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Modeling the Prospects for Hydrogen Powered Transportation Through 2100

Reynaldo Sandoval, Valerie J. Karplus, Sergey Paltsev and John M. Reilly

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This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives. Titles in the Report Series to date are listed on the inside back cover.

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Reynaldo Sandoval, Valerie J. Karplus, Sergey Paltsev and John M. Reilly*

Abstract

Hydrogen fueled transportation has been proposed as a low carbon alternative to the current gasoline-powered fleet. Using a computable general equilibrium model of the world economy we explore the economic viability of hydrogen transportation in several different tax and carbon dioxide stabilization policy scenarios. We represent the capital, labor, fuel and other costs of hydrogen production and hydrogen powered vehicles in the economic model. We examine scenarios where the hydrogen fuel price and vehicle cost are varied over a wide range to evaluate what technology improvements would be needed, in terms of cost reductions, for hydrogen vehicles to penetrate the market. We consider scenarios with and without climate policy, and in competition with other reduced-carbon fuel substitutes, such as ethanol-blend fuels. We find that hydrogen-powered fuel-cell vehicles could make a significant contribution to de-carbonization of the transportation fuel cycle if production of hydrogen itself is not carbon-intensive. Cost targets needed for the technology to penetrate in the USA are such that the hydrogen fuel would need to be in the range of 1 to 1.7 times the 1997 price of gasoline and the vehicle mark-up above an average fuel cell automobile would need no more than 1.3 to 1.5 times an average conventional vehicle. At the lower end of these cost ranges, the vehicle fleet could be competitive by 2020 but at the upper end we would only see entry of the fleet toward the end of the century. High fuel taxes in Europe makes fuel-efficient hydrogen fuel cell technology more competitive there than in the USA. Along with cost reductions, these results assume that technical issues are solved and that market hurdles of establishing the fuel distribution system are overcome. For those involved in hydrogen vehicle research this analysis provides cost targets that would need to met and, given they are achieved, an idea of when vehicles could be competitive and under what conditions.

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1. INTRODUCTION

The transportation sector is responsible for a significant fraction of global anthropogenic emissions. The IEA (2006) estimates that transportation is the second-largest sector (after power generation) for energy-related CO_2 emissions worldwide, with its share of total emissions stable at around 20 per cent both in historic data for 1990-2004 and in their projections to 2030. At the

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same time, the IEA projects that global CO_2 emissions (both from transportation and total energy-related emissions) will increase by 55 per cent from 2004 to 2030. In most developed countries, emissions from transportation make an even larger contribution to carbon dioxide emissions. For example, the EIA (2006) reports that the share of CO_2 emissions from transportation in the U.S. was about 31 per cent in 1990, rising to 33 per cent in 2004.

Potential improvements in current internal combustion engine technology fueled with petroleum products are likely not to be enough to achieve the CO_2 emissions reduction needed under, for example, a climate policy goal of stabilization of greenhouse gas emissions. Even significant fleet efficiency improvements such as those promised by further penetration of electric-gasoline hybrid vehicles are probably are not enough to offset growth in miles driven and other increases in demand for power and performance in a sector that is growing rapidly worldwide. Awareness of the need for deep reductions in emissions has created interest in alternative vehicle technologies and fuels. Among the alternative technologies that offer further reductions in emissions from transportation are replacement of gasoline and diesel with biofuels, all-electric cars or near all-electric plug-in hybrids, and hydrogen fuel-cell vehicles. In this paper we focus on the latter option and apply the MIT Emissions Prediction and Policy Analysis (EPPA) model (Paltsev *et al.*, 2005) to assess the potential for hydrogen transportation in a carbon-constrained world.

Existing engineering studies of the potential for hydrogen vehicles show that the technology must advance significantly to be commercially competitive (Ogden *et al.*, 2004; NRC, 2004; Rogner, 1998; Kosugi *et al.*, 2004). The contribution of our analysis is to examine the potential for hydrogen transportation within a computable general equilibrium (CGE) model of the world economy, in which it must explicitly compete with other technologies that are changing, where fuel costs are rising, and under different assumptions about carbon dioxide control policies.

In the next section we briefly review the hydrogen vehicle technology including technologies to produce and deliver the hydrogen. In Section 3, we describe our strategy for examining the potential for hydrogen using the EPPA model and offer detail on our addition of hydrogen production and distribution sectors and a fuel cell vehicle technology. In Section 4 we simulate the model to examine conditions that would favor entry of a fleet of hydrogen vehicles. Given the relatively high current cost of a hydrogen fuel cell-based automobile fleet, our primary strategy is to simulate many pairs of fuel and vehicle costs to identify those that would result in penetration of the fleet under different economic and policy conditions. We do not claim that the technology breakthroughs needed to achieve these costs are on the immediate horizon. Instead, our goal is to help establish the targets needed in research on the hydrogen vehicles if they are to make a contribution. We then consider a specific fuel and vehicle cost pair, assuming that ongoing research is successful in reducing the cost of the technology to these levels, to consider the extent to which availability of hydrogen technology would reduce carbon emissions and lower the cost of achieving emissions reductions. Section 5 concludes.

2. TECHNOLOGY FOR A HYDROGEN FUEL CELL VEHICLE FLEET

If a hydrogen fuel cell vehicle fleet is to become a reality it requires advances in vehicle technology and reliable and cost-effective means of hydrogen production and distribution. Hydrogen does not exist in pure form on earth but can be obtained from two main sources, hydrocarbons and water. Natural gas is a promising candidate for hydrogen production because of its high hydrogen to carbon ratio, which results in lower CO_2 emissions per unit of hydrogen produced compared with other cost-effective sources, such as coal. However, for either to offer significant reductions in CO_2 emissions, carbon capture and storage (CCS) would need to be part of the hydrogen production process. Other forms of hydrogen production such as electrolysis, or through thermochemical water splitting, are more expensive. We thus focus our modeling attention on hydrogen production from natural gas and coal because they are the least costly sources at present and are likely to remain so.

A hydrogen vehicle fleet would require an extensive fueling infrastructure, serviced by a fuel distribution system. Developing this infrastructure is a challenge, since industry is unlikely to invest without evidence of consumer demand for hydrogen. At the same time, consumers are unlikely to purchase vehicles that lack a convenient fueling infrastructure. Programs such as California's Hydrogen Highway Network would be needed to overcome this chicken-egg problem (California, 2007).

Turning to the literature on production and distribution costs, surveys have often revealed highly disparate estimates of hydrogen production costs but many studies do not explicitly state the assumptions used when calculating costs (Padró and Putsche, 1999; Adamson and Pearson, 2000; Iwasaki, 2003; Simbeck and Chang, 2002; Kreutz *et al.*, 2004; Prince-Richard *et al.*, 2005; Sandoval, 2006). Without detail on sources of costs and cost differences these reviews cannot be used as a basis for parameterizing our model where we must identify separately the feedstock cost, efficiency of conversion and other input costs. While the cost of feedstock (natural gas and coal) is one source of variation in hydrogen cost estimates, the larger differences in the literature appear to depend on whether the cost of delivering the fuel is included, assumptions about how it is delivered, and whether carbon capture and storage is included or not. To consider the ability of the hydrogen to make a contribution to world energy needs one must include not only the cost of production but the cost of transport and distribution and of the end-use technology for utilizing the fuel. And if the concern is climate change, the implications for carbon emissions depend critically on the specific hydrogen producing technology, the efficiency of conversion and utilization of the fuel, and what happens to any carbon emissions along the way. For our purposes we combine the cost of producing and delivering the fuel in a single sector within the EPPA model, and then a separate transportation producing sector that represents the fleet of vehicles.

Literature sources that identify these different components of production and distribution costs include a detailed study by Simbeck and Chang (2002) for the National Renewable Energy Laboratory (NREL) and a review carried out by the National Research Council (NRC, 2004). **Figure 1** shows a comparison of the cost per kg in these two studies with different assumptions about feedstock used, the means of distribution, and whether CCS is included. It further shows costs broken down into four components: fuel (*i.e.*, feedstock), electricity, capital, and labor. Notably the NRC estimates of costs are about one-half those in the NREL study even though the feedstock cost is about the same, and the NRC study used the same cost model used in the NREL study. As described in the NRC study, the difference primarily reflects different assumptions about the cost of developing the distribution and refueling network (NRC, 2004).

