Quantitative Analysis of Alternative Transportation Under Environmental Constraints

by

Reynaldo Sandoval López

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Signature of Author ____
Engineering Systems Division and Department of Civil and Environmental Engineering
May 15, 2006

Certified by ____
John Reilly
Senior Research Scientist, Laboratory for Energy and the Environment
Associate Director for Research for the Joint Program on the Science and Policy of Global Change
Thesis supervisor

Certified by ____
David H. Marks
Morton and Claire Goulder Family Professor of Civil and Environmental Engineering
Director for the Laboratory for Energy and the Environment
Thesis supervisor

Accepted by ____
Andrew Whittle
Professor of Civil and Environmental Engineering
Chairman, Departmental Committee for Graduate Students

Accepted by ____
Dava J. Newman
Professor of Aeronautics and Astronomics and Engineering Systems
Director, Technology and Policy Program

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Abstract

This thesis focuses on the transportation sector and its role in emissions of carbon dioxide (CO_2) and conventional pollutant emissions. Specifically, it analyzes the potential for hydrogen based transportation, introducing this technological option within a computable general equilibrium (CGE) model of the economy. The transportation sector accounts for an important part of CO_2 emissions and analyses that have imposed carbon limits on the economy have shown relatively limited reductions in transportation emissions with current technology, thus the interest in technological options that would make it economic to reduce emissions. The US Federal government has been particularly focused on developing fuel cell technology for vehicles that, when powered by hydrogen, would offer a technological solution that potentially eliminates emissions of both CO_2 and other conventional pollutants from the transportation sector. This work examines the economic conditions under which such a technology might successfully compete in the market.

The thesis begins with an overview of the fuel-cell vehicle technology and the technologies used to produce hydrogen. This review serves as a basis for modeling this technological option. The main conclusions are the following:

- Under market conditions and in the absence of climate policy that would price carbon, hydrogen fuel cell vehicles penetrate the USA market when the cost of vehicles is no more than 1.30 times the cost of conventional vehicles, and assuming hydrogen can be produced at 1.30 times the 1997 price of gasoline. Even if this cost target is reached and hydrogen vehicles enter the market, CO_2 emissions for the US are reduced only very slightly because coal is used to produce the hydrogen and there is no incentive to sequester the carbon when the hydrogen is produced.

- The existing fuel tax structure in Europe strongly 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 assuming the tax rate is per unit of energy, this implies a lower tax per vehicle mile traveled. 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 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 European governments would lose all fuel tax revenue.

- An emissions constraining policy would favor hydrogen transportation allowing US penetration with vehicle costs up to 1.7 times conventional vehicle costs.

- The availability of biomass fuels (e.g. ethanol) is a strong competitor, which can prevent or delay hydrogen entry. When the biomass fuel option was removed, hydrogen vehicles entered 10 years sooner.

Overall, hydrogen technology faces significant technological hurdles. Cost-reductions of more than an order of magnitude are needed before hydrogen technology penetrates the market. The vehicles must also obviously offer comparable or improved features compared with existing vehicles, and the hydrogen fuel must be conveniently and safely supplied. Even if significant cost reductions occur, the technology may face competition from other technologies such as ethanol. Finally, if hydrogen technology is able to penetrate the transportation sector, CO_2 emissions will not be reduced unless a policy either provides price incentives or mandates the sequestration of emissions from the hydrogen producing plants.

Thesis Supervisor: Dr. John Reilly
Senior Research Scientist, Laboratory for Energy and the Environment
& Associate Director for Research for the Joint Program on the Science and Policy of Global Change

Thesis Supervisor: Dr. David Marks
Morton and Claire Goulder Family Professor of Civil and Environmental Engineering & Director for the Laboratory for Energy and the Environment

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1. Introduction

Air pollution and climate change are important environmental problems caused by anthropogenic emissions. The transportation sector accounts for an important part of these emissions. Analyses have shown relatively limited reductions in transportation emissions with current technology. Hydrogen-fuel-cell powered vehicles would offer a technological solution for eliminating both CO_2 and other pollutants from the transportation sector. This work examines the conditions under which this technology would penetrate the market.

