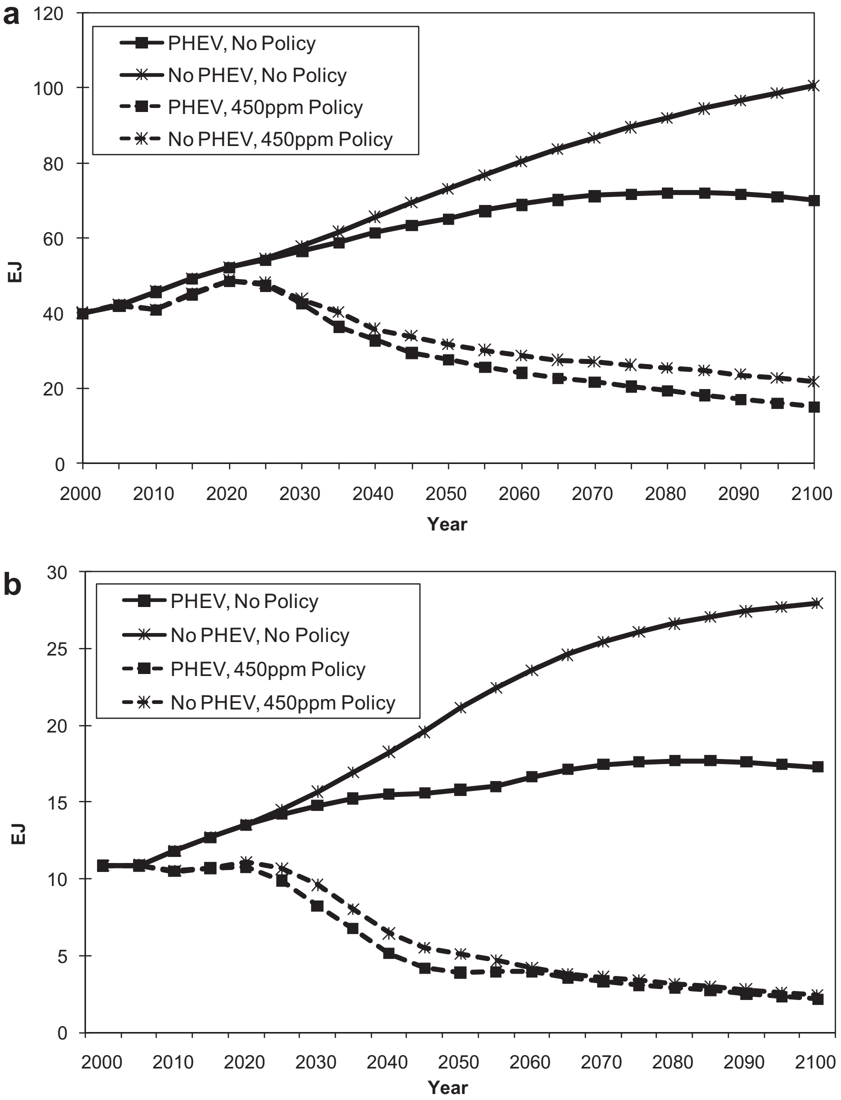

Fig. 10. Impact of PHEV adoption on refined oil consumption in (a) the United States and (b) Japan.

Policy case compared to the No Policy case is a result of the difference in PHEV uptake by the household vehicle fleet. Also, the increase in percentage terms is greater because non-PHEV electricity demand is depressed relative to the reference because of higher prices. This result indicates the two forces operating in opposite directions on electricity demand. On the one hand, employing low carbon power generation technologies raises the cost of electricity, causing electricity users to adopt more efficient end-use technologies. On the other hand, where there are no other low carbon options and electricity can be substituted for liquid fuels (such as in transportation with PHEVs), a carbon policy will tend to increase the demand for electricity.

In Japan, electricity use increases by 9% in response to universal household PHEV adoption by the end of the century in the No Policy case as shown in Fig. 9b. In the 450 ppm Policy case, electricity usage is 86% higher by the end of the century when the PHEV is available compared to when it is not, since increasing usage of (decarbonized) electricity to displace petroleum-based fuels from transportation is an economically attractive way to satisfy the CO_2 constraint.

