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Modelling Prospects for Hydrogen-powered Transportation Until 2100

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

Address for correspondence: John M. Reilly, Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, 77 Massachusetts Avenue, E19-411, Cambridge MA 02139-4307, USA (jreilly@mit.edu).

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Abstract

Hydrogen 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 stabilisation policy scenarios. For each scenario, various combinations of hydrogen fuel price and vehicle mark-ups are used as inputs to explore what technological improvements in terms of cost reductions would be necessary for the technology to penetrate the market. The effect of introducing reduced-carbon fuel substitutes, such as ethanol-blend fuels, on the economic viability of hydrogen transportation is also explored. Hydrogen-powered fuel cell vehicles could make a significant contribution to de-carbonisation of transportation if production of hydrogen itself is not carbon-intensive. For those involved in hydrogen research, this analysis provides cost targets that would need to be met for hydrogen transportation to be economically viable within the next century. 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 of an average fuel cell automobile would need to be no more than 1.3 to 1.5 times an average conventional vehicle.

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1.0 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 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 the total carbon dioxide emissions. For example, EIA (2006) reports that the share of CO_2 emissions from transportation in the USA was about 31 per cent in 1990, rising to 33 per cent in 2004.

Improvements in internal combustion engine technology are not likely to be adequate to achieve the CO_2 emissions reductions needed, for example, under a climate policy goal of stabilisation of greenhouse gas emissions. Even significant fleet fuel economy improvements, such as those promised by further penetration of electric–gasoline hybrid vehicles, are probably 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. Among the technology options for further reducing 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. Although large-scale adoption of all of these alternatives has the potential to significantly reduce tailpipe emissions, the total impact on emissions will depend on the carbon intensity of the energy crop and the conversion of any primary energy source to fuel, electricity, or hydrogen. In this paper, we focus on the hydrogen 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 compete with other technologies that are changing, where fuel costs are rising, and under different assumptions about carbon dioxide control policies.

The analysis begins in Section 2 with an overview of the technologies and costs associated with the production and distribution of hydrogen.

Section 3 discusses characteristics of hydrogen vehicles. In Section 4 we describe our strategy for representing hydrogen production and transportation in the EPPA model. In Section 5 we simulate a variety of scenarios to identify conditions that would favour entry of hydrogen vehicles into the household transportation fleet. 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 then consider a specific fuel and vehicle cost pair and, assuming that ongoing research is successful in reducing the cost of the technology to these levels, evaluate the extent to which hydrogen technology would lower the cost of achieving emissions reductions under a climate policy. In Section 6, we discuss the outcomes of the scenario analysis and offer some conclusions.

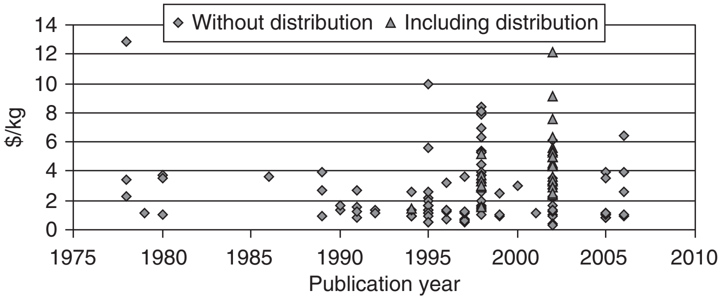
2.0 Hydrogen Fuel Production

If a hydrogen fuel cell vehicle fleet is to become a reality, it requires advances in vehicle technology and reliable, 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. Coal is, however, less expensive and is more abundant. For either to offer significant reductions in CO_2 emissions, carbon capture and storage (CCS) would need to be a part of the hydrogen production process. Other forms of hydrogen production, such as electrolysis or thermochemical water splitting, are more expensive. In our model, we consider hydrogen production only from natural gas and coal because they are the least costly sources at present and are likely to remain so.

Extensive fuel storage and distribution infrastructure would also be necessary components of a hydrogen transportation system. Developing this infrastructure would be 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 fuelling infrastructure. Programmes such as California's Hydrogen Highway Network would be needed to overcome this chicken–egg problem (California, 2007).

Figure 1

Published Cost Estimates for Hydrogen Production by Publication Date



Source: Sandoval (2006).

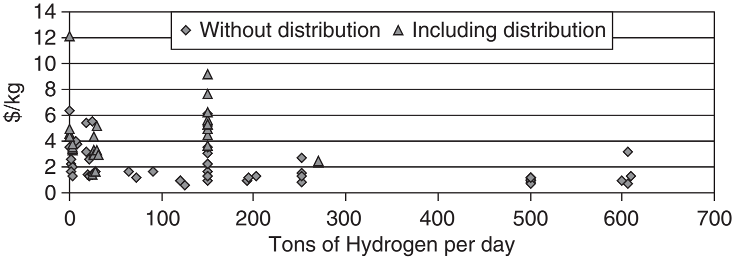
Turning to the literature on production and distribution costs, surveys have often revealed highly disparate estimates of hydrogen production costs that are hard to compare, given that assumptions behind the estimates are often not explicitly stated (Padró and Putsche, 1999; Adamson and Pearson, 2000; Iwasaki, 2002; Simbeck and Chang, 2002; Kreutz *et al.*, 2004; Prince-Richard *et al.*, 2005; Sandoval, 2006). Below we compare estimates of hydrogen production costs, depending on whether distribution costs were included, the size of the production facility, and which hydrogen source technology was assumed. Cost estimates for the production of hydrogen with and without distribution made over the last thirty years are shown in Figure 1, with no obvious trend over time.