There exist today some alternatives to enable meeting transportation needs while completely solving vehicle emissions but they are all extremely uneconomical. This work looks mainly at one of the technologies, hydrogen fuel cells, which may bring break-through reductions in transportation emissions. This technology is jointly analyzed with that of battery-powered electric vehicles, which is closely related to it. The objective of this work is to analyze alternative transportation within a general equilibrium model of the economy. Past studies have projected penetration of hydrogen transportation based on a set of assumptions about the costs of this technology and the price of oil. There is also extensive literature analyzing how hydrogen costs and fuel cell costs may decline over time due to the learning curve effects. Nevertheless, there is little work done on how a hydrogen transportation sector would behave in a general equilibrium model. This model brings new insights to this analysis because it allows observation of the effects of competing technologies and of different emission taxing policies.

The first chapter gives the background for the two environmental problems (i.e., climate change and air pollution) that make this work relevant. It then presents the emissions of the transportation sector and their growth forecasts. After showing the importance of alternative technologies, it describes two of them: battery electric vehicles and hydrogen vehicles. An overview of the technologies used to produce hydrogen and a review of the literature on hydrogen production costs are presented in Chapter Two.   The third chapter describes the model used for this work, explaining in detail how transportation is represented in the model and then how the hydrogen transportation sector was introduced, with the use of two cost indexes, one for the cost of the fuel cell car and one for the cost of hydrogen. Results of this work appear in the fourth chapter. It compares various scenarios in order to understand the effects of the most important factors determining the penetration of the hydrogen transport sector. Those factors analyzed in this work were taxes, carbon emission constraining policies and the presence of competing technologies such as ethanol fuel.

Chapter Five summarizes the findings and describes the issues that could be further analyzed to gain deeper understanding of hydrogen transportation’s potential in the 21st century.

2. Alternative Transportation: Importance and current technologies

This work finds its purpose within the efforts to solve two great problems that our civilization's economic growth has caused. The first is climate change. The second is air pollution, which to some extent has been reduced in the past decades.

This section provides the setting of global climate change and urban air pollution and their importance. It analyzes the role of the transportation sector in these two issues by quantifying its emissions and their future growth. It establishes the importance of alternative transportation to mitigate the emissions of the transportation sector. This chapter then covers two alternative transportation technologies.

2.1. Climate Change and Air Pollution

Certain gases in the atmosphere play a heat-retaining role at the global level. These gases are now commonly called greenhouse gases (GHGs) because they are transparent to incoming solar radiation (light) yet absorb outgoing infrared radiation (heat). Naturally occurring GHGs include water vapor, carbon dioxide, methane, nitrous oxide, and ozone. Certain human activities, however, add to the levels of most of these naturally occurring gases. The increase in GHG concentrations due to anthropogenic emissions can increase the capacity of the atmosphere to capture the heat that is radiated from the surface of the earth towards space.

Anthropogenic emissions of GHGs have seen rapid growth in the last two centuries and this has caused their concentration in the atmosphere to increase as well.

Numerous studies have causally linked this increase in GHG concentrations to the fact that the earth's temperature is rising. Since the industrial revolution in the 19th century, the concentration of CO_2 has risen from 300ppm to 375ppm, while it had not risen above 300ppm in the past 400,000years. There exists today a consensus among scientists on the fact that a continuing increase in GHG concentrations in the atmosphere will create an energy imbalance that will result in changes in the climate of the planet and this has emerged as a great concern in the 21st century (IPCC, 2001).

The GHG concentration would continue to rise even if emissions started to be reduced today, because humans are emitting much more than the self-sustaining volume. Reducing emissions would slow the rate of growth in concentration, eventually allowing us to reach low enough emissions to have a stable GHG concentration.