5.2. Impact of PHEV on refined oil consumption

We further consider the potential of the PHEV to reduce demand for refined petroleum-based fuels. As shown in Fig. 10a, in the absence of a climate policy, refined oil consumption in the United States would drop significantly with the introduction of the plug-in hybrid electric vehicle, reaching 34% below what it would have otherwise been in 2100 in the absence of the PHEV. In the 450 ppm Policy case, refined oil consumption is far lower in both the presence and absence of the PHEV than

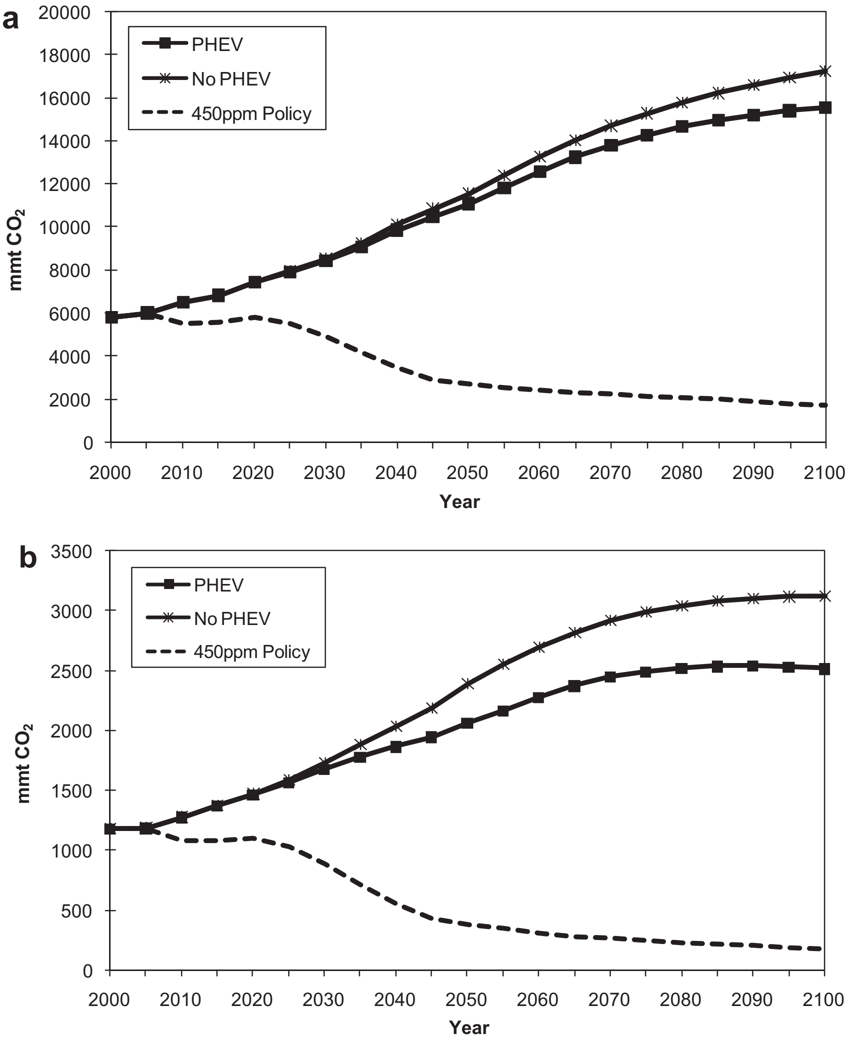

Fig. 11. Impact of PHEV adoption on total fossil fuel carbon dioxide emissions in (a) the United States and (b) Japan.

it was in either of the No Policy cases due to the carbon constraint. The difference due to the PHEV is far less significant in the 450 ppm Policy case because the magnitude of the reduction required to comply with the policy is so large that the PHEV does not make a significant contribution. The carbon constraint must be met whether or not the PHEV is available and there are few options left after 2050 other than to reduce emissions in transportation. In the 450 ppm Policy case, refined oil consumption drops significantly even in the absence of a PHEV.

In Japan, the PHEV similarly reduces total refined oil consumption, although the drop in demand is much sharper due to its more rapid adoption (see Fig. 10b). As personal vehicle transportation is allowed to grow unconstrained through the remainder of the century, refined oil consumption once again increases, with the end-of-century year-on-year reduction in consumption reaching 30%. This percentage change reflects displacement of refined oil in the transportation sector but the continued use of refined oil in other sectors, such as electricity generation. In the 450 ppm Policy case, the PHEV allows an incremental decrease in refined oil usage compared to the No PHEV case, which is less pronounced by the end of the century.

5.3. Effect of PHEV on carbon dioxide emissions

5.3.1. Total carbon dioxide emissions

The opposing pressures of PHEV entry on electricity output and refined oil consumption lead us to ask how net changes in the use of underlying carbon-intensive primary energy sources affect the total carbon dioxide emissions from the US and Japanese economies. The model outputs shown in Fig. 11a indicate that PHEV adoption, even without a carbon constraint, results in a reduction in total carbon emissions of around 10% in the year 2100 in the US, by which time the PHEV accounts