Cost estimates plotted against the size of the hydrogen production facility also fail to reveal a trend, as presented in Figure 2; however, all facilities currently operating are probably small relative to the size that would be required if hydrogen vehicles were used at a significant level.

Cost estimates from the literature are also shown in Figure 3, classified according to technology of production. Two cost groups emerge — a more

Figure 2

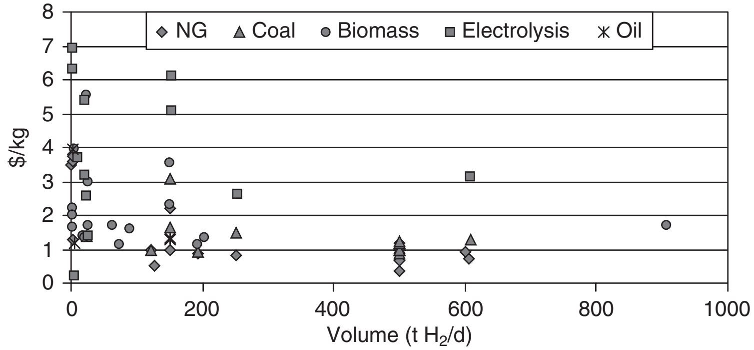
Published Cost Estimates for Hydrogen Production by Plant Size



Source: Sandoval (2006).

Figure 3

Published Cost Estimates for Hydrogen Production by Technology



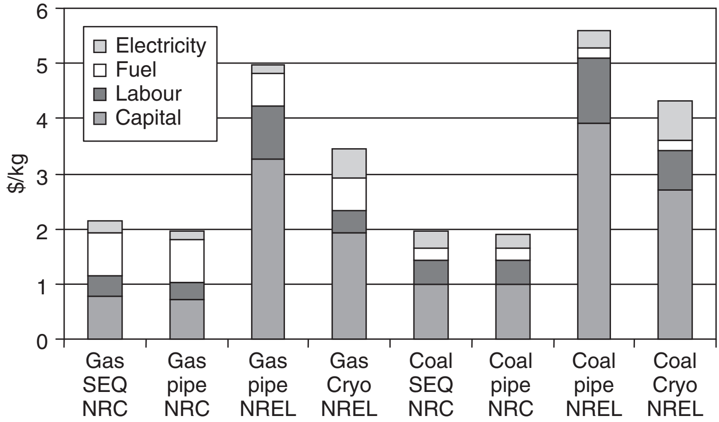
Source: Sandoval (2006).

expensive cluster includes electrolysis and biomass conversion, while natural gas, coal, and residual oil are less expensive. Since only a few estimates included the cost of distribution, all estimates presented in Figure 3 have been recalculated to exclude distribution costs so that they are more directly comparable.

While the set of literature reviewed above provides a broad overview of costs and cost trends, without detail on sources of costs and cost differences these reviews do not provide the detail needed for parameterising 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 fuel is included, assumptions on how it is delivered, and whether or not CCS is included. 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 of the end-use technology for utilising the fuel. If the concern is climate change, the implications for carbon emissions depend critically on the specific hydrogen production technology, the efficiency of conversion and utilisation 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 and a review carried out by the National Research Council (NRC, 2004).

Figure 4
Estimated Hydrogen Cost per kilogram by Means of Production and Distribution



Note: *Gas SEQ NRC* — Natural Gas with CSS 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.

Figure 4 shows a comparison of the hydrogen cost per kilogram in these two studies with different assumptions about feedstock used, the means of distribution, and whether carbon capture and sequestration is included. It further shows costs broken down into four components: fuel (or feedstock), electricity, capital, and labour. Notably, the NRC estimates are about one-half of those in the NREL study even though the feedstock cost is about the same, and the NRC study used the same cost model as the NREL study. As described in the NRC study, the difference primarily reflects different assumptions about the cost of developing the distribution and refuelling network (NRC, 2004).

3.0 Hydrogen Vehicles

Regarding the vehicle fleet, two possible hydrogen vehicle technologies exist: one would retain an internal combustion engine fuelled 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 onboard 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 by-product 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 favourable estimated fuel economy of around 66 miles per gallon of gasoline-energy equivalent (Padró and Putsche, 1999). Large-scale substitution of hydrogen for gasoline or diesel as a transportation fuel would also have the advantages of centralising emissions at the point of hydrogen production for easier control, allowing greater flexibility in the choice of a primary energy source used to produce the hydrogen, and reduce dependence on oil and refined products.

So far, however, a number of practical constraints exist to market penetration of fuel cell vehicles. Fuel cell performance, durability, and cost limit 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 commercialisation 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 commercialisation targets.

4.0 Modelling Hydrogen Transport in the EPPA Model

Before turning to a technical description of the EPPA model augmented to include hydrogen vehicles and production, it is useful to lay out our modelling strategy. As is clear from the previous section, both technical and cost hurdles must be overcome in order to make a hydrogen-fuelled 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 hydrogen technology are highly uncertain, basic conversion efficiencies of feedstock to 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 (such as 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 that 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 that they have different CO_2 emissions implications.

Our modelling strategy is to parameterise a hydrogen fuel cell vehicle fleet and hydrogen production/distribution sectors based on key conversion efficiencies and the non-fuel cost shares based on existing literature assuming near-competitive costs, that is, assuming that the 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 fuel cost. If, for example, the goal of an R&D programme 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 programme that would be needed to achieve them, but indicates under what conditions their achievement would lead to market penetration.