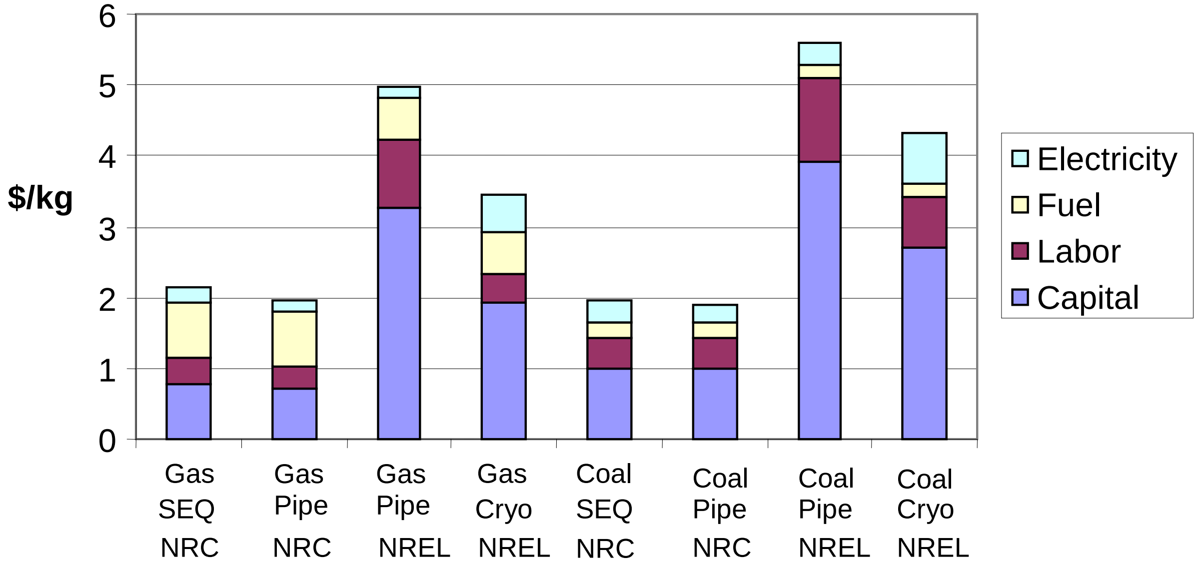

Figure 1. Estimated hydrogen cost per kilogram by means of production and distribution. Note: *Gas SEQ NRC* - Natural Gas with carbon capture and storage distributed by pipeline reported by NRC study (NRC, 2004); *Gas Pipe NRC* - Natural Gas without carbon capture distributed by pipeline reported by NRC study; *Gas Pipe NREL* - Natural Gas without carbon capture distributed by pipeline reported by NREL study (Simbeck and Chang, 2002); *Gas Cryo NREL* - Natural Gas without carbon capture distributed in liquid form by tanker trucks reported by NREL study; the four "Coal" labels represent the corresponding estimates using coal feedstock.

Regarding the vehicle fleet, two possible hydrogen vehicle technologies exist: one would retain an internal combustion engine fueled by hydrogen in a manner similar to using compressed natural gas to power a vehicle. The other approach is to replace the internal combustion engine with fuel cells where hydrogen is reacted with oxygen to generate electricity that drives an electric motor. Both designs require on-board hydrogen storage. Hydrogen can be stored as compressed gas, in liquid form, or by absorption on metal hydrides or carbon-based materials (Padró and Putsche, 1999). Aside from design modifications to allow for safe and efficient storage and conversion of hydrogen, hydrogen-powered vehicles are otherwise expected to be functionally similar to conventional designs.

Hydrogen fuel cells offer several advantages over conventional vehicle technology. The major byproduct of hydrogen conversion is water, resulting in near-zero tailpipe emissions. Fuel cell conversion also offers very high theoretical conversion efficiency compared with hydrocarbon combustion in an internal combustion engine (Kromer and Heywood, 2007). Although present fuel cell technology does not reach this upper bound, fuel cell electric vehicles powered by hydrogen still have a favorable estimated fuel economy of around 66 miles per gallon of gasoline equivalent (Padró and Putsche, 1999).

So far, however, a number of practical constraints exist to market penetration of fuel cell vehicles. Fuel cell performance, durability, and cost limit its competitiveness with conventional technology. As of 2004, engine specific power and cold start time lagged far behind U.S. Department of Energy performance targets for competitiveness with conventional technology (Kromer and Heywood, 2007). In the review of the FreedomCAR and Fuel Partnership, the NRC (2005) estimated that fuel cell durability measured in load hours was only one-fifth of commercialization targets.

Apart from these technological challenges, at present the cost of a fuel cell vehicle is essentially prohibitive at ten to twenty times that of a conventional vehicle (NRC, 2004). The cost and performance of on-board hydrogen storage will also need to be improved to meet commercialization targets.

3. MODELING HYDROGEN TRANSPORT IN THE EPPA MODEL

Before turning to a technical description of the EPPA model augmented to include hydrogen vehicles and hydrogen production it is useful to lay out our modeling strategy. As is clear from the previous section, there are both technical and cost hurdles which must be overcome at several steps in order to make a hydrogen fueled vehicle fleet a reality. The implication is that if we introduce the technology into the model at its current cost there would be virtually no conditions under which it would enter—the cost is prohibitive. While many aspects of the technology are highly uncertain, basic conversion efficiencies of feedstock to hydrogen and the hydrogen needed to power a vehicle are reasonably described in the technical literature. Given the representation of transportation demand in EPPA we can therefore model the derived demand for hydrogen and the further derived demand for the feedstock with reasonable accuracy assuming the hydrogen vehicle fleet becomes economically competitive. The EPPA model projects endogenously changing conventional fuel (gasoline/diesel) and feedstock (*i.e.*, natural gas and coal) prices. As these change over time, the relative competitiveness of the hydrogen fleet will change.

The EPPA model also allows for the introduction of greenhouse gas emissions policies which result in a price for CO_2 which is in turn reflected in the cost of fuels that emit CO_2 when combusted and in the cost of products where CO_2 was emitted in production. Thus, a greenhouse gas policy will also change the relative economics of hydrogen and conventional technologies to the extent they have different CO_2 emissions implications.

Our modeling strategy is to parameterize a hydrogen fuel cell vehicle fleet based on key conversion efficiencies and the non-fuel cost shares based on existing literature assuming near-competitive costs, *i.e.*, assuming that necessary breakthroughs occur. We then use a mark-up factor to scale the cost for both the vehicle and the hydrogen production/distribution sectors to evaluate different combinations of costs for fuels and the vehicle fleet. We choose many pairs (vehicle, fuel production) of cost mark-ups and map out fleet penetration frontiers to indicate those cost mark-up pairs that result in penetration in different years. The cost mark-up pairs can be viewed as R&D targets for hydrogen vehicle and production/distribution. If, for example, the goal of an R&D program was to have vehicle fleet penetration by 2030, our frontiers would indicate combinations of hydrogen and vehicle costs that would be necessary to achieve that goal under different assumptions regarding greenhouse gas policy. Our research does not say anything directly about whether these cost goals are realistic, or the size of the R&D program that would be needed to achieve them but indicates under what conditions achievement of them would lead to penetration.

Turning to the modeling details, we introduce into the EPPA model two hydrogen production sectors, one that uses natural gas and one that uses coal, with both including an option of carbon capture and storage. These sectors include distribution/fueling and cost shares and markups are intended to cover the full retail cost of delivering hydrogen. We introduce an alternative private automobile technology to represent a fuel cell vehicle fleet that runs on hydrogen. Before providing detail on these new sectors and technologies, we briefly describe the existing model structure.

EPPA 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, CO_2; methane, CH_4; nitrous oxide, N_2O; hydrofluorocarbons, HFCs; perfluorocarbons, PFCs; and sulphur hexafluoride, SF_6) and air pollutants (sulphur dioxide, SO_2; nitrogen oxides, NOx; black carbon, BC; organic carbon, OC; ammonia, NH_3; carbon monoxide, CO; and non-methane volatile organic compounds, VOC) emissions based on United States Environmental Protection Agency inventory data and projects. 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 (the EPPA regions and sectors are shown in **Table 1**).