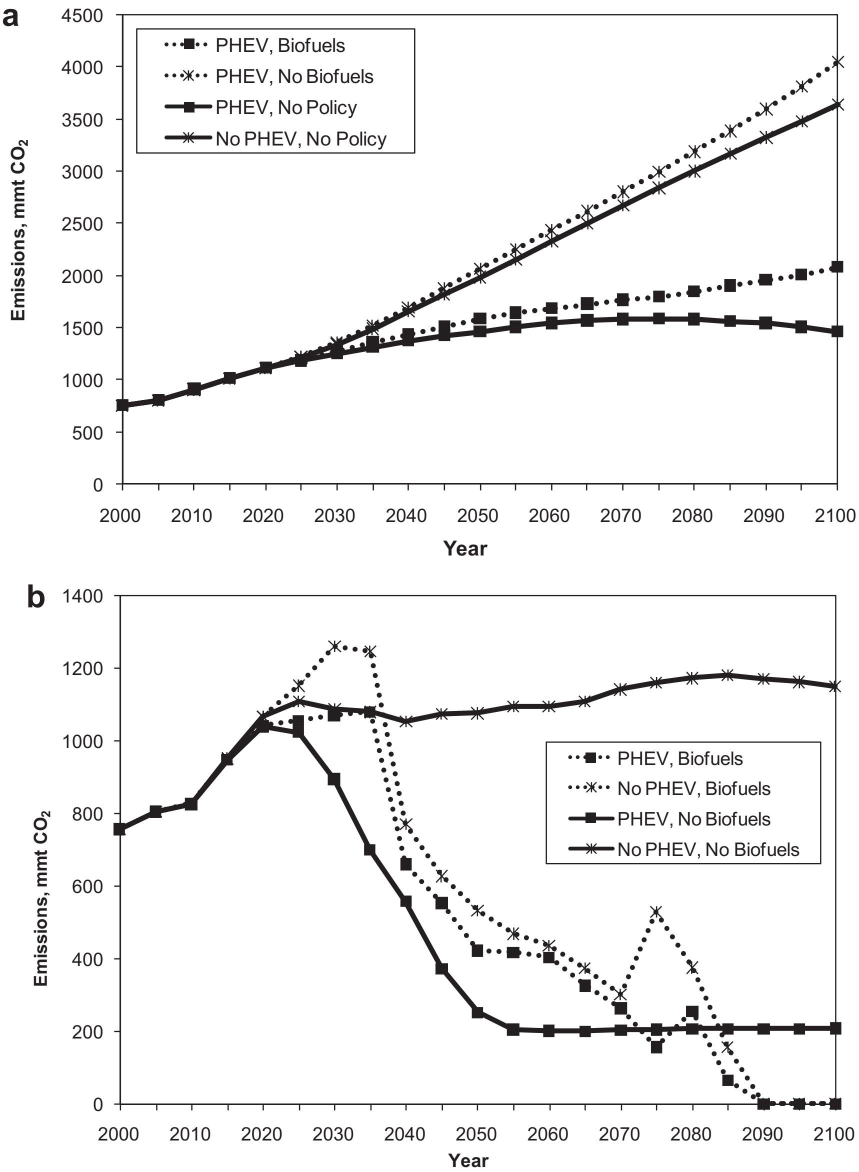

Fig. 12. Impact of PHEV adoption on emissions from the US household vehicle transport sector in the (a) No Policy and (b) 450 ppm Policy cases.

for around 70% of the personal vehicle fleet. Emissions are constrained to meet a specific path in the 450 ppm Policy case and so they are unaffected by PHEV availability.

In Japan, the reduction in emissions due to the PHEV occurs sooner due to the earlier PHEV fleet penetration and continues as the fleet expands (using PHEVs instead of ICE-only vehicles) (see Fig. 11b). Carbon emissions are reduced in Japan by 19% relative to the No PHEV case. Although larger than the US in percentage terms, end-of-century reductions in Japan due to the PHEV are only 30% of the US reductions in absolute terms. Still, the PHEV may represent an important solution in Japan, both because it is economically viable sooner and can achieve significant reductions in the near term due to the lower average carbon intensity of electricity generation.

5.3.2. Effect on carbon dioxide emissions in household transportation

Now we turn to the impact of the PHEV on emissions from personal vehicle transportation only, ignoring for the moment any corresponding increases in upstream electricity or refining sector emissions. A comparison of household transportation emissions was made with and without a low cost PHEV in both the presence and absence of biofuels. In the No Policy case, significant PHEV market penetration leads to a dramatic reduction in sector emissions, almost 60% below the No PHEV case, when biofuels are not available (Fig. 12a). When biofuels are available, emissions rise relative to the No Biofuels cases (due in