Turning to the modelling 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 CCS. The sector mark-ups 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.

The EPPA model is a recursive-dynamic general equilibrium model of the world economy developed by the MIT Joint Program on the Science and Policy of Global Change (Paltsev *et al.*, 2005). The EPPA model is built on the GTAP dataset (Hertel, 1997; Dimaranan and McDougall, 2002), which accommodates a consistent representation of energy markets in physical units as well as detailed data on regional production 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, NO_x; 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 sixteen regions and twenty-four sectors with several advanced technology sectors that are not explicitly represented in GTAP (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 five-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 the MPSGE modelling language (Rutherford, 1995). The EPPA model has been used in a wide variety of policy applications (for example, see Jacoby *et al.*, 1997; Reilly *et al.*, 1999; Babiker *et al.*, 2003; Reilly and Paltsev, 2006; US CCSP, 2007; Paltsev *et al.*, 2007).

Because of the focus on climate and energy policy, the model uses disaggregated GTAP data for transportation and existing energy supply technologies. It also 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, policy, and other forces driving economic growth such as savings, investment, energy-efficiency improvements, and productivity of labour. Additional information on the EPPA model can be found in Paltsev *et al.* (2005).

Table 1

Sectors and Regions in the EPPA Model

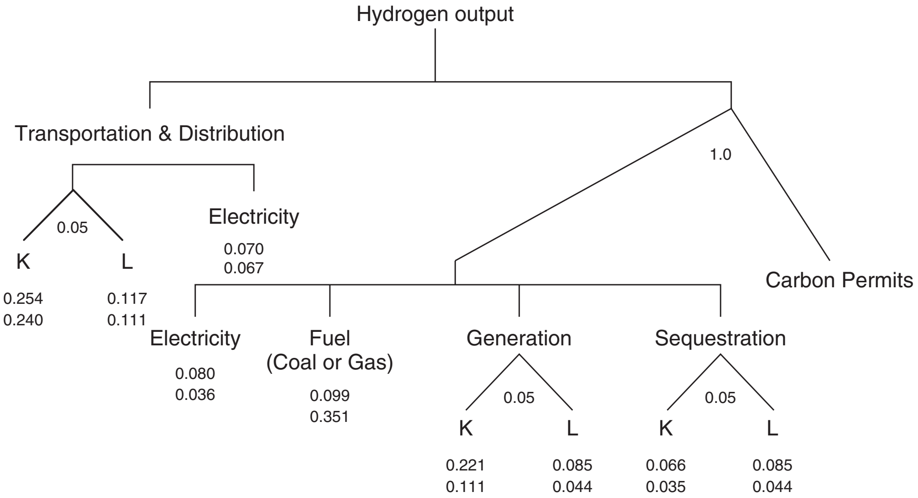
Sectors	*Regions*
Non-energy	**Developed**
Agriculture	USA
Services	Canada
Energy-intensive products	Japan
Other industries products	European Union + Australia & New Zealand
Industrial transportation	Former Soviet Union
Household transportation: internal combustion vehicles	Eastern Europe
Household transportation: hydrogen vehicles	
Energy	**Developing**
Coal	India
Crude oil	China
Refined oil	Indonesia
Natural gas	East Asia
Electric: fossil	Mexico
Electric: hydro	Central & South America
Electric: nuclear	Middle East
Electric: solar and wind	Africa
Electric: biomass	Rest of World
Electric: natural gas combined cycle	
Electric: natural gas combined cycle with 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 were not operating in the base year or do not exist explicitly in the GTAP dataset; details on advanced technology sectors and regional grouping are provided 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 production of hydrogen fuel is modelled as two independent and competing sectors. The first produces hydrogen from natural gas using steam methane reforming technology, and the second produces hydrogen from coal using coal gasification technology. Both hydrogen production

Figure 5
Structure of the Hydrogen Production Sector

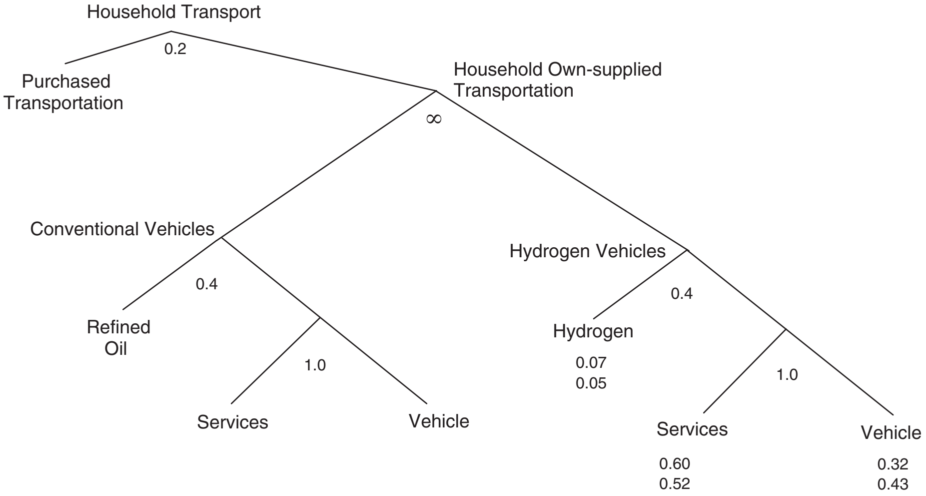


Note: Cost shares are shown for hydrogen production from coal (top) and natural gas (bottom), and are identical in the USA and Europe.

sectors are equipped with CCS set to capture 90 per cent of carbon emissions. We model CCS technology as presented in McFarland *et al.* (2004). The generic structure of a hydrogen production sector is shown in Figure 5.