Much of the sectoral detail 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 gases. The base year of the EPPA model is 1997. From 2000 it is solved recursively at 5-year intervals. The EPPA model production and consumption sectors are represented by 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 MPSGE modeling language (Rutherford, 1995). The EPPA has been used in a wide variety of policy applications (*e.g.*, Jacoby *et al.*, 1997; Reilly *et al.*, 1999; Babiker, Metcalf, and Reilly, 2003; Reilly and Paltsev, 2006; US CCSP, 2007; Paltsev *et al.*, 2007).

Table 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: Hydrogen Vehicles	Eastern Europe
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 CO_2 Capture and Storage	
Electric: Integrated Coal Gasification with CO_2 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; hydrogen vehicles, solar and wind power, biomass electricity, natural gas combined cycle, natural gas combined cycle with CO_2 capture and storage, integrated coal gasification with CO_2 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).

Because of the focus on climate and energy policy, the model further disaggregates the GTAP data for transportation and existing energy supply technologies and includes a number of alternative energy supply technologies that were not in widespread use in 1997 but could take market share in the future under changed energy price or climate policy conditions. Bottom-up engineering details are incorporated in EPPA in the representation of these alternative energy supply technologies. Advanced technologies endogenously enter only when they become economically competitive with existing technologies. Competitiveness of different technologies depends on the endogenously determined prices for all inputs, as those prices depend on depletion of resources, economic policy, and other forces driving economic growth such as savings, investment, energy-efficiency improvements, and productivity of labor. Additional information on the model's structure can be found in Paltsev *et al.* (2005).

As presented in Table 1, the EPPA model disaggregates household transportation into purchased transportation and own-supplied transportation, which includes privately owned vehicles operated directly by households. This disaggregation is described in Paltsev *et al.* (2004).

The natural gas-based hydrogen production sector is parameterized to represent production using steam methane reforming technology. The coal-based sector uses gasification technology. Both hydrogen production sectors are equipped with carbon capture and storage (CCS) set to capture 90 percent of carbon emissions. We model CCS technology as presented in McFarland *et al.* (2004). The structure of the sector is shown in **Figure 2**, with elasticities of substitution between input shares and factor shares for each input shown below the inputs with the coal-based factors shares the top number and the gas-based factor shares the bottom number. Where the inputs are shown with vertical lines, the structure is Leontief, *i.e.*, the elasticity of substitution is zero. The factor shares are based on the Simbeck and Chang (2002) study conducted for NREL. Reflecting that study, the cost shares of inputs in transportation and distribution are a substantial fraction of the cost (over 40%), and fuel cost share for gas is much higher than for coal reflecting the much lower coal price—but that makes capital and labor costs a higher share, particularly in the hydrogen production nest. It is also worth noting that a substantial amount of electricity is used in the production and transport process. One of the virtues of the CGE modeling framework in this regard is that the electricity input will also have carbon implications depending on how electricity is produced. A broad cap and trade policy that prices carbon would make electricity less carbon intensive but more expensive, and the cost effect is automatically passed through to the hydrogen production sector and the hydrogen fuel while at the same time the carbon implications of less carbon intensive electricity are also captured.

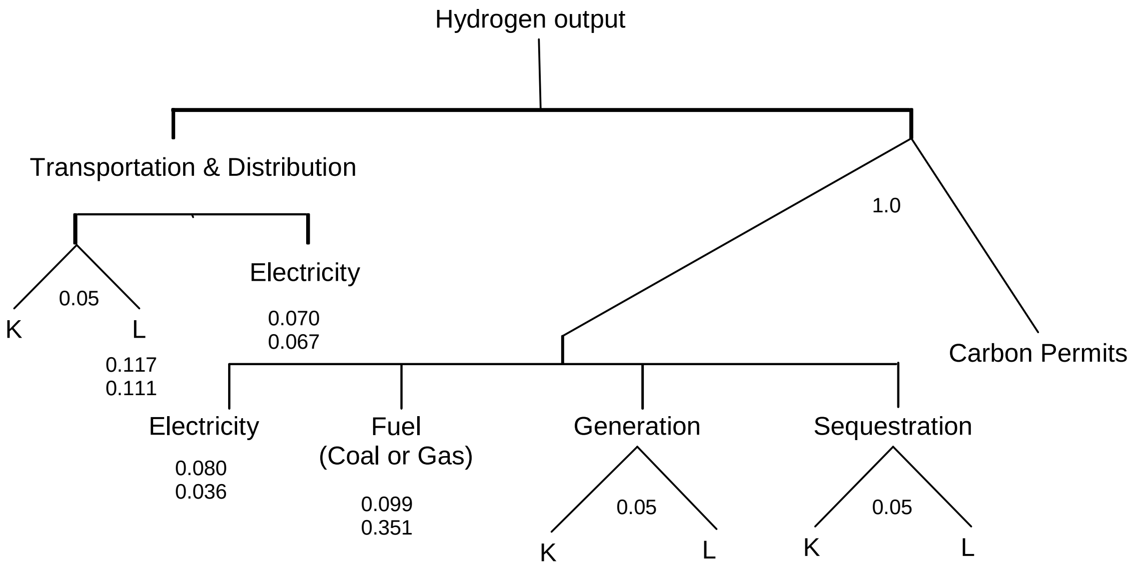

Figure 2. Structure of the hydrogen production sector. Substitution elasticities between inputs cost shares are shown beneath inputs for coal-based production (top number) and gas-based production (bottom number).

For hydrogen-based household transport we introduce a new sector as shown in **Figure 3**. The hydrogen fleet is in direct competition with pre-existing own-supplied household transportation (*i.e.*, private automobiles) and is similar in structure. The characteristics of vehicles in terms of, for example, power, performance, safety, reliability, interior space, refueling and range are important considerations in vehicle choice. We make the simplifying assumption that the conventional and hydrogen fuel cell vehicles are perfect substitutes. This means that the different power source is essentially invisible to the consumer—any problematic aspects of the hydrogen technology have been successfully addressed—and all that matters is the relative cost of the vehicle and fuel cost per mile, accounting for greater efficiency of hydrogen use in a fuel cell compared with a conventional internal combustion engine. The production structure of the conventional and hydrogen fleet are identical except for the replacement of hydrogen for conventional fuel. Differences among the technologies are reflected by values of parameters that control input cost shares.

Own-supplied household transportation relies on the outputs of three sectors: fuels (refined oil or hydrogen), services, and Other Industries Products, with elasticities of substitution shown between inputs and factor shares shown beneath the inputs with the USA shares shown as the top number and Europe shares as the bottom number. The vehicle input is an output of the Other Industries sector capturing the cost of the automobiles, since automotive industry is part of that sector in the data base. The fuel input represents the cost of fuel for private automobiles which, based on initial parameterization, implies a specific physical quantity of hydrogen fuel and with other parameters of the production function also implices an efficiency of power conversion that depends on the fuel mark-up as discussed below. Note that a modeling convention adopted here is that the fuel cost shares are pre-tax shares. Conventional fuel in Europe is taxed at a high rate, and if such a tax were also applied to hydrogen the cost share, inclusive of the tax, would be much higher. We later examine implications of taxing or not taxing hydrogen at the same rate per energy content as conventional fuel. The Services share represents all non-fuel operational costs. Among these are the costs of insurance, financing, and maintenance and these are assumed to be the same as for the conventional vehicle fleet. For more information on the parameterization of conventional household transportation see Paltsev *et al.* (2004).