The MIT Integrated Global System Model (IGSM) forecasts an increase of the CO2 atmospheric concentration to 850ppm by 2100 in the business-as-usual scenario. With a similar increase in other GHG, the IGSM predicts an increase in the average surface temperature of 3 to 4°C (Sokolov, et al., 2005)

Air pollution is a problem also arising from the emissions of fossil fuel burning and other industrial processes. Air pollution refers to gases and aerosols that have an adverse effect on human health causing or aggravating conditions like asthma, bronchitis, emphysema and other respiratory diseases. Important pollutants are carbon monoxide, sulfur oxides, nitrogen oxides, hydrocarbons such as methane, and particulate matter.

Some of these pollutants such as methane, nitrogen oxides and some particulate matter, also play a role as GHGs.

There are natural as well as anthropogenic sources of air pollution. Volcanic activity for example produces sulfur compounds and ash particulates that are extremely harmful. Anthropogenic sources are power plants that use fossil fuels, motor vehicles, and other sources that burn fossil fuels or biomass.

Unlike GHGs, air pollutants are subject to regulation and monitoring in most countries and efforts to use cleaner fuels that emit fewer pollutants have been mandated by some of these regulations.

2.2. Emissions by the transportation sector

The transportation sector consumes large amounts of fossil fuels, burning them in the internal combustion engines of vehicles. Part of the transportation sector is powered by electricity which, to a large extent, comes from fossil fuels, but most transportation relies on engines that consume refined oil in the form of gasoline, diesel, and other fuels (shown in Figure 2.1). The consumption of this refined oil produces the emissions that were presented in the previous section. The emission of air pollutants has been significantly reduced in the past decades due to improvements in the purity of the fuel and addition of devices like particle filters. Nevertheless, air pollution has not been completely eliminated. GHG emissions are an even greater concern because they are greater in volume and no device would be able to eliminate them unless it captured all exhaust gases. Considering this kind of solution for each vehicle would be extremely uneconomical or even impossible.

Carbon capture and sequestration technology has been developed to make it possible to capture a large proportion of the GHGs emitted from large power plants. This allows envisioning a world in which power plant GHG emissions would be reduced significantly. However, due to the decentralized nature of its emissions, the transportation sector cannot benefit from such a solution if vehicles continue to be powered by internal combustion engines that use fossil fuels.

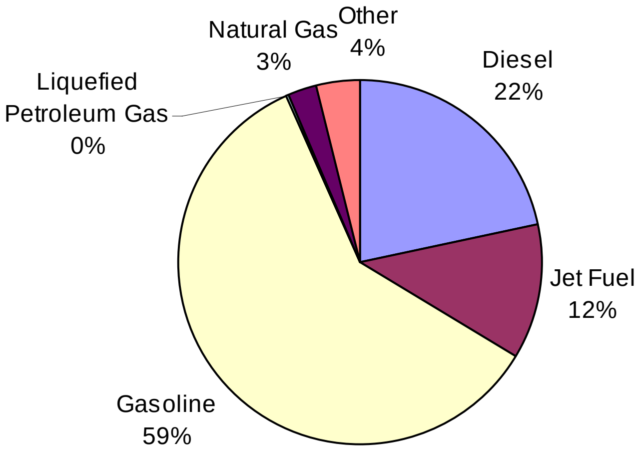

Figure 2.1: Fuel demand by the transportation sector in the US

(Source: Data compiled from Energy Information Administration)

The transportation sector is likely to grow strongly in the decades to come. First, mobility, measured in kilometers driven per person per year, will increase as wealth increases. Second, there will be an increase in the number of drivers, thereby multiplying the first effect. This increase in the number of drivers is especially rapid in developing countries as people leave poverty and achieve an income allowing them to own vehicles.

The Energy Information Administration (EIA) estimates that, for the US, the distance traveled per year per driver will reach 15,000 miles (24,000km) in 2025, an increase of 25% on the 2005 figures. The number of drivers is estimated to reach 318 million. The fuel mix for the US transportation sector is projected by the EIA to remain dominated by refined oil products. Natural gas fuels will grow faster than refined oil but from a very small base. The share of diesel will also be increased at the expense of the gasoline share.