Elasticities of substitution between input shares and factor shares for each input are shown below the inputs with the coal-based factor shares the top number and the gas-based shares the bottom number. Where the inputs are shown with vertical lines, the structure is Leontief, that is, 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 per cent), and the fuel cost share for natural gas is much higher than for coal reflecting the higher gas price — but that makes capital and labour costs a lower 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 modelling 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. At the same time, the carbon implications of the electricity production technology are also captured.

Figure 6
Structure of Household Transportation Sector



Note: Cost shares are shown for hydrogen transport in USA (top numbers) and Europe (bottom numbers). For a more detailed explanation of cost shares for vehicle and services in private transportation, see Paltsev *et al.* (2004).

In order to model hydrogen-based household transport, we introduce a new transportation sector that is shown in Figure 6. This hydrogen fleet is in direct competition with the pre-existing own-supplied household transportation (private automobiles) and is similar in structure. The characteristics of vehicles in terms of, for example, power, performance, safety, reliability, interior space, refuelling, 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 the greater efficiency of hydrogen use in a fuel cell compared with gasoline or diesel use in a conventional internal combustion engine. The production structure of the conventional and hydrogen fleet are identical except for the replacement of conventional fuel with hydrogen. Differences among the technologies are reflected by values of parameters that control input cost shares.

As shown in Figure 6, 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 the factor shares shown beneath the inputs (US shares shown as the top number and Europe shares shown as the bottom number). The vehicle input is an output of the other industries sector, capturing the cost of automobiles, since the automotive industry is part of that sector in the database. The fuel input represents the cost of fuel for private automobiles which, based on initial parameterisation, implies a specific physical quantity of hydrogen fuel and, along with other parameters of the production function, also implies an efficiency of power conversion that depends on the fuel mark-up as discussed below. Note that a modelling 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 the implications of taxing or not taxing hydrogen at the same rate per energy content as conventional fuel. The services share represents all non-fuel operation 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 how input shares are used to calibrate the model, see Paltsev *et al.* (2004).

The mark-up approach described briefly at the beginning of the 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 (that is, 1997) of the advanced technology relative to the one against which it competes. If the mark-up is larger than 1.0 it indicates that the new technology is more expensive relative to its conventional counterpart, given the input costs in the base year. A technology with a mark-up greater than 1.0 can eventually enter if the price of inputs it requires in large amounts falls (or rises 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 mark-ups are used for 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 mark-up, but produce many simulations of the model in which we vary the mark-ups 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 mark-up for hydrogen production from natural gas and coal. This strategy seems reasonable since much of the uncertainty in hydrogen production costs involves basic production processes and, especially, the cost distribution, which does not depend on whether gas or coal is used as the feedstock.

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 can then 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 dataset. For a fuel mark-up 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, the efficiency of fuel cell vehicles is about 66 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 parameterisation 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 per cent 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. Hydrogen vehicles compete against this potentially low carbon alternative but we also consider cases where biofuels are not an option.[1]

5.0 Scenario Analysis

As discussed above, we used the modified EPPA model to examine the timing of hydrogen sector penetration under different policy constraints and different estimates about the mark-ups. We focus on the initial date and conditions at which hydrogen transport becomes cost-competitive

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[1] The carbon intensity of biofuels is highly dependent on how it is produced and the land use implications of a large biofuels industry. In the EPPA model, biofuels are produced using a cellulosic process that does not require fossil fuel use and any land use emissions are not explicitly treated. Examining cases where the biofuel option is not available thus considers the situation where those relatively optimistic assumptions about biofuels are not realised.

with conventional technology and starts penetrating 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 stabilisation policy. Cap-and-trade results are directly applicable to a carbon tax with the same coverage and emissions target. Second, we analyse the impact of the availability of low-carbon fuel substitutes. Finally, we compare predicted consumption growth if an aggressive greenhouse gas reduction policy is implemented in the presence and absence of a cost-competitive hydrogen transportation alternative. We focus on Europe and the USA in the presentation of our results.

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 stabilised at 550 ppmv was considered. We use the 550 ppmv stabilisation scenario developed for the US 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 analysed in this paper. It includes the following policy cases: fuel taxes are imposed (at current rates)

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 stabilisation at 550 ppmv, hydrogen fuel is taxed at the current gasoline tax rates
550 with no fuel taxes	Climate policy leads to a stabilisation at 550 ppmv, hydrogen fuel and gasoline are not taxed
550 with no hydrogen tax	Climate policy leads to a stabilisation at 550 ppmv, hydrogen fuel is not taxed
550 with no biofuels	Climate policy leads to a stabilisation at 550 ppmv, hydrogen fuel is taxed at the current gasoline tax rates, no advanced biofuels available

both on gasoline and hydrogen use in transportation; fuel taxes are imposed (at current rates) on gasoline but not on hydrogen fuel; and no fuel taxes are imposed. We test these scenarios in a no-climate-policy case (baseline), in a policy case constraining carbon emissions that stabilises CO_2 concentration at 550 ppmv, and in a case where there is no development in advanced biofuels.