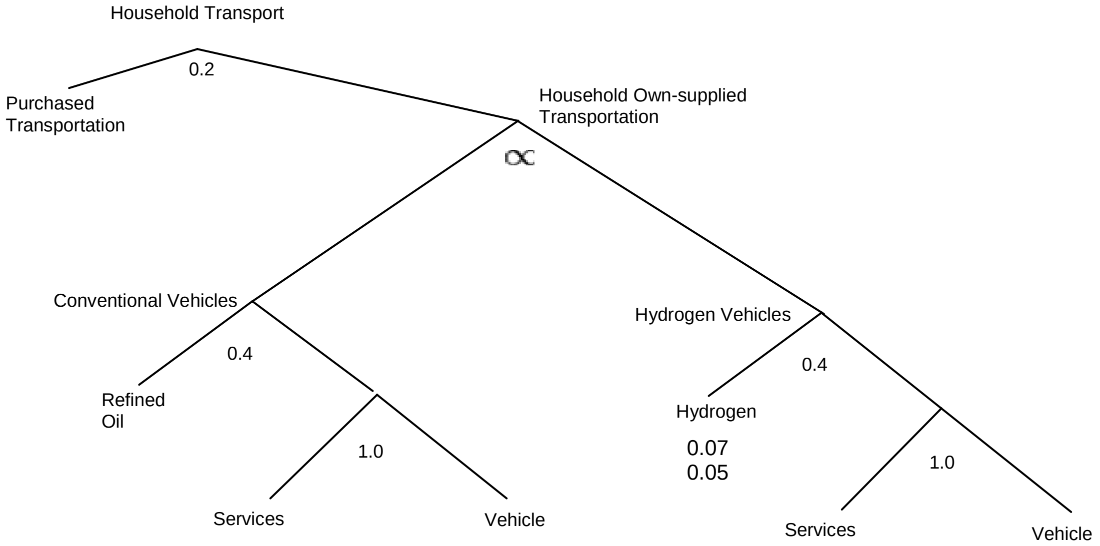

Figure 3. Structure of household transportation sector, substitution elasticities are shown between inputs and factor shares for hydrogen vehicles are shown beneath inputs for US (top number) and Europe (bottom number).

The mark-up approach described briefly at the beginning of this section is a standard approach used within the EPPA model for representing new technologies. A mark-up is a multiplicative factor that reflects the cost in the model base year (*i.e.*, 1997) of the advanced technology relative to the one against which it competes. If the markup is larger than 1.0 it indicates that the new technology is more expensive relative to its conventional counterpart given the inputs costs in the base year. A technology with a markup greater than 1.0 can eventually enter if the price of inputs it requires in large amounts fall (or rise less) relative to the price of inputs required by its conventional counterpart. Thus, a technology that uses less fuel, or a fuel whose price does not rise as fast, can eventually compete successfully, and if carbon dioxide emissions differ between the technologies a carbon price will also differentially affect them.

Three markups are used for the hydrogen, one for the vehicle fleet and one for each of the two hydrogen production/distribution sectors, however, for the analysis conducted in the following sections we assume the non-feedstock, coal- and gas-based production costs vary together. As noted previously, we do not choose a single markup but produce many simulations of the model where we vary them to span a range that results in penetration of the hydrogen vehicle fleet in different years. We vary the mark-ups in pairs for the fuel and the vehicle, and thus do not independently vary the markup for hydrogen production from natural gas and coal.

The overall efficiency of the hydrogen fuel cycle (from coal to production of hydrogen to miles driven) can be compared to the conventional fleet in terms of miles per energy content of the fuel, which then can be converted to miles per gallon equivalent based on the energy content of gasoline. In the model, it is determined by the fuel shares in production of hydrogen and in the hydrogen share in the specification of the vehicle fleet, and since we apply the production sector mark-up to all inputs, including the coal or gas feedstock it also depends on the mark-up. To determine these parameters (and thus the implied efficiency) we use the supplemental physical flows of energy and implied energy prices in the EPPA data set. For a fuel markup of 1.0 the implied hydrogen vehicle fleet efficiency is 3.36 times more efficient than the conventional fleet in the USA and 3.70 times more efficient in Europe. For example, if the average fleet efficiency of cars (and light trucks) on the road in the USA is 20 mpg, that implies efficiency of fuel cell vehicle of about 67 mpg in energy equivalents. This implied efficiency varies inversely with the mark-up—if the fuel production mark-up is 1.3, the relative efficiency of hydrogen vehicles in the US is 2.58—a 52 mpg equivalent. The parameterization was chosen to be consistent with the literature reviewed in Section 2.

The EPPA model includes significant continuing advances in gasoline and diesel vehicles with their efficiency improving at 1.0 percent per year, but also increasing fossil fuel prices. Thus our analysis reflects a world where the existing technologies do not "stand still." As noted above, the EPPA model also includes a biofuel technology, and so hydrogen vehicles compete against this low CO_2 emitting alternative but we also consider cases when biofuels are not an option.

4. SCENARIO ANALYSIS

As discussed above, we use the modified EPPA model to examine the timing of hydrogen sector penetration under different policy constraints and different estimates about the markups. We focus on the initial date and conditions at which hydrogen transport becomes cost-competitive with conventional technology and enters the market. The timing of hydrogen sector entry is expected to vary depending on the relative prices of hydrogen and gasoline fuel and relative price of hydrogen vehicles. First, we assess the effects of increasing the price of gasoline relative to hydrogen fuel, either through a direct fuel consumption tax or through a cap-and-trade carbon emissions stabilization policy that results in a price on CO_2 emissions. Second, we analyze the impact of the availability of low-carbon fuel substitutes. Finally, we compare how the presence or absence of a cost-competitive hydrogen transportation alternative affects the price of carbon that emerges if an aggressive greenhouse gas reduction policy is implemented. We focus on Europe and the United States in the presentation of our results.

Table 2. Scenarios.

Scenario Name	Description
Baseline	No climate policy, hydrogen fuel is taxed at the current gasoline tax rates
No Fuel Taxes	No climate policy, hydrogen fuel and gasoline are not taxed
No Hydrogen Tax	No climate policy, hydrogen fuel is not taxed
550 ppmv	Climate policy leads to a stabilization at 550 ppmv, hydrogen fuel is taxed at the current gasoline tax rates
550 with No Fuel Taxes	Climate policy leads to a stabilization at 550 ppmv, hydrogen fuel and gasoline are not taxed
550 with No Hydrogen Tax	Climate policy leads to a stabilization at 550 ppmv, hydrogen fuel is not taxed
550 with No Biofuels	Climate policy leads to a stabilization at 550 ppmv, hydrogen fuel is taxed at the current gasoline tax rates, no advanced biofuels available

To investigate the impact of implementing a tax, we consider the possibility of taxing gasoline at the current rate but not taxing hydrogen, taxing both fuels or not taxing either. To explore the impact of climate change mitigation policies, the case in which carbon concentrations in the atmosphere would be stabilized at 550 ppmv was considered. We use the 550 ppmv stabilization scenario developed for the U.S. Climate Change Science Program (US CCSP, 2007). The policy is implemented in the model by constraining GHG emissions and allowing for trading in GHG emission permits across sectors to determine a carbon-equivalent price.

Table 2 provides a description of the scenarios analyzed in this paper. It includes the following policy cases: fuel taxes are imposed (at current rates) both on gasoline and hydrogen use in transportation; fuel taxes are imposed (at current rates) on gasoline but not on hydrogen fuel; and no fuels taxes are imposed. We test these scenarios in a no climate policy case (baseline), in a policy constraining carbon emissions that stabilizes CO_2 concentration at 550 ppmv; and in a case where there is no development in advanced biofuels.

For each combination of markups, the EPPA model runs for the whole century to determine the decade in which hydrogen transportation would become viable. The timing of hydrogen sector entry for each markup combination is represented by frontier curves that trace boundaries between the decades through the year 2100.

4.1 Effects of Fuel Taxes on Hydrogen Sector Entry

First, we explore in **Figure 4** the potential for hydrogen sector entry in the Baseline (that is, no climate policy) cases in Europe (panel a) and the United States (panel b) with hydrogen fuel tax at the level of gasoline tax in each region. For Europe, the frontiers indicate, for example, that combinations of fuel markup of 0.9 and vehicle markups of less than 1.6 or a vehicle mark-up of 1.0 and fuel mark-ups of less than 1.4, or other combinations inside the frontier between these points would lead to hydrogen vehicle entry by 2020. If the mark-up is above 3.0 and the fuel mark-up is not lower than 0.9 we find no entry through the year 2100 horizon of the model, and even if the vehicle mark-up is as low as 2.2 but the fuel mark-up is 1.7 there is also no entry by 2100.. To generate these frontiers, hundreds of simulations of the model were run to exhaustively map out combinations of markups that lead to entry of hydrogen vehicles through the century, and thus to locate the frontiers.