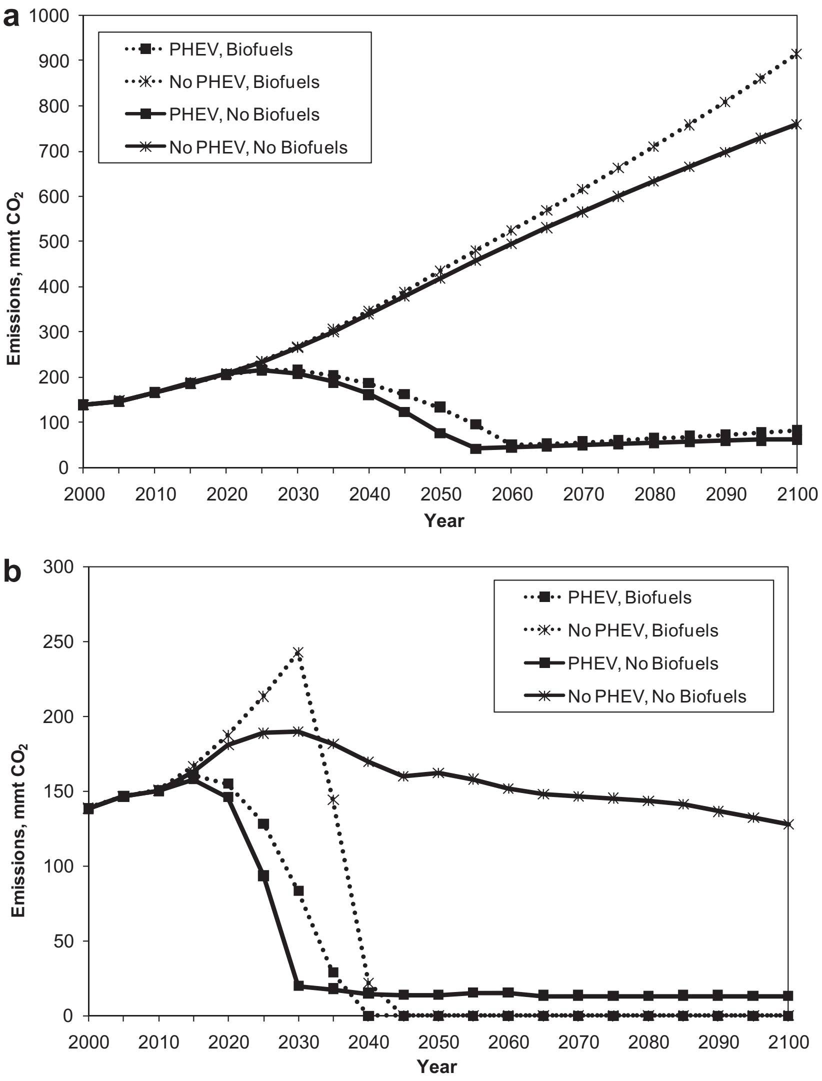

Fig. 13. Impact of PHEV adoption on emissions from the household vehicle transport sector in Japan in the (a) No Policy and (b) 450 ppm Policy cases.

part to increased transportation demand made possible by the lower gasoline price), and the reduction in emissions due to the PHEV shrinks to around 48%.

In the 450 ppm Policy case, emissions are reduced significantly compared to the No Policy case for every combination of factors considered here (Fig. 12b). However, differences in the magnitude of reductions can be attributed to PHEV and biofuels availability. When biofuels are available, emissions from transportation reach zero under the constraint (because the model assumes that biofuels provide a carbon neutral substitute for refined oil). When the PHEV is available, but biofuels are not, emissions do not reach zero because there is some residual demand for refined oil for the ICE in the PHEV. However, if neither biofuels nor the PHEV is available, significant cuts in household transportation emissions become very costly, and thus reductions in carbon emissions from other sectors are favored over additional reductions in household transportation emissions. The spike in emissions around 2025–2035 in the Biofuels cases is due to the fact that biofuels simultaneously allow emissions reductions from other modes of transportation that rely on refined oil, such as heavy-duty freight vehicles and other forms of transport, and thus reductions in personal vehicle transportation are delayed. However, these sources of reductions are not available in the No Biofuels cases, forcing all reductions to come sooner by adopting the PHEV in household transportation.

Comparison with the Japanese case shown in Fig. 13 reveals a few interesting differences, consistent with the rapid uptake of the PHEV and limited role of biofuels (which must be imported). The main difference from the US case is the sharper decrease in emissions in the near term between 2020 and 2040 (Fig. 13a), consistent with rapid and complete adoption of the PHEV into the personal vehicle fleet. In the 450 ppm Policy case, the PHEV allows a significant reduction in emissions but