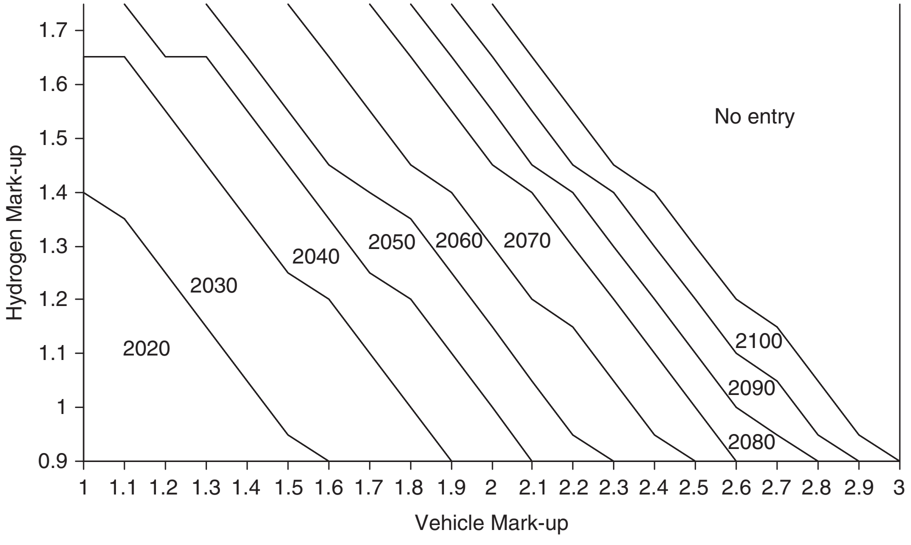
For each combination of mark-ups, the EPPA model runs for the whole century to determine the decade in which hydrogen transportation would become viable. The timing of hydrogen sector entry for each mark-up combination is represented by curves that trace boundaries between the decades labelled in the adjacent regions through to the year 2100.

5.1 Effects of fuel taxes on hydrogen sector entry

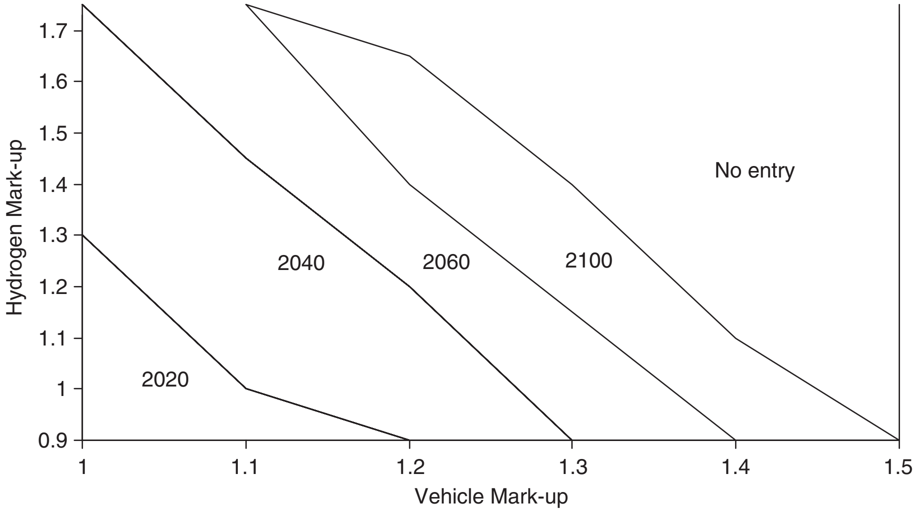
First, we explore the potential for hydrogen sector entry in the Baseline (that is, no climate policy) cases in Europe and the USA with hydrogen fuel tax at the level of gasoline tax. Figure 7a shows in which decade the technology will become viable at various initial mark-up combinations in Europe and Figure 7b provides the same information for the USA. For Europe, the frontiers indicate, for example, that combinations of fuel mark-up of 0.9 and vehicle mark-ups of less than 1.6 or a vehicle mark-up of 1.0 and a fuel mark-up 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 that there is no entry through to the year 2100 time horizon of the model. To generate these frontiers, hundreds of simulations of the model were run exhaustively to map out combinations of mark-ups that lead to entry of hydrogen vehicles through the century.

Comparing Europe to the USA, the striking difference is that for entry sometime before 2100 to occur, the mark-ups must be much lower in the USA. If the vehicle mark-up is larger than 1.5, the hydrogen fleet does not enter at all in the twenty-first 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 the 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 vehicles. Thus, the existing fuel tax policy in Europe is more favourable to entry of hydrogen vehicles even if the tax is extended to hydrogen on the basis of the energy content of the hydrogen fuel.