The International Energy Agency (IEA; 2004) predicts primary energy demand to continue concentrating in the power generation and transportation sectors. By 2030 they are expected to reach 60% of energy demand together. As mentioned above, the main difference between the emissions coming from these two sectors is their degree of decentralization. IEA estimates the transportation sector's CO_2 emissions to grow by 78% between 2002 and 2030, with an increase of 170% in developing countries. The percentage of oil consumption dedicated to the transportation sector will also continue to grow to 54% in 2030 compared to 47% today and 33% in 1971.

The MIT IGSM forecasts under a business-as-usual scenario that the household transportation sector in the US will grow by 170% by 2030 and that the fuel consumed will grow by 100%.

As an illustration of the smaller potential for emissions reduction within the transportation sector with current technology, we can consider the “Alternative Scenario” explored by IEA in the 2004 World Energy Outlook. This scenario assumes a total reduction of 6,013 MMT (million metric tons) of CO_2, which represents 16% of the business-as-usual scenario. To achieve this, the power sector emissions are estimated to be reduced by 3,905MMT, which represents a 24% reduction and the transportation emissions by 997MMT, which represents only 11%.

In addition to vehicle emissions, the emissions related to transportation also include those that are emitted in the process of producing the fuel for the vehicles. For current technology, these are the emissions of the extraction and refining of oil to produce gasoline or diesel. In the case of electric vehicles, they are the emissions from power generation, and for hydrogen vehicles, they are the emissions from hydrogen production.

2.3. Alternatives to the internal combustion engine

As explained in the previous section, the transportation sector’s emissions are likely to grow rapidly in the coming decades and they are extremely difficult to reduce because they are much decentralized. The solution to this dilemma would be a technology that allows centralizing the emissions, making it cost-effective to capture them. Two potential technological solutions are battery powered electrical vehicles and hydrogen powered vehicles. Both of these technologies would allow having emission-free vehicles by using clean energy carriers but their economic feasibility is in question.

Although this work focuses specifically on hydrogen powered transportation, this section analyzes battery powered vehicles because they have been offered as a solution to emissions problems for a long time. Nevertheless, as will be explained below there currently does not exist a battery technology capable of storing the necessary energy and power within the constraints of the vehicle.

Hydrogen vehicles can be powered by fuel cell vehicles, which produce electricity that is used to move the vehicle. Fuel cells generate electricity from hydrogen with an electrochemical process that is the inverse of electrolysis. It is represented by the following equation:

$$2H_2 + O_2 \rightarrow 2H_20$$

It is also possible to use hydrogen to power internal combustion engines with zero emissions. Nevertheless, this arrangement has a significantly lower efficiency than the electric motor alternative. By having a lower efficiency, it required more hydrogen to travel the same distance and therefore increases the emissions from the hydrogen production process.

Propulsion system

Battery and hydrogen fuel cell powered vehicles use the same propulsion system, which is powered with electricity. The propulsion system converts the electrical energy it receives from the battery or the fuel cell, to mechanical energy. DC motors were common in the past for propulsion due to their capacity to provide high torque at low speeds. Today, they have been displaced by more advanced motors such as the permanent magnet motor, which achieves the highest efficiency and power density. The vector-controlled induction motor is the most popular although it has somewhat lower efficiency. Table 2.1 shows the motor types that are used in some electrical vehicle prototypes. Table 2.2 shows how they compare in performance aspects and cost on a scale of one to five on each category.

Table 2.1: Applications of electric vehicle motors.

EV models	EV motors
Fiat Panda Elettra	Series dc motor
Mazda Bongo	Shunt dc motor
Conceptor G-Van	Separately excited dc motor
Suzuki Senior Tricycle	PM dc motor
Fiat Seicento Elettra	Induction motor
Ford Think City	Induction motor
GM EV1	Induction motor
Honda EV Plus	PM synchronous motor
Nissan Altra	PM synchronous motor
Toyota RAV4	PM synchronous motor
Chloride Lucas	Switched reluctance motor

Source: Chan, Chau, 2001

Table 2.2: Evaluation of EV motors.