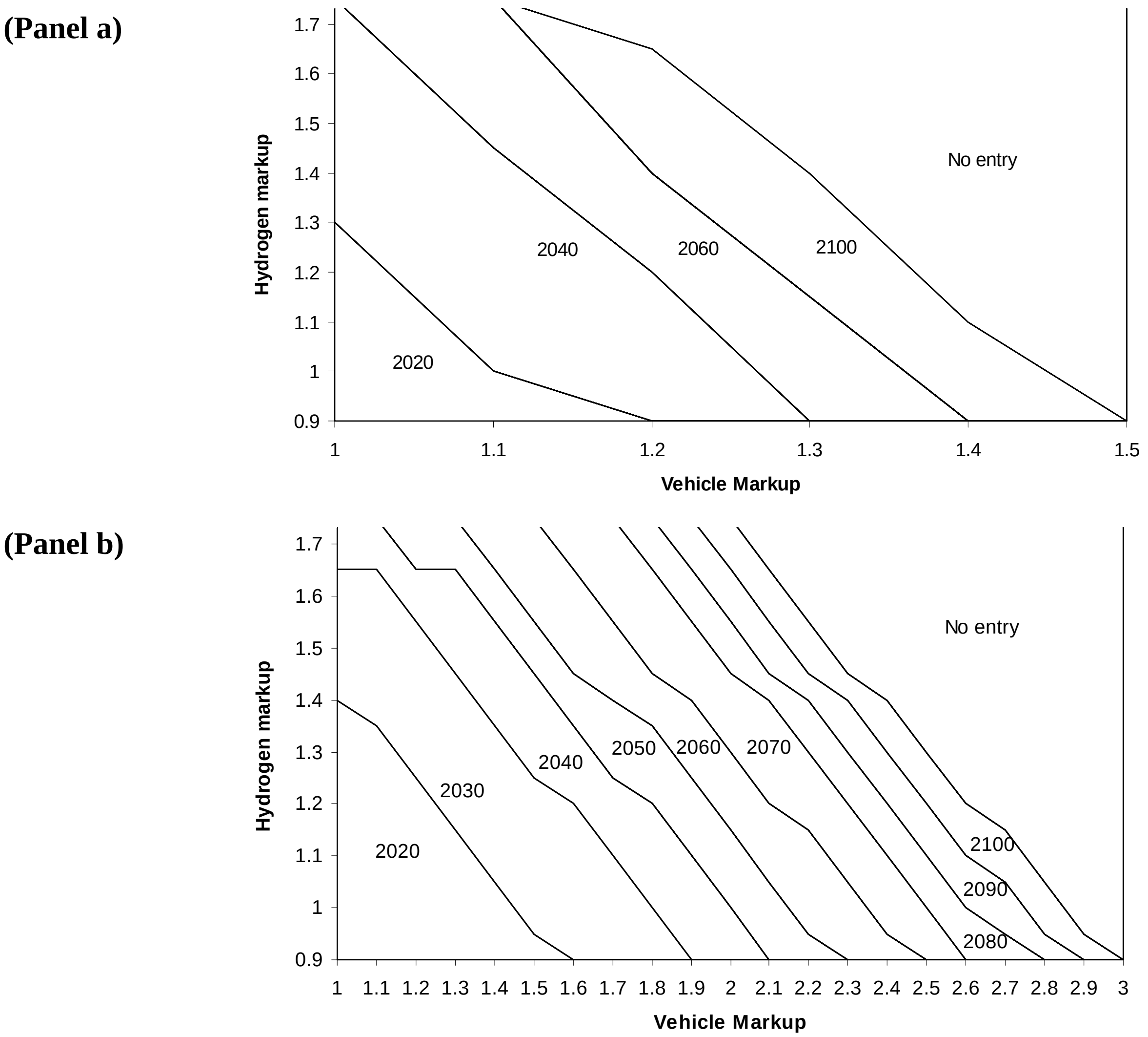

Figure 4. Entry decade for hydrogen transportation in the Baseline scenario. (Panel a) USA, (Panel b) Europe.

Comparing the USA to Europe, the striking difference is that for entry sometime before 2100 the mark-ups must be much lower in the USA. If the vehicle markup is larger than 1.5, the hydrogen fleet does not enter at all in the 21st century. The main reason for the difference between the USA and Europe, which is revealed by additional scenarios reported below, is that fuel taxes are very high in Europe compared to the USA. Note that in this scenario we applied the same rate of tax per energy unit to hydrogen as is applied to conventional fuel in Europe. But because the efficiency of the fuel cell vehicle is so much higher the “per mile” tax is much lower for hydrogen than for conventional fueled vehicles. Thus the existing fuel tax policy in Europe is more favorable to entry of hydrogen vehicles even if the tax is extended to hydrogen on the basis of energy content of the hydrogen fuel.

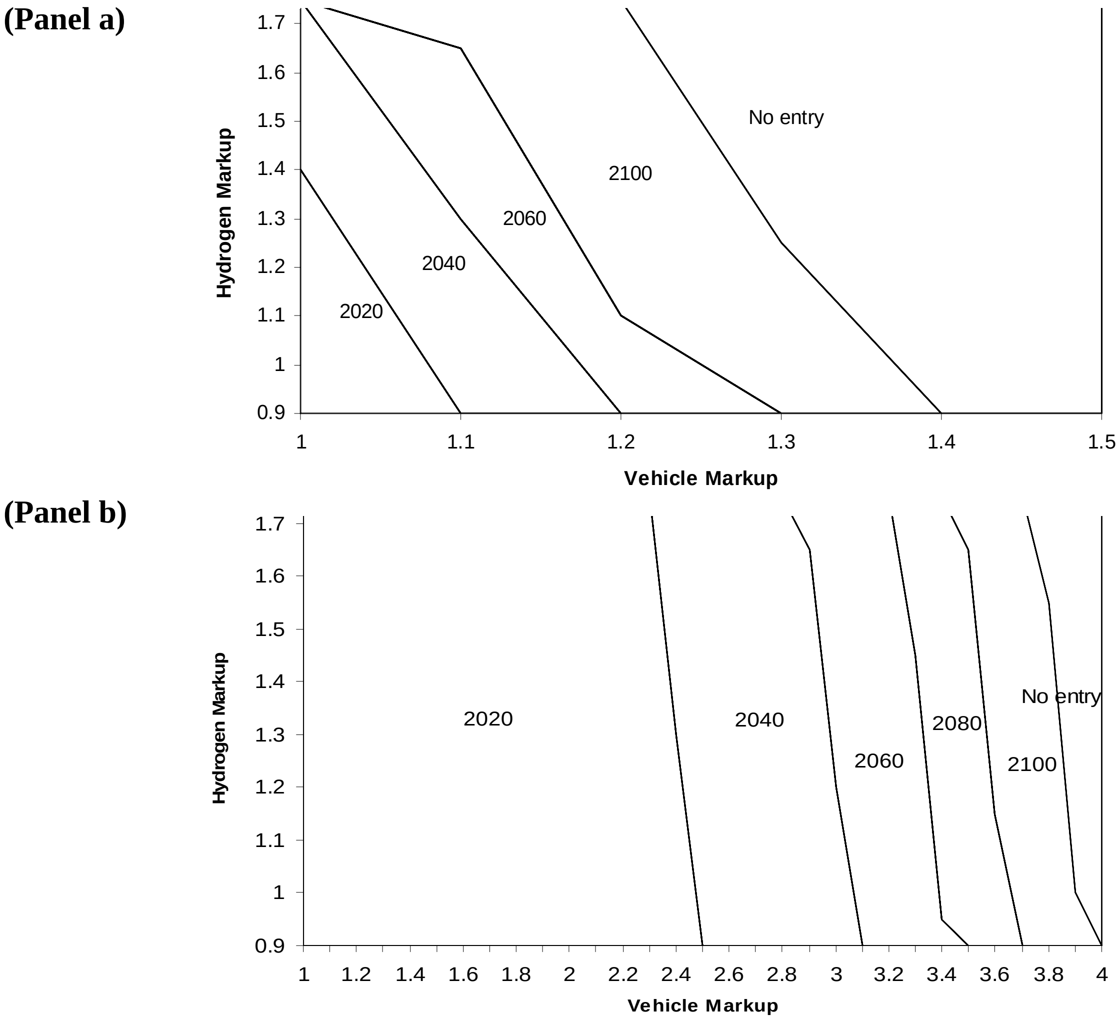

Figure 5. Entry decade for hydrogen transportation in the Baseline scenario. (Panel a) *No Fuel Tax* Scenario, (Panel b) *No Hydrogen Tax* Scenario.