Figure 7
Entry Decade for Hydrogen Transportation in (a) Europe and (b) USA in the Baseline Scenario



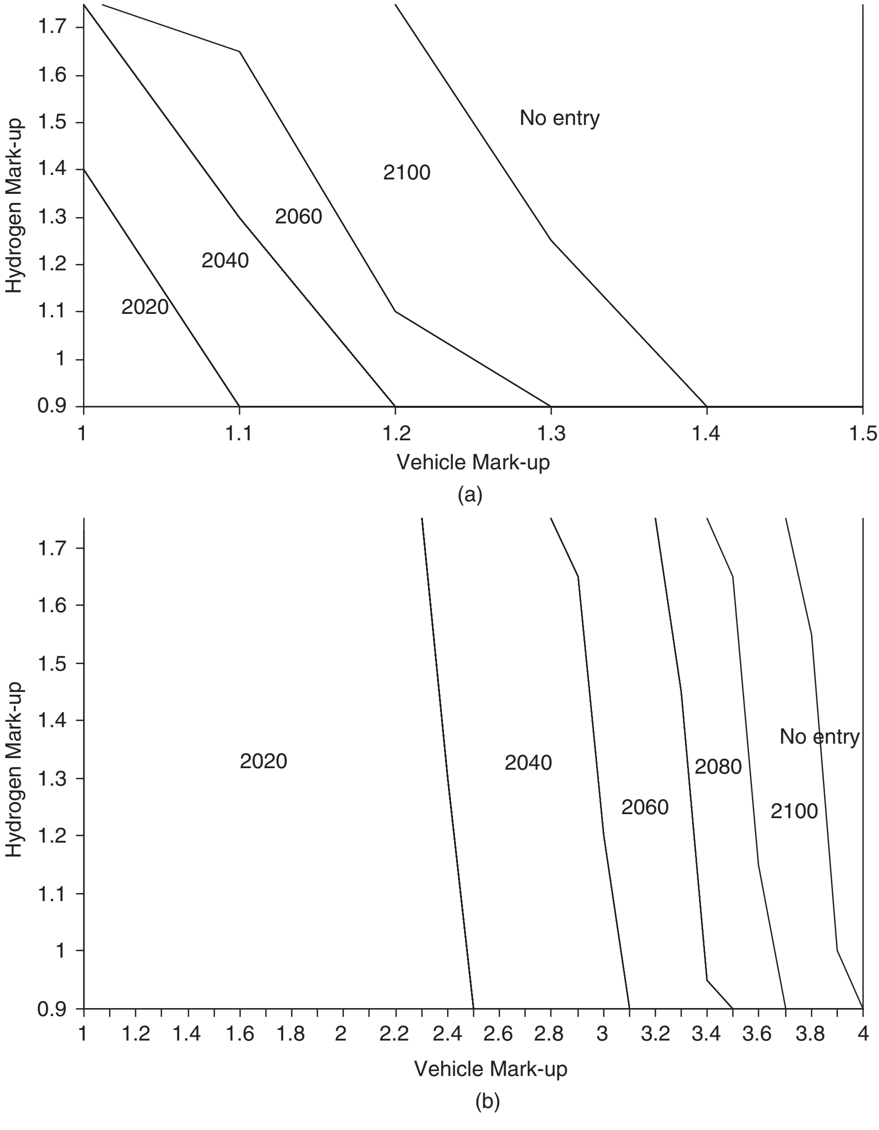
(a)



(b)

In Figure 8, we show the results on the role of fuel taxes in Europe where they are significant. In Figure 8a, we remove fuel taxes from conventional fuel and from hydrogen (No Fuel Taxes scenario), and in Figure 8b we assume fuel taxes are not applied to hydrogen at all but remain on conventional fuels (No Hydrogen Tax scenario).

Figure 8
Entry Decade for Hydrogen Transportation in Europe in the (a) No Fuel Taxes Scenario and (b) No Hydrogen Tax Scenario



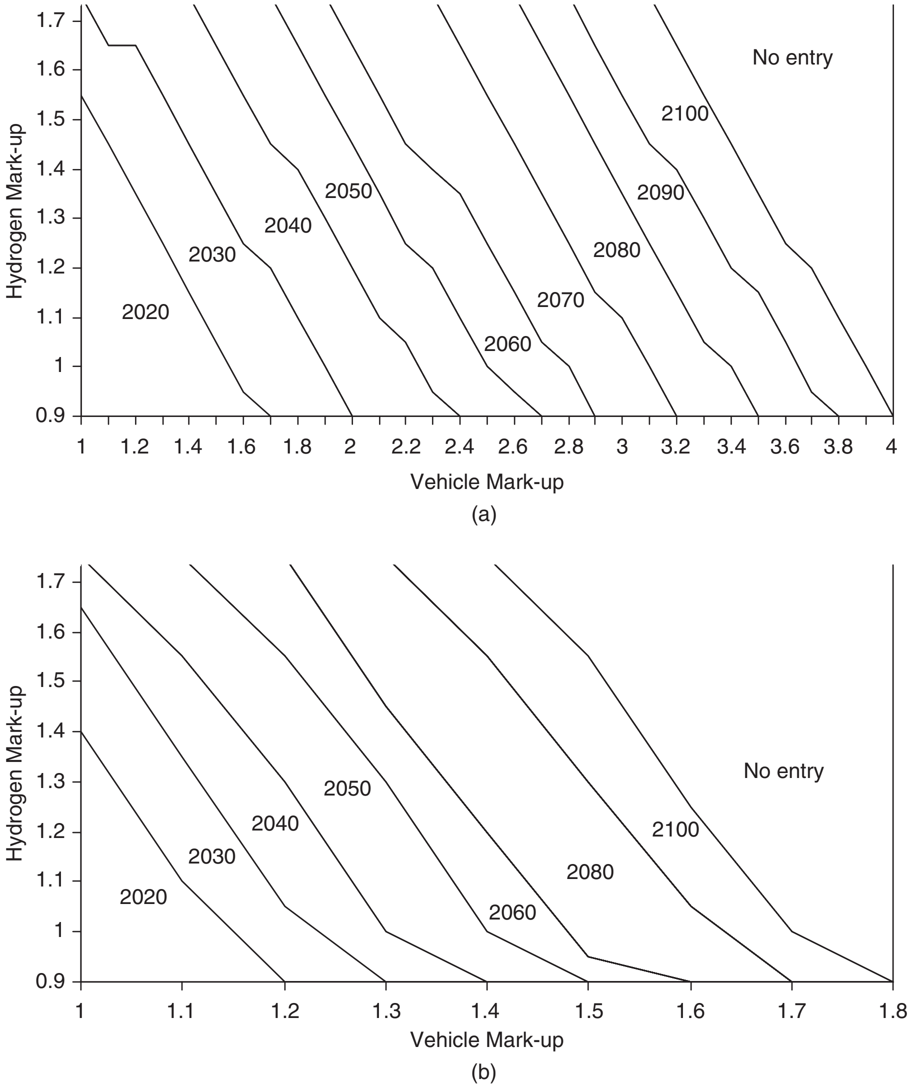
In the No Fuel Taxes scenario a vehicle mark-up larger than 1.4 is prohibitive through 2100, which is very similar to the results for the USA, where fuel taxes are very low. On the other hand, if Europe were to continue taxing gasoline at the same rate that it does today but hydrogen fuel was not taxed (No Hydrogen Tax scenario), this would create an even more favourable environment for hydrogen transport. Under this scenario, as shown in Figure 8b, entry by 2100 is possible if the vehicle mark-up is as high 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 mark-up 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 probably 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 revenue, they would need to increase the tax on hydrogen to compensate for the higher efficiency, thus potentially erasing the apparent advantage the hydrogen fleet would have.