	Dc motor	Induction motor	PM Brushless motor	SR motor	PM hybrid motor
Power density	2.5	3.5	5	3.5	4
Efficiency	2.5	3.5	5	3.5	5
Controllability	5	4	4	3	4
Reliability	3	5	4	5	4
Maturity	5	5	4	4	3
Cost	4	5	3	4	3
Total	22	26	26	26	26

Source: Chan, Chau, 2001

Most electrical and mechanical characteristics of these motors are outside the scope of this work, but it is important to emphasize the characteristic that sets them apart from internal combustion, which is efficiency. The electrical propulsion has the advantage of offering high efficiency at average power, whereas internal combustion engines offer high efficiency close to their maximum power and lower efficiency in the average power range. Thanks to new electronic control technology electric motors only need one gear to perform at all speeds. The comparison in speed-torque relation between a five-gear conventional motor and a one-gear electric vehicle is shown in Figure 2.2. One can see that the torque-speed graph of the one-gear electric motor, emulates the "useful" parts of the five curves that represent each gear for a conventional vehicle. Figure 2.3 shows the efficiency along the torque-speed feasible region, and shows that the highest efficiency can be reached at average driving conditions.

An important characteristic of electric motor vehicles that allows greater motor efficiency is regenerative braking. A regenerative system allows the battery to be charged while the vehicle decelerates. This is done by using the wheel's kinetic energy as a generator with increasing resistance.

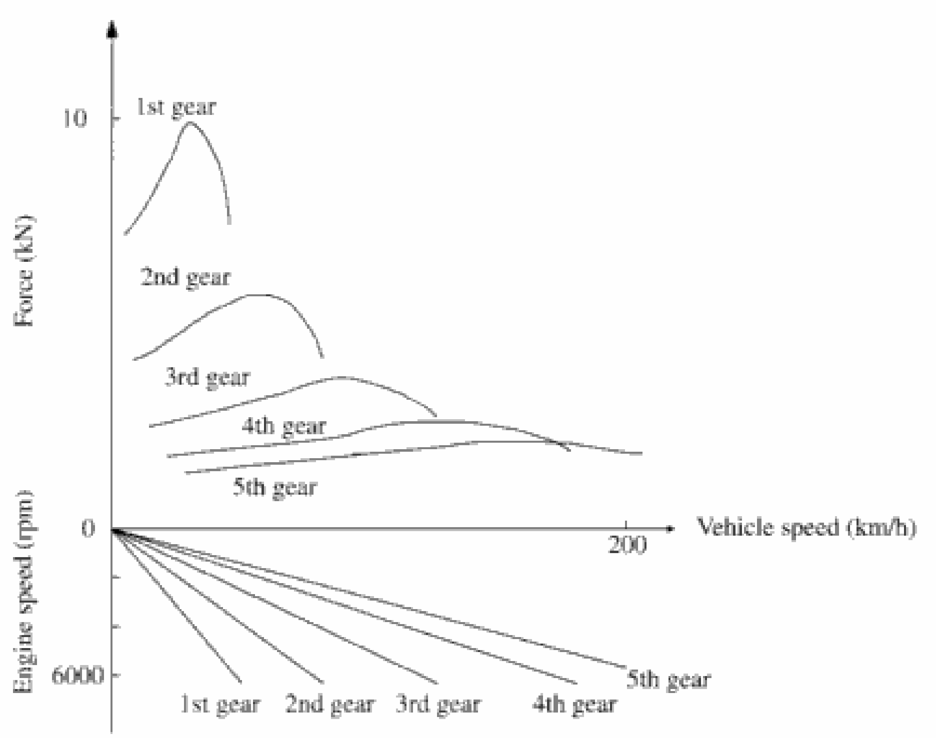

Figure 2.2: Torque-speed characteristics of an internal combustion engine with five gear transmission. (Source: Chan, Chau, 2001)