Figure 5 investigates the role of fuel taxes in Europe where they are significant. In panel a we remove fuel taxes from conventional fuel and from hydrogen (*No Fuel Taxes* scenario) and in panel b we assume fuel taxes are not applied to hydrogen at all but remain on conventional fuels (*No Hydrogen Tax* scenario). In the *No Fuel Taxes* scenario a vehicle markup larger than 1.4 is prohibitive through 2100, which is very similar to the results for the USA, where fuel taxes are very low. On the other hand, if Europe were to continue taxing gasoline at the same rate that it does today but hydrogen fuel was not taxed (*No Hydrogen Tax* scenario), this would create an even more favorable environment for hydrogen transport. Under this scenario, as shown in panel b of Figure 5, entry by 2100 is possible if the vehicle mark-up is as much as 4.0, compared to 3.0

for the case in which both fuels are taxed, and entry by 2020 is possible if the vehicle markup is 2.5. Thus, the treatment of hydrogen with regard to fuel taxes has a very large effect on entry requirements for the hydrogen vehicle fleet. One issue that arises is that European countries rely on fuel taxes for a significant share of government revenue, and thus if hydrogen were not taxed, the governments would like have to find other tax revenue sources. Even if it were taxed at the same energy content level, the tax revenue would be reduced because of the greater efficiency of the hydrogen fleet. Thus, if European governments sought to maintain levels of fuel tax revenues they would need to increases the tax on hydrogen to compensate for the higher efficiency, thus erasing the apparent advantage the hydrogen fleet would have.

4.2 Effects of Carbon Emissions Constraints on Hydrogen Sector Entry

When a policy aimed at stabilizing atmospheric carbon concentrations at 550 ppmv is introduced, a carbon-equivalent price emerges as GHG allowances are traded among economic agents. In the transportation sector, a price on carbon would effectively raise the cost of supplying gasoline to consumers, who would bear some of the added cost burden. The carbon dioxide price will also affect hydrogen production costs because electricity is used and, even with CCS, not all of the carbon in the coal or gas is captured, however, we expect that higher carbon prices will favor hydrogen. In the CCSP stabilization scenarios that are the basis for the constraints imposed in our 550 ppmv scenario, the carbon dioxide price paths were determined to increase over time at 4% per year. In the 550 ppm stabilization scenario they started at $20 per ton CO_2 in 2020, rising to $475 by 2100. This would create a strong advantage for hydrogen, but as we will see in Section 4.4 the availability of a low cost hydrogen vehicle option has a large effect on CO_2 price needed to achieve these reductions. The penetration frontiers include this endogenous effect on the CO_2 price.

Not surprisingly, the effect of the 550 ppmv scenario is to shift the frontiers forward in time for a given mark-up, as shown in **Figure 6**. The climate policy effect is stronger in later years because of the underlying tightening of the carbon policy, relative to baseline emissions, over time. The maximum allowable vehicle markup in Europe rises from 3.0 to 4.0, an effect of the same magnitude as not taxing hydrogen in the No Hydrogen Tax scenario presented in Figure 5, panel b. In the U.S. the maximum markup for entry by 2100 was 1.5 in the Baseline scenario while in the Baseline scenario it rises to 1.8. Nevertheless, this increase is relatively smaller than in Europe. The difference between Europe (panel a) and the USA (panel b) is again due to the effect of the high fuel tax in Europe. As discussed in Section 2, current estimates for the hydrogen vehicle markup are between 10 and 20. Thus, even with strong greenhouse gas policy, the R&D would have to push down the cost of the vehicle by an order of magnitude for penetration in the US. The competitive situation in Europe, given high fuel taxes, reward the relative efficiency of the fuel cell vehicle more than in the USA but substantial cost reductions would be needed there as well.

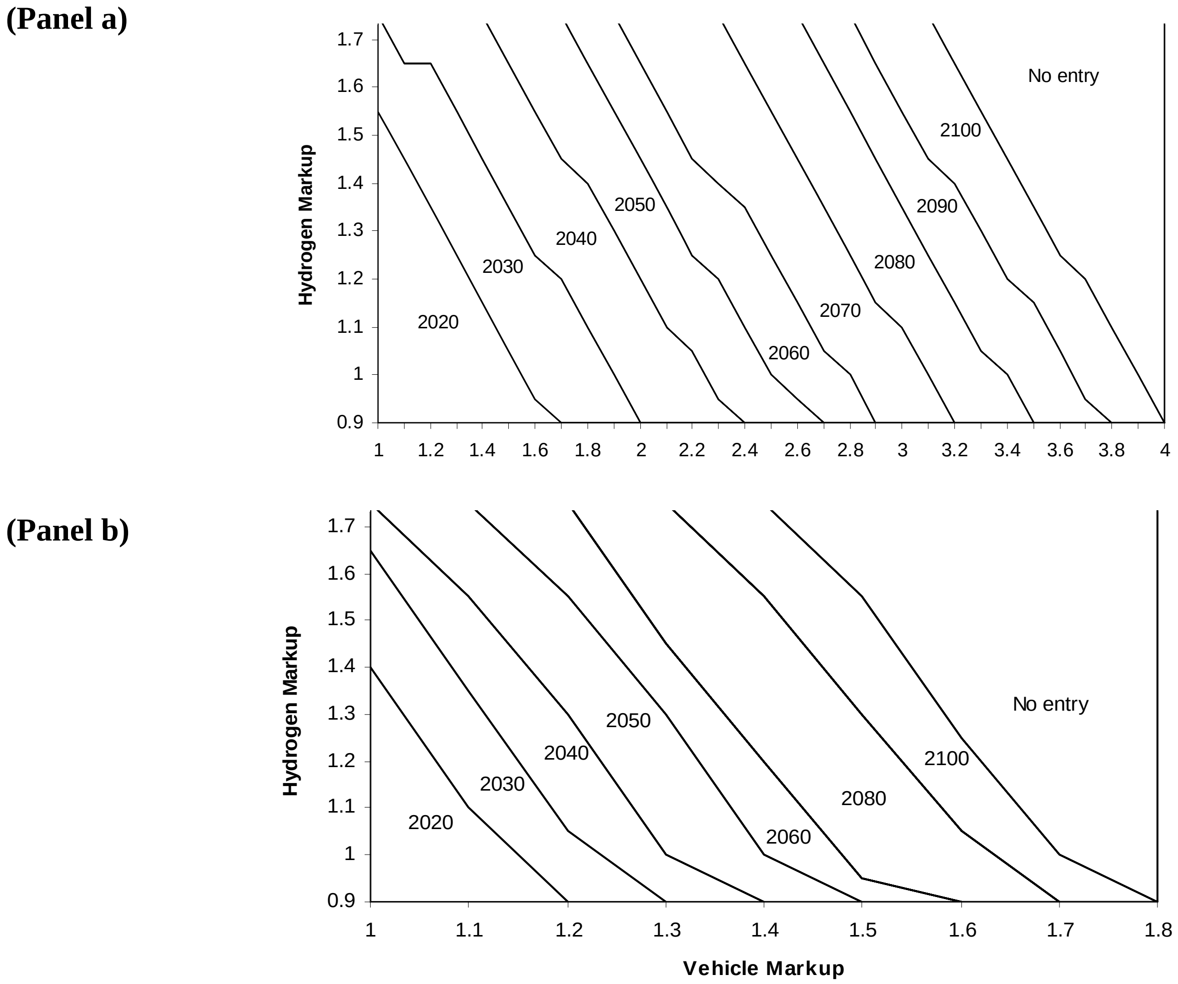

Figure 6. Entry decade for hydrogen transportation in the *550 ppmv* scenario. (Panel a) Europe, (Panel b) USA.

Figure 7 illustrates the results where Europe taxes conventional fuel but does not tax hydrogen and simultaneously imposes a carbon emission constraining policy (550 with *No Hydrogen Tax*). This is the most favorable scenario for hydrogen transportation among the ones we explore here. In this scenario it is possible for hydrogen transport to penetrate the market in the 21st century even at costs of four to five times the cost of internal combustion vehicles.

4.3 Effects of Carbon Emissions Constraints on Hydrogen Sector Entry

As shown in Table 1, the EPPA model has an advanced biofuel sector which represents lignocellulosic conversion of biomass (Reilly and Paltsev, 2007). Biofuels offer a significant alternative, particularly under a carbon dioxide emissions constraint, but is ultimately limited by rising land prices. If this alternative is not available, then the hydrogen vehicle fleet would penetrate earlier and at higher mark-ups as shown for the U.S. in the 550 with No Biofuels scenario (**Figure 8**). Hydrogen vehicles can enter the market within the 2100 time horizon even at vehicle markups of up to 3.0, nearly twice the level when biofuels are available.

