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

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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

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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 PHEV*X*, 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).