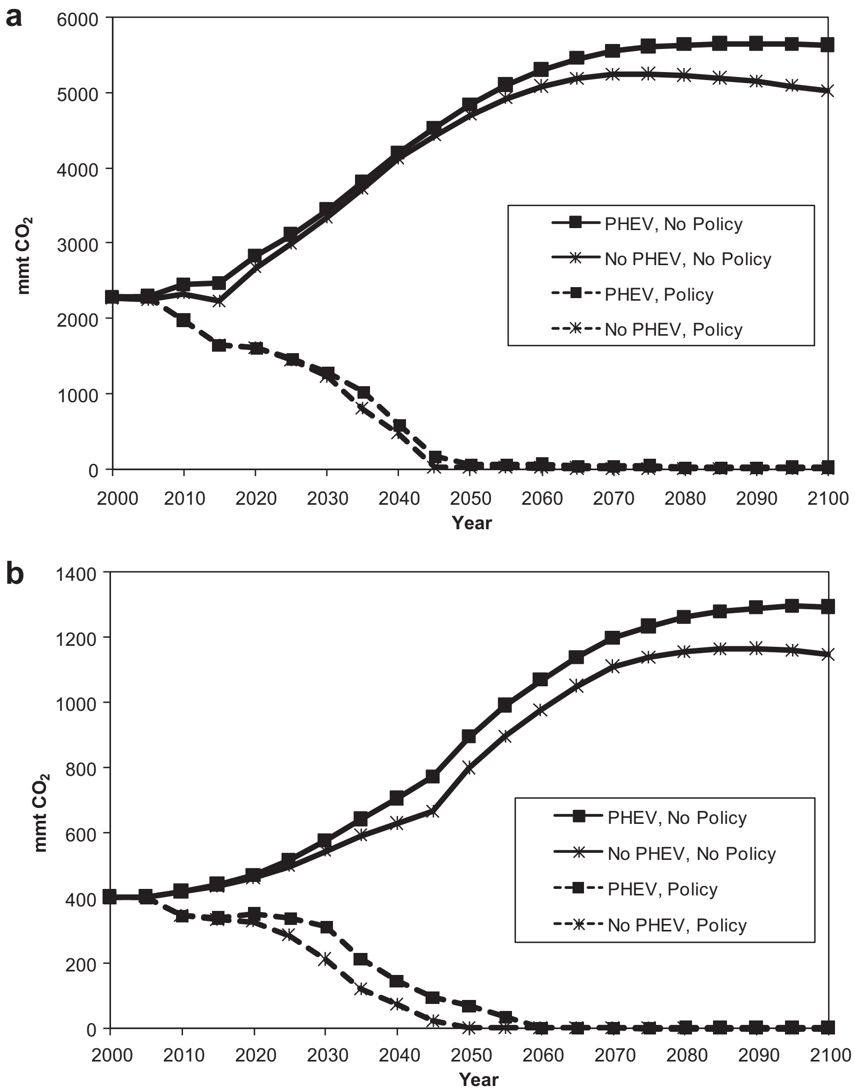

Fig. 14. Impact of PHEV adoption on electric power sector emissions in (a) the United States and (b) Japan.

reliance on refined oil is never completely eliminated, similar to the US case. As long as biofuels are available, household vehicle transport emissions are completely eliminated by the end of the century (Fig. 13b).

5.3.3. Impact on electric power sector emissions

In both regions, the additional CO_2 emissions due to the increased electric power output needed to support the PHEV fleet is more than offset by decreases in emissions from household transportation. In the US, the magnitude of the increase in electric power sector emissions was measured by the model to be around 13% in 2100 (see Fig. 14a). Power sector emissions were calculated based on the average grid mix, which evolves endogenously in the model. This reduction is even larger when the increase in emissions from petroleum extraction and refining are considered (not shown). In Japan, the increase in electric power sector emissions was also approximately 13% in 2100 (see Fig. 14b).

A comparison of the grid mixes in both countries with and without a policy constraint (Fig. 15) shows the effect of policy in reducing generation from carbon-intensive sources and thus CO_2 emissions from the power sector. The PHEV is assumed to be available in both countries. In the 450 ppm Policy cases, from mid-century onwards virtually all coal-fired generation is retrofitted with CCS. In the US, the availability of CCS facilitates the switch to almost complete reliance on coal-fired generation by the end of the century. Japan, by contrast, relies on both gas and nuclear as well as CCS as part of its carbon reduction strategy.

The impact of the PHEV on CO_2 emissions depends on the changing mix of power generation sources over time. The model does not distinguish between time-of-day use of the grid or differences among regions of the US. As a result, electricity used