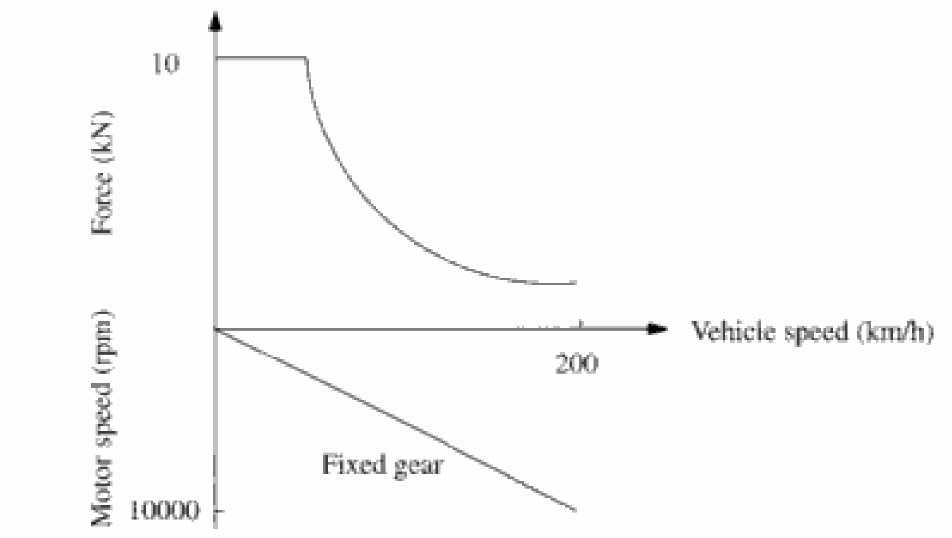

Figure 2.3: Torque-speed characteristics of an electric motor with one gear.
(Source: Chan, Chau, 2001)

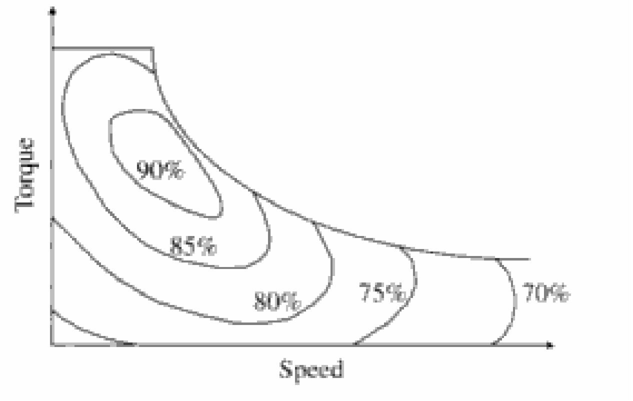

Figure 2.4: Efficiency at different torque-speed combinations for a one-gear electric motor. (Source: Chan, Chau, 2001)

Power sources

Battery electric vehicles as well as hydrogen fuel cell vehicles face significant obstacles especially regarding their power sources. There is currently no available battery capable of providing the energy needed for an acceptable range within the volume and weight limitations of the vehicle. To compare the performance of different battery technologies, most studies use specific energy, specific power and energy density. Specific energy refers to the energy that can be stored in the battery per kilogram of weight. The power density refers to the power that can be provided by the battery per unit of weight at a fixed discharge rate. This allows us to understand how much the battery would weigh if we needed it to provide 80kW of power, a standard power need. Finally, we use the energy-volume ratio called energy density. Table 2.3 shows the comparison of the different battery technologies with the objectives of the US Advance

Battery Consortium (USABC;) on the last line. Several current battery technologies can reach one or two criteria set by the USABC but they fail in the others, especially in cost, by several multiples.