5.2 Effects of carbon emissions constraints on hydrogen sector entry

When a policy aimed at stabilising 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. 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 favour hydrogen. In the CCSP stabilisation scenarios that are the basis for the constraints imposed in the 550 ppmv scenario, the carbon dioxide price paths were determined to increase over time at 4 per cent per year. In the 550 ppmv stabilisation 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 5.4, the availability of a low-cost hydrogen vehicle option has a large effect on the CO_2 price needed to achieve these reductions. The penetration frontiers include this endogenous effect of the CO_2 price.

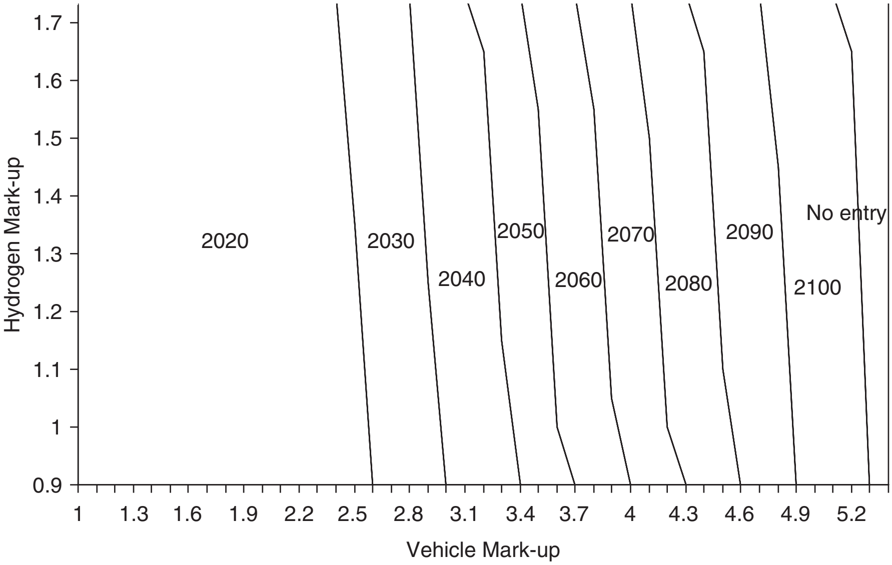
Not surprisingly, the effect of the 550 ppmv scenario is to shift the frontiers forward in time for a given mark-up, as shown in Figures 9a and 9b. The climate policy effect is stronger in later years because of the underlying tightening of the carbon policy, relative to baseline emissions, over time. The maximum allowable mark-up for entry by 2100 was 1.5 in the Baseline scenario, while in the 550 ppmv scenario, it rises to 1.8. Nevertheless, this increase is relatively smaller than in Europe. The difference between Europe (Figure 9a) and the USA (Figure 9b) is again due to the

Figure 9
Entry Decade for Hydrogen Transportation in (a) Europe and (b) USA in the 550 ppmv Scenario



effect of the high fuel tax in Europe. As discussed in Section 2, current estimates for the hydrogen vehicle mark-up are between 10 and 20. Thus, even with strong a climate policy, R&D would have to push down the cost of the vehicle by an order of magnitude for penetration in the USA. The competitive situation in Europe, given high fuel taxes, rewards the

Figure 10
Entry Decade for Hydrogen Transportation in Europe in the 550 ppmv with No Hydrogen Tax Scenario



relative efficiency of the fuel cell more than in the USA but substantial cost reductions would be needed there as well.