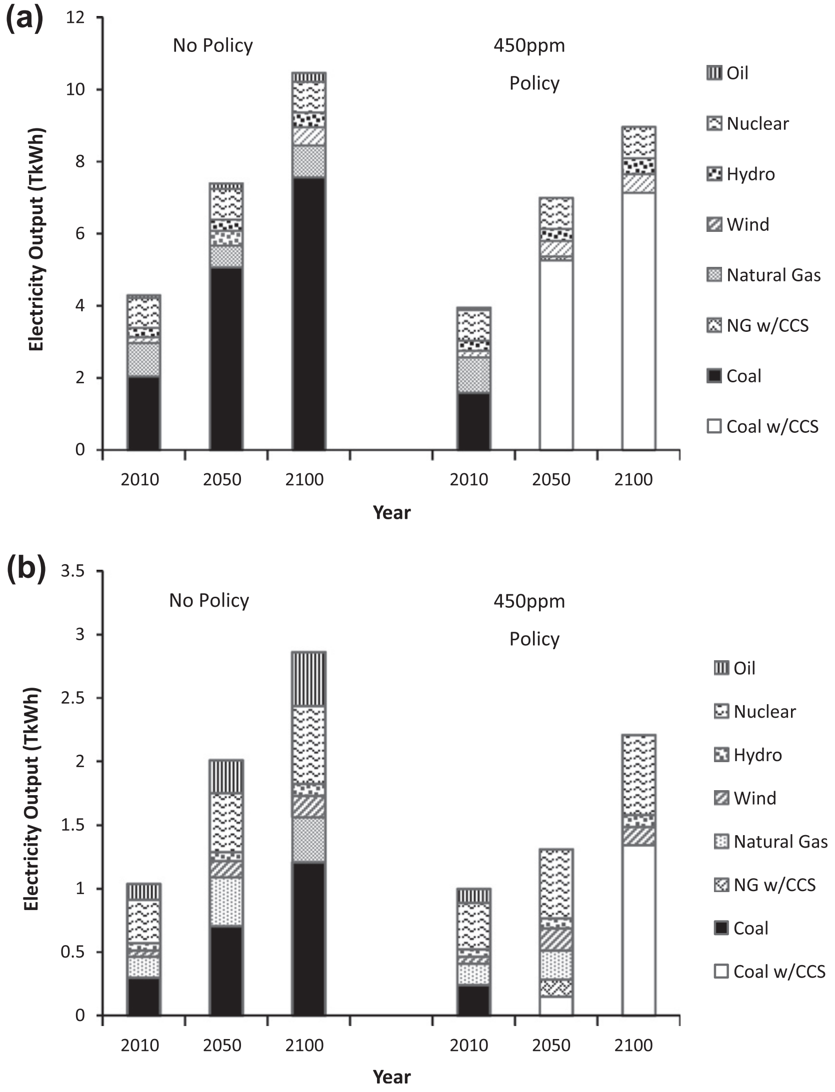

Fig. 15. The mix of primary energy sources used to produce electricity in the (a) United States and (b) Japan as predicted by the EPPA model.

to recharge PHEVs, as well as any carbon reduction, reflects the average grid mix at each point in time. This mix changes endogenously in each successive period as the model optimizes the allocation of energy resources, and the electricity sector grows more efficient over time (Paltsev et al., 2005). Although the PHEV 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. Without corresponding reductions in electric power emissions, PHEV adoption alone does not come close to substituting for climate policy in terms of its impact on household transport-related emissions, which continue to increase through 2100 in the absence of an economy-wide constraint.

5.4. Impact of PHEV on carbon price

As discussed above, the PHEV could offset the cost of implementing climate policy by providing an affordable low-carbon alternative to conventional transportation. This effect could be especially important if biofuels are not available. We track the carbon price for the PHEV entry scenarios defined above, and find that in both countries, the PHEV enables significant reductions in the carbon price that emerges under the strict constraints used here. In the US, the end-of-century CO_2 price drops from around US $3000/ton CO_2 to US $730/ton CO_2 when the PHEV is available (see Fig. 16). The mitigating effect in Japan is even greater – PHEV availability scenarios yield carbon prices of around US $3000/ton CO_2 while prices rise higher than US $5000/ton CO_2 in No PHEV scenarios. When biofuels are available, the CO_2 price does not rise above US $100/ton (not shown), indicating the significant potential impact of low-carbon alternatives in transportation on the CO_2 price.

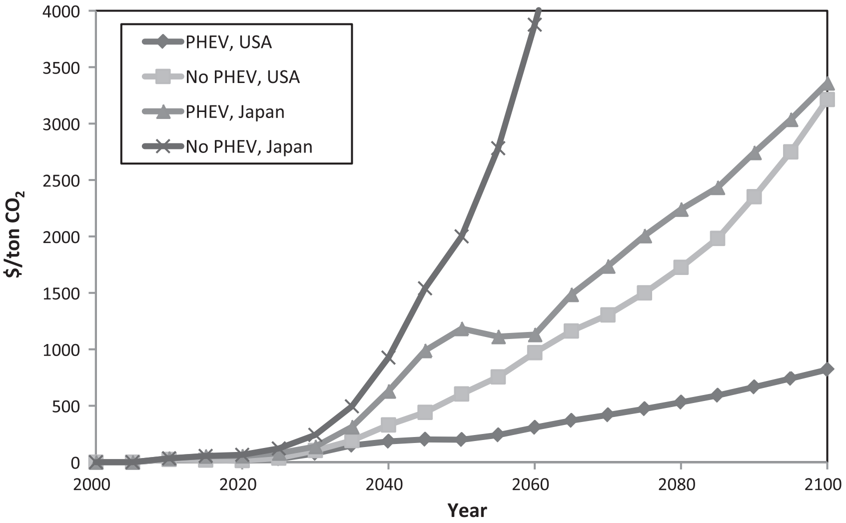

Fig. 16. Carbon dioxide price trajectories for the PHEV/No PHEV in the United States and Japan. In Japan, the strict carbon constraint causes the carbon price to reach over US $5000 by the end of the century.