Table 2.3: Performance and cost for different battery technologies

	Specific energy (Wh/kg)	Energy density (Wh/l)	Specific power (W/kg)	Cycle life (cycles)	Projected cost (USD/kWh)
VRLA	30-40	60-90	200-300	400-600	150
Ni-Cd	40-60	80-110	150-350	600-1200	300
Ni-Zn	60-65	120-130	150-300	300	100-300
Ni-MH	60-70	130-170	150-300	600-1200	200-350
Zn/Air	230	269	105	NA	90-120
Al/Air	190-250	190-200	7-16	NA	NA
Na/S	100	150	200	800	250-450
Na/NiCl2	86	149	150	1000	230-350
Li-Polymer	155	220	315	600	NA
Li-Ion	90-130	140-200	250-450	800-1200	>200
USABC	200	300	400	1000	<100

Source: Chan, Chau, 2001

For hydrogen vehicles there are also various fuel cell technologies that have been developed. They are compared in Table 2.4. The Proton Exchange Membrane (PEM; also called Solid Polymer) fuel cell is the one considered the best candidate for automotive applications. This is because it works at a lower temperature (below 100°C) than other kinds of fuel cells, has the highest power density and only uses water. The electrolyte used is solid and therefore has no risk of leakage, power reduction or damage to the vehicle.

Table 2.4: Performance and cost for different fuel cell technologies.

	Working temperature (°C)	Power density (W/cm^2)	Projected life (kh)	Projected cost (USD/kWh)
Phosphoric Acid (PAFC)	150-210	0.2-0.25	40	1000
Alkaline (AFC)	60-100	0.2-0.3	10	200
Molten Carbonate (MCFC)	600-700	0.1-0.2	40	1000
Solid Oxide (SOFC)	900-1000	0.24-0.3	40	1500
Proton Exchange membrane (PEMFC)	50-100	0.35-0.6	40	200
Direct Methanol (DMFC)	50-100	0.04-0.23	10	200

Source: Chan, Chau, 2001

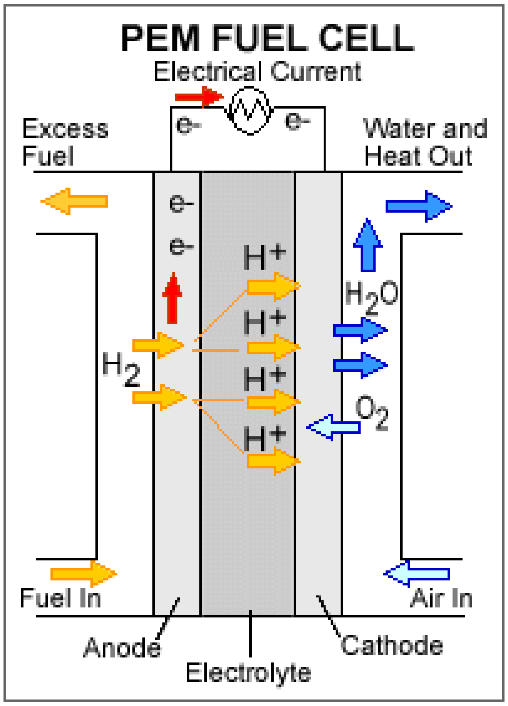

Figure 2.5: PEM fuel cell components
Source: Department of Energy

Figure 2.5 shows the cross section of a PEM fuel cell. The first step towards the generation of electricity takes place at the anode, where the hydrogen molecules get split into protons and electrons, according to the following equation:

$$H_2 \rightarrow 2H^+ + 2e^-$$

The protons go through the polymer electrolyte to the cathode, where they are combined with oxygen molecules and electrons to form water. The electrons do not go through the membrane but around the circuit, creating an electric current. The final equation is the following, which creates a potential of 1.229V per mol.

$$4H^+ + 4e^- + O_2 \rightarrow 2H_2O$$

The efficiency of the PEM fuel cell is between 40 and 50%. The main limiting factor is the absence of an adequate catalyst to separate oxygen molecules. Platinum is currently used, just as it is used to break hydrogen molecules, but this drives the cost of the fuel cell up and still faces considerable resistance in the oxygen molecule breaking process.