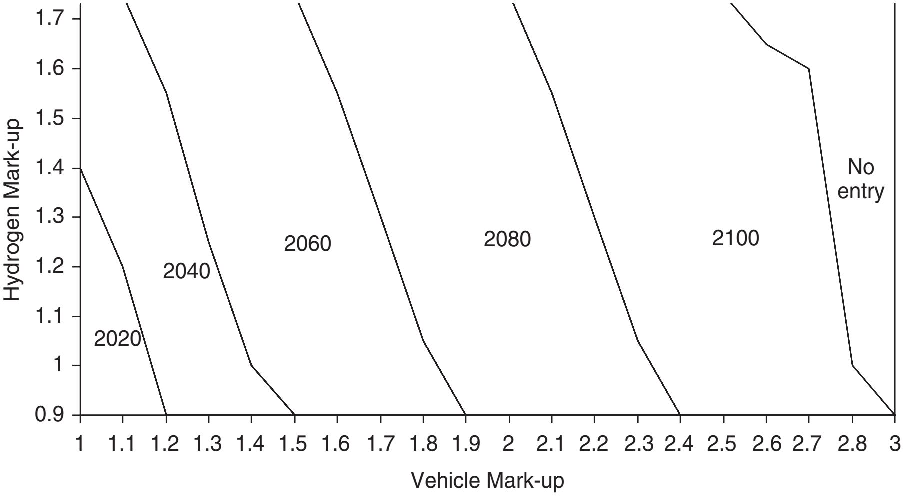
Figure 10 illustrates the results where Europe taxes conventional fuel but not hydrogen and simultaneously imposes a carbon emission constraining policy (550 ppmv with No Hydrogen Tax). This is the most favourable scenario for hydrogen transportation among the ones we explore here. In this scenario, it is possible for hydrogen transport to penetrate the market in the twenty-first century even at costs of four to five times the cost of conventional internal combustion engine vehicles.

5.3 Effects of alternative fuels 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 vehicle fuel alternative, particularly under a carbon dioxide emissions constraint, but are 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 USA in the 550 ppmv with No Biofuels scenario (Figure 11). Hydrogen vehicles can enter the market within the 2100 time horizon even at vehicle mark-ups of up to 3.0, nearly twice the level when biofuels are available.

Figure 11

Entry Decade for Hydrogen Transportation in USA in the 550 ppmv with No Biofuels Scenario



5.4 Implications of a hydrogen vehicle fleet for CO_2 emissions and climate policy costs

To evaluate the impact of a reasonably priced hydrogen-fuelled transportation fleet on GHG emissions and the cost of implementing a climate policy, we compare two cases. A first set of scenarios were run with both hydrogen fuel and vehicle mark-ups set to very low levels (1.0 and 1.3, respectively) with and without a carbon stabilisation policy. A second scenario was run with both of the hydrogen fuel and vehicle mark-ups set to prohibitively high levels (resulting in no entry of the hydrogen transportation sector) with and without a carbon stabilisation policy. In all scenarios, the advanced biofuel sector was included, and gasoline and hydrogen were taxed in Europe.

The impact on emissions was evaluated by comparing cases with and without hydrogen transportation in the absence of a climate policy. In the first period in which the fleet has been completely replaced with hydrogen vehicles (2050), both fossil CO_2 emissions and GHG emissions are larger by about 3 per cent over emissions in the same year in the No Hydrogen scenario. The near total elimination of tailpipe emissions is offset by an increase in the emissions associated with the conversion of coal to produce hydrogen, suggesting that the climate benefits of hydrogen will depend on hydrogen source.

We also quantify the macroeconomic cost of emissions mitigation measures in terms of reduction in total consumption. For stabilisation 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). 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 the USA only and in Europe only without emissions trading with other regions and with GHG reductions in these countries as in a 550 ppmv scenario. This allows us to obtain a more accurate picture of the implications for cost of just the breakthrough in hydrogen technology (US CCSP, 2007).

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 stabilisation policy in both the USA 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 USA 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 USA 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 relative to the Baseline, as prices of gasoline rise more in the No Hydrogen scenarios, suggesting that the availability of hydrogen or another alternative could have welfare benefits even without considering the potential benefits of reducing emissions.

The impact of hydrogen on expected policy-related welfare loss is illustrated further by comparing the CO_2 price that emerges in the policy cases in the presence and absence of hydrogen. Without the hydrogen transportation alternative, the CO_2 price rises to \$600 per ton in Europe and \$170 per ton in the USA by 2100. However, with a hydrogen alternative, the price in both regions remains well below \$100 per ton. Of course, these estimates depend on hydrogen achieving the breakthroughs assumed in these scenarios — if the breakthroughs achieve a more modest reduction in hydrogen costs, the reduction in CO_2 price and consumption loss would not be as big.

6.0 Conclusions

Our analysis of the behaviour 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 mark-up of less than 1.5 over conventional vehicles to penetrate the US market before 2100. However, even if hydrogen vehicles do penetrate the market, carbon emissions for the USA increase 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 favours 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 travelled. Entry is possible 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 fuel 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.

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

If advanced biofuel technology is not available so that it does not compete with hydrogen transportation technology, the favourable effect is much larger. If the 550 ppmv stabilisation policy is imposed in the absence of advanced biofuels, hydrogen transportation can penetrate the US market with a vehicle mark-up of up to 3.0. This scenario is the most favourable for hydrogen transportation in the USA.

Without a low-carbon alternative technology in the transportation sector, the consumption losses in both the USA 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 limited emissions reduction potential of the current transportation fleet. However, to put these results in perspective, it is important to remember that current estimates of the cost of a hydrogen vehicle with comparable performance and durability are ten and twenty times that of a conventional vehicle. For those involved in hydrogen vehicle research, this analysis provides some cost targets that would need to be met and, given that these targets are achieved, an idea of when the vehicle could be competitive and under what conditions.

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