6. Conclusions

We examined the commercial potential of PHEVs, their implications for electricity and petroleum use, and their potential contribution to reducing CO_2 emissions in the US and Japan. The results indicated that PHEV vehicle cost could be a significant barrier to market entry, particularly in the absence of a climate policy. The strong climate policy we considered requires a solution to transportation emissions and if the PHEV is the primary low-carbon alternative the policy becomes a very strong incentive for adoption. PHEV costs of 15% above conventional vehicles are very favorable for adoption but markups above 80% are prohibitive unless there are no other low carbon transportation alternatives and there is a strong carbon constraint. Many PHEV cost estimates suggest a cost premium today of around 30–80% above conventional vehicles. At 30% PHEVs become marginally competitive by mid-century without a carbon policy. Thus, a significant contribution from PHEVs would require advances in battery technology that reduce cost and increase range at the optimistic end of experts' estimates. Another factor affecting the attractiveness of the vehicle is the all-electric range and how that influences the proportion of miles traveled only on electricity. Varying this proportion (essentially the all-electric range of the vehicle) had some effect on commercial viability but much less than the vehicle cost.

Availability of other low-carbon alternatives (we consider biofuels) also could affect strongly the commercial viability of the PHEV, especially under a carbon constraint. The availability of biofuels provides an additional cost-competitive source of emissions reductions and thus reduces the incentive to adopt PHEVs. As a result, when biofuels are available, a stringent climate policy has only a mild effect on hastening the market penetration of the PHEV.

If PHEVs are available at a 15% cost premium over conventional vehicles, they would significantly penetrate the vehicle fleet even without a climate policy over the next century. Their use would contribute to reducing both carbon dioxide emissions related to transportation as well as reliance on refined oil in the US and Japan. In the absence of climate policy, the introduction of the PHEV results in an increase in electricity use and in emissions from electric power generation. However, the reduction in tailpipe emissions more than offsets this increase to yield a net reduction in CO_2 emissions. In percentage terms, the net emissions reductions are larger in Japan than in the United States because in Japan PHEV adoption is more rapid and power generation is less CO_2-intensive than in the US. Under the climate policy we considered, electricity generation eventually comes exclusively from low carbon sources and so the CO_2 benefits of PHEV introduction are greater. Thus technology-specific policies that focus exclusively on promoting the PHEV as a solution for CO_2 emissions will not take full advantage of them to the extent they rely on CO_2-intensive electricity. In the near term, PHEVs may also be more effective in countries such as Japan where power generation is less CO_2-intensive than in the US, which relies heavily on coal.

Acknowledgments

The authors gratefully acknowledge the financial support for this work provided by the BP-MIT Advanced Conversion Research Program and the MIT Joint Program on the Science and Policy of Global Change through a consortium of industrial sponsors and Federal Grants.

References

Anderman, M., Kalhammer, F.R., MacArthur, D., 2000. Advanced Batteries for Electric Vehicles: An Assessment of Performance, Cost, and Availability. State of California Air Resources Board, Sacramento, CA.

Brinkman, N., Wang, M., Weber, T., Darlington, T., 2005. Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems – A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions. Argonne National Laboratory, Argonne, IL.

Dimaranan, B., McDougall, R., 2002. Global Trade, Assistance, and Production: The GTAP 5 Data Base. Center for Global Trade Analysis, Purdue University, West Lafayette, Indiana.

DOE, 2008. HEV Sales by Model. US Department of Energy, Washington, DC. <http://www.afdc.energy.gov/afdc/data/vehicles.html>.

Duvall, M., 2004. Advanced Batteries for Electric-Drive Vehicles: A Technology and Cost-effectiveness Assessment for Battery Electric Vehicles, Power Assist Hybrid Electric Vehicles, and Plug-in Hybrid Electric Vehicles. Electric Power Research Institute, Palo Alto, CA.

Duvall, M., Knipping, E., 2007. Environmental Assessment of Plug-in Hybrid Electric Vehicles. Nationwide Greenhouse Gas Emissions. Report No. 1015325, vol. 1. Electric Power Research Institute, Palo Alto, CA. <http://www.epri-reports.org/Volume1R2.pdf>.

EIA (Energy Information Administration), 2006. Emissions of Greenhouse Gases in the United States 2005. US Department of Energy, Washington, DC.

EIA (US Energy Information Administration), 2008. US Gasoline and Diesel Retail Prices. US Department of Energy, Washington, DC. <http://tonto.eia.doe.gov/dnav/pet/hist/mg_tt_usa.htm>.

EPA (US Environmental Protection Agency), 2006. Greenhouse Gas Emissions from the US Transportation Sector, 1990–2003. US Environmental Protection Agency, Washington, DC. <http://www.epa.gov/OMS/climate/420r06003.pdf>.