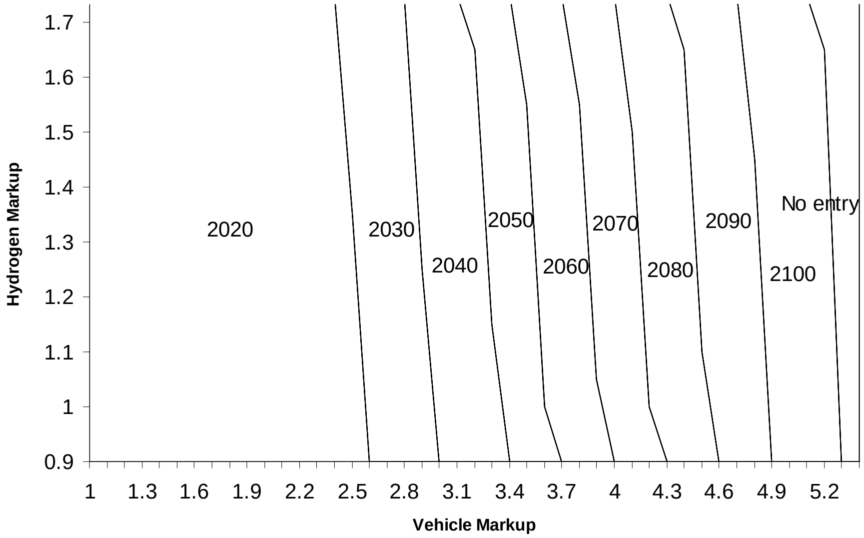

Figure 7. Entry decade for hydrogen transportation in Europe in the *550 with No Hydrogen Tax* scenario.

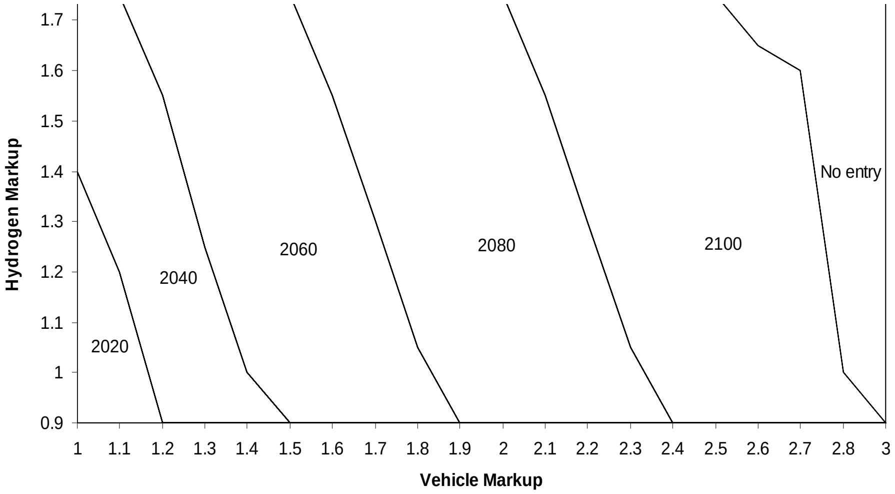

Figure 8. Entry decade for hydrogen transportation in USA in the *550 with No Biofuels* scenario.

4.4 Does Availability of Hydrogen Transportation Reduce Predicted Economic Losses?

We measure the macroeconomic cost of mitigation measures in terms of reduction in total consumption. For stabilization policies, these costs can be quite large in part due to the absence of good low carbon technology options in the transportation sector (US CCSP, 2007). To offer initial insight on this potential link, we compare two cases. A first set of scenarios were run with both hydrogen fuel and vehicle markups set to very low levels (1.0 and 1.3, respectively), assuming that R&D breakthroughs are successful. Scenarios with and without a carbon stabilization policy were run to compare the macroeconomic loss. A second set of scenarios was run with both the hydrogen fuel and vehicle markups set to prohibitively high levels (resulting in no entry of the hydrogen transportation sector) with and without a carbon stabilization policy. In all scenarios, the advanced biofuel sector was included and gasoline and hydrogen were taxed in Europe. A complicating factor in the analysis for individual regions is the particular allocation of reduction among countries, resulting in possible benefits related to selling of excess allowances in an international permit market, and other terms of trade effects. To eliminate these complicating factors, we consider a climate policy in USA only and in Europe only without emissions trading and with GHG reductions in these countries as in a stabilization policy aiming at 550 ppmv CO_2 concentration (US CCSP, 2007). These policies thus achieve the same reductions in these regions as in the 550 ppmv scenario but we get a more accurate picture of the implications for cost of just the breakthrough in hydrogen technology.

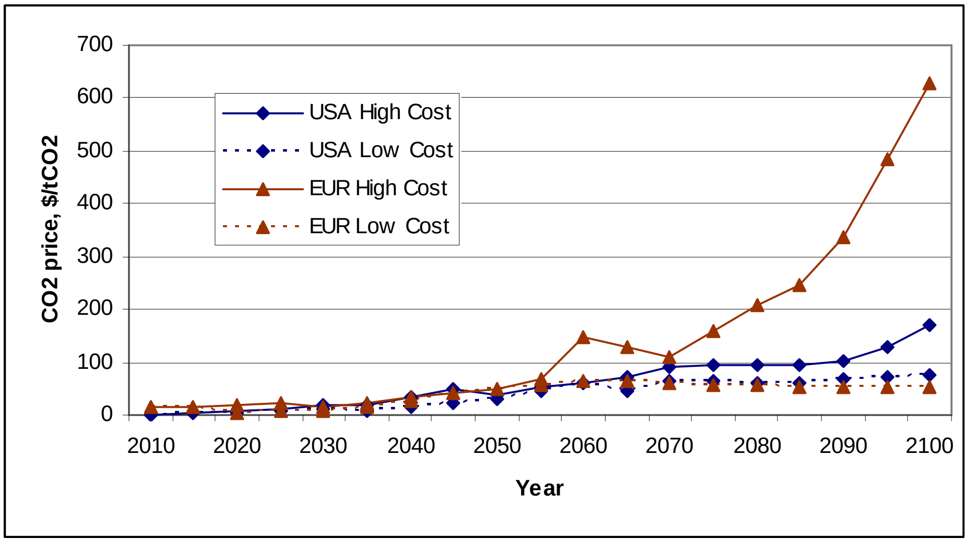

Figure 9. Effects on the CO_2 price of hydrogen technology breakthroughs.

The results of this scenario analysis indicate that a carbon-free alternative in the transportation sector could mitigate consumption losses associated with the introduction of a carbon stabilization policy in both the U.S. and Europe. When the cost of hydrogen transportation is prohibitive, the introduction of a carbon policy results in consumption losses of 0.4 per cent and 3.2 per cent in the U.S. and Europe respectively, compared to the expected 2100 consumption levels in the no climate policy case. However, if hydrogen transportation is available at the time the policy takes effect, these losses are reduced to only 0.3 per cent and 0.9 per cent in the U.S. and Europe respectively. We also found out that even in the absence of a policy to limit emissions, the availability of a reasonably priced low carbon alternative enables modest increases in consumption, as prices of gasoline rise more in the no hydrogen scenarios, suggesting that the availability of hydrogen or another alternative could have sizeable welfare benefits.

Figure 9 shows the impacts on the CO_2 price needed to meet these targets, which is substantial. When hydrogen technology is prohibitively expensive the CO_2 price rises to over \$600 per ton in Europe and to over \$170 in the USA by 2100. The large difference simply reflects the relative level of reduction in these two regions and options to abate in other sectors. The USA is more dependent on coal electric generation and it can meet much of its target through elimination of emissions from electric generation and from biofuels. Europe must cut deeper into transportation emissions, and with limited options the CO_2 price must rise enough to reduce use of transportation. With the assumed breakthroughs in hydrogen production and vehicles the required CO_2 price in both regions is well under \$100/ton. Of course these estimates depend on achieving the particular breakthroughs we have assumed in these scenarios. If the breakthroughs achieve less reduction in hydrogen costs, the reduction in the CO_2 price and consumption loss would not be as big.