PEM fuel cells have some problematic features. For example, PEM fuel cells can be damaged by carbon monoxide. The quantity of water in the fuel cell is also an important factor because the membrane will not function adequately under excessive water or with too little water.

Other factors

There are other important factors that will strongly affect the feasibility of alternative vehicles. For battery-powered vehicles there are charging characteristics. Each battery technology has specific recharging characteristics and these will determine the charging time, which is an important constraint if charging is to be done by the household. Another alternative requiring less stringent charging times would be to set up an infrastructure to provide either rapid charging equipment or battery swapping. An ideal but still unrealistic solution would be to have induction charging while driving.

For hydrogen powered vehicles, the storage question remains. Hydrogen's specific energy (kWh/kg) is comparable to that of gasoline but hydrogen has a much lower density. This results in a very small quantity of energy if the gasoline reservoir were to be filled with compressed or even liquid hydrogen. The most important drawback remains the cost, "fuel cell costs are at least an order of magnitude too high," (Ramage, 2004).

The chapter establishes the importance of alternative transportation in the context of rapidly growing transportation emissions that contribute to climate change and air pollution. It described two candidate technologies for providing alternative transportation. The rest of this work will focus specifically on hydrogen-based transportation.

3. Hydrogen production: technologies and costs

While Chapter Two presented the importance of alternative transportation as well as the vehicle level technologies, advantages and problems, this chapter focuses on hydrogen production. The first section presents the main hydrogen production technologies and the second makes a literature review of cost estimates for hydrogen production and compares them to the cost of gasoline. This is done on a cost-per-kilometer basis to account for vehicle efficiency differences.

3.1. Hydrogen production technologies

Hydrogen does not exist in pure form on earth; it can be obtained from two main sources, hydrocarbons and water. The main sources of hydrocarbons are natural gas, coal, and residual oil. This section explains the most relevant technologies for this work.

Steam methane reforming

Steam methane reforming is the technology used to produce hydrogen from natural gas, which is mainly composed of methane. Natural gas is good for hydrogen production because it has a high hydrogen-carbon ratio and therefore allows producing more hydrogen with less CO_2 emissions. Steam methane reforming is done by combining methane and steam at high temperatures in the presence of a catalyst (usually Nickel). This technology is widely used today to produce hydrogen.

The reactions that take place are the following:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

$$CO + H_2O \rightarrow CO_2 + H_2$$

The CO_2 produced when separating natural gas can be captured and sequestered, resulting in an emission-free fuel-production cycle, which is the reason to introduce hydrogen altogether.

Coal Gasification

Since hydrogen production from coal is very similar to power generation from coal, it is an economical way to produce hydrogen in large central facilities. The technology that most authors consider to be the best to produce hydrogen from coal is coal gasification, since it allows for plants with lower emissions, which is the reason to produce hydrogen. This reduces the need for carbon sequestration.

The gasification process starts with the partial oxidation of the coal with steam and oxygen at high temperature and pressure. This process yields a combination of CO and hydrogen as well as some steam and CO_2. From this mix, it is possible to separate CO_2 and other gases from hydrogen. Moreover, thanks to the temperature of operation, NOx compounds are only produced in small quantities.

Other hydrogen production technologies

In addition to the extraction of hydrogen from hydrocarbons (fossil fuels), we can also obtain hydrogen from water by separating the molecule. This may be done with simple electrolysis, which has the problem of low efficiency, or with thermo-chemical water splitting. One of the most attractive ways of doing thermo-chemical splitting is with nuclear energy from high temperature reactors, which is advantageous in terms of emissions.

3.2. Hydrogen cost versus gasoline cost

In order to compare the production costs of hydrogen with those of conventional transportation (i.e., gasoline internal combustion), we must express both in terms of cost-per-kilometer. Since one kilogram of hydrogen contains an amount of energy