Gaines, L., Cuenca, R., 2000. The Cost of Lithium Ion Batteries for Vehicles. Argonne National Laboratory, Chicago, IL. <http://www.transportation.anl.gov/pdfs/TA/149.pdf>.

Gately, D., 1980. Individual discount rates and the purchase and utilization of energy-using durables: comment. The Bell Journal of Economics 11 (1), 373–374.

GGIOJ (Greenhouse Gas Inventory Office of Japan), 2008. National GHGs Inventory Report of Japan. <http://www-gio.nies.go.jp/aboutghg/nir/nir-e.html>.

Graham, R., 2001. Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options. Electric Power Research Institute, Palo Alto, CA.

Hackney, J., de Neufville, R., 2001. Life cycle model of alternative fuel vehicles: emissions, energy, and cost trade-offs. Transportation Research Part A 35 (3), 243–266.

Hausman, J., 1979. Individual discount rates and the purchase and utilization of energy-using durables. The Bell Journal of Economics 10 (1), 33–54.

Hertel, T., 1997. Global Trade Analysis: Modeling and Applications. Cambridge University Press, Cambridge, United Kingdom.

IEA (International Energy Agency), 2006. World Energy Outlook 2006. Paris, France.

Jacoby, H.D., Reilly, J.M., McFarland, J.R., Paltsev, S., 2004. Technology and Technological Change in the MIT EPPA Model. Report No. 111. MIT Joint Program on the Science and Policy of Global Change, Cambridge, MA. <http://web.mit.edu/globalchange/www/MITJPSPGC_Rpt111.pdf>.

Kromer, M., Heywood, J.B., 2007. Electric Powertrains: Opportunities and Challenges in the US Light-Duty Vehicle Fleet. Report No. LFEE 2007-02-RP. MIT Laboratory for Energy and the Environment, Cambridge, MA.

Liu, Y., Helfand, G.E., 2009. The Alternative Motor Fuels Act, alternative fuel vehicles, and greenhouse gas emissions. Transportation Research Part A 43 (8), 755–764.

McFarland, J.R., Herzog, H., Reilly, J., 2004. Representing energy technologies in top-down economic models using bottom-up information. Energy Economics 26 (4), 685–707.

MOE (Ministry of Environment, Japan), 2007. National Greenhouse Gas Inventory Report of Japan. National Institute for Environmental Studies, Ibaraki, Japan.

NRC (National Research Council), 2004. The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs. National Academies Press, Washington, DC.

Paltsev, S., Viguier, L., Babiker, M., Reilly, J., Tay, K.H., 2004. Disaggregating Household Transport in the MIT EPPA Model. Technical Note 5. MIT Joint Program on the Science and Policy of Global Change, Cambridge, MA. <http://web.mit.edu/globalchange/www/MITJPSPGC_TechNote5.pdf>.

Paltsev, S., Reilly, J., Jacoby, H., Eckhaus, R.S., McFarland, J., Sarofim, M., et al., 2005. The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4. Report No. 125. MIT Joint Program on the Science and Policy of Global Change, Cambridge, MA. <http://web.mit.edu/globalchange/www/MITJPSPGC_Rpt125.pdf>.

Parks, K., Denholm, P., Markel, T., 2007. Costs and Emissions Associated with Plug-In Hybrid Electric Vehicle Charging in the Xcel Energy Colorado Service Territory. National Renewable Energy Laboratory, Golden, CO. <http://www.nrel.gov/docs/fy07osti/41410.pdf>.

Reilly, J., Paltsev, S., 2007. Biomass Energy and Competition for Land. Report No. 145. MIT Joint Program on the Science and Policy of Global Change, Cambridge, MA. <http://web.mit.edu/globalchange/www/abstracts.html#a145>.

Rutherford, T.F., 1995. Extension of GAMS for complementarity problems arising in applied economic analysis. Journal of Economic Dynamics and Control 19 (8), 1299–1324.

Sandoval, R., Karplus, V., Paltsev, S., Reilly, J.M., 2009. Modelling prospects for hydrogen powered transportation until 2100. Journal of Transport Economics and Policy 43 (3), 291–316.

Schafer, A., 1998. The global demand for motorized mobility. Transportation Research Part A 32 (6), 455–477.

Schafer, A., Victor, D.G., 2000. The future mobility of the world population. Transportation Research Part A 34 (3), 171–205.

Simpson, A., 2006. Cost-Benefit Analysis of Plug-in Hybrid Electric Vehicle Technology. Report No. NREL/CP-540-40485. National Renewable Energy Laboratory, Golden, CO.

US CCSP (United States Climate Change Science Program), 2007. CCSP synthesis and assessment product 2.1, Part A: Scenarios of greenhouse gas emissions and atmospheric concentrations. In: Clarke, L. et al. (Eds.), US Climate Change Science Program. Department of Energy, Washington, DC.