5. CONCLUSIONS

Our analysis of the behavior of a hydrogen transport sector within a general equilibrium model of the economy provides several important insights. Under reference conditions (that is, in the absence of taxes or a climate policy), hydrogen fuel cell vehicles would have to reach a markup of less than 1.5 over conventional technology vehicles to penetrate the U.S. market before 2100. However, even if hydrogen vehicles do penetrate the market, carbon emissions for the US are reduced only slightly because coal is used to produce the hydrogen and there is no incentive to sequester the carbon when the hydrogen is produced in the absence of climate policy.

The existing fuel tax structure in Europe favors the entry of hydrogen transportation, even when hydrogen is taxed at the same rate as gasoline. This is because the hydrogen vehicles are more efficient, and for a given tax rate per unit of energy, this implies a lower tax per vehicle mile traveled. Entry is possible in Europe in the middle of the century when hydrogen vehicles are twice as expensive as conventional vehicles when the fuel taxes based on energy content of the fuel are equal. If hydrogen fuel were not taxed at all, then hydrogen vehicles could enter if they were less than four times as expensive as conventional vehicles, but this would mean that European governments would lose fuel tax revenue. It is perhaps unrealistic to assume that the governments could afford to forego hydrogen tax revenues, especially if hydrogen became the dominant transportation fuel. On the other hand, it may also be unrealistic to consider this tax rate as fixed. As the price of gasoline increases, European governments would be able to collect the equivalent revenue with lower tax rates and they would probably face increasing pressure to lower the rate.

A carbon constraining policy favors the entry of hydrogen transportation to some extent. A 550 ppmv stabilization policy increases the maximum vehicle markup that allows entry in Europe from 3.0 to 4.0. In the USA, it increases the maximum markup by 0.3, to a maximum markup of 1.7.

If advanced biofuel technology is not available and does not compete with hydrogen transportation technology, the favorable effect is much larger. If the 550 ppmv stabilization policy is imposed in the absence of advanced biofuels, hydrogen transportation can penetrate the U.S. market with a vehicle markup of up to 3.0. This scenario is the most favorable for hydrogen transportation in the USA.

Without a low carbon alternative technology in the transportation sector, the consumption losses in both the U.S. and Europe could be far larger than if such an alternative were available. Our analysis shows that the availability of a low carbon alternative could reduce the consumption loss, an expected result of the limited emissions reduction potential of the current transportation fleet. Even in the absence of a policy to limit emissions, the availability of a reasonably priced low carbon alternative is expected to enable modest increases in consumption, especially if prices of gasoline rise as expected, suggesting that the availability of hydrogen or another alternative could have sizeable welfare benefits. However, to put these results in perspective, it is important to remember that current vehicle markups are between 10 and 20. In the absence of a strong carbon tax policy, hydrogen would not play a significant role in the twenty-first century unless there is a significant decrease in vehicle cost. For those involved in hydrogen vehicle research, this analysis provides some cost targets they would need to meet and, given those are achieved, an idea of when vehicle could be competitive and under what conditions.

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6. REFERENCES

Adamson, K.-A., and P. Pearson, 2000. Hydrogen and methanol: a comparison of safety, economics, efficiencies and emissions. *Journal of Power Sources*, **86**: 548–555.

Babiker, M.H., G.E. Metcalf and J. Reilly, 2003. Tax distortions and global climate policy, *Journal of Environmental Economics and Management*, **46**: 269-287.

California, 2007. California Hydrogen Highway Network: Ca H2 Net Blueprint Plan Fact Sheet http://www.hydrogenhighway.ca.gov/media/blueprintfacts.pdf.

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

EIA [Energy Information Administration], 2006. Emissions of Greenhouse Gases in the United States 2005. U.S. Department of Energy, Washington, DC.

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.

Iwasaki, W., 2003. A consideration of the economic efficiency of hydrogen production from biomass. *International Journal of Hydrogen Energy*, **28**: 939-944.

Jacoby, H.D., R.S. Eckhaus, A.D. Ellerman, R.G. Prinn, D.M. Reiner and Z. Yang, 1997. CO_2 emissions limits: economic adjustments and the distribution of burdens. *The Energy Journal*, **18**(3): 31-58.

Kosugi, T., A. Hayashi and K. Tokimatsu, 2004. Forecasting development of elemental technologies and effect of R&D investments for polymer electrolyte fuel cells in Japan. *International Journal of Hydrogen Energy*, **29**: 337-346.

Kreutz, T., R. Williams, S. Consonni, and P. Chiesa, 2004. Co-Production Of Hydrogen, Electricity And CO_2 From Coal With Commercially Ready Technology. Part B: Economic Analysis, *International Journal of Hydrogen Energy*, **30**: 769-784.

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

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

NRC [National Research Council], 2005. Review of the Research Program of the FreedomCAR and Fuel Partnership, National Academies Press, Washington, D.C.

NRC [National Research Council], 2004. The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs. National Academies Press, Washington, D.C.

Ogden, J. M., R.H. Williams, and E.D. Larson, 2004. Societal Lifecycle Costs of Cars with Alternative Fuels/Engines. *Energy Policy*, **32**: 7-27.

Padró, C., and V. Putsche, 1999. Survey of the Economics of Hydrogen Technologies, National Renewable Energy Laboratory. Golden, Colorado. NREL/TP-570-27079.

Paltsev, S., H. Jacoby, J. Reilly, L. Viguier, and M. Babiker, 2004. Modeling the Transport Sector: The Role of Existing Fuel Taxes in Climate Policy, MIT Joint Program on the Science and Policy of Global Change, *Report 117*, Cambridge, MA. (http://web.mit.edu/globalchange/www/MITJPSPGC_Rpt117.pdf).

Paltsev, S., J.M. Reilly, H.D. Jacoby, R.S. Eckaus, J. McFarland, M. Sarofim, M. Asadoorian, and M. Babiker, 2005. The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4, MIT Joint Program for the Science and Policy of Global Change, *Report 125*, Cambridge, MA. (http://web.mit.edu/globalchange/www/MITJPSPGC_Rpt125.pdf).

Paltsev, S., J. Reilly, H. Jacoby, A. Gurgel, G. Metcalf, A. Sokolov, and J. Holak, 2007. Assessment of US Cap-and-Trade Proposals, MIT Joint Program on the Science and Policy of Global Change, *Report 146*, Cambridge, MA. (http://web.mit.edu/globalchange/www/MITJPSPGC_Rpt146.pdf).

Prince-Richard, S., M. Whale, and N. Djilali, 2005. A Techno-Economic Analysis Of Decentralized Electrolytic Hydrogen Production For Fuel Cell Vehicles, *International Journal of Hydrogen Energy*, **30**: 1159-1179.

Reilly, J., Prinn, R.,J. Harnisch, J. Fitzmaurice, H. Jacoby, D. Kicklighter, J. Melillo, P. Stone, A. Sokolov and C. Wang, 1999. Multi-gas assessment of the Kyoto Protocol, *Nature*, **401**: 549-555.

Reilly, J. and S. Paltsev, 2006: European Greenhouse Gas Emissions Trading: A System in Transition. In: Economic Modeling of Climate Change and Energy Policies, M. De Miguel *et al.* (eds.), Edward Elgar Publishing, pp. 45-64.

Reilly, J. and S. Paltsev, 2007. Biomass Energy and Competition for Land, MIT Joint Program on the Science and Policy of Global Change, *Report 145*, Cambridge, MA. (http://web.mit.edu/globalchange/www/MITJPSPGC_Rpt145.pdf).

Rogner, H. H. 1998. Hydrogen Technologies and the Technology Learning Curve, *International Journal of Hydrogen Energy*, **23**: 833-840.

Rutherford, T. 1995. Demand Theory and General Equilibrium: An Intermediate Level Introduction to MPSGE, GAMS Development Corporation, Washington, DC.

Sandoval, R., 2006. Quantitative Analysis of Alternative Transportation under Environmental Constraints, Master of Science Thesis, Technology and Policy Program, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Simbeck, D. and E. Chang, 2002. Hydrogen Supply: Cost Estimate for Hydrogen Pathways – Scoping Analysis. National Renewable Energy Laboratory, July. *Report No. SR-540-32525*.

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, L. Clarke *et al.*, US Climate Change Science Program, Department of Energy, Washington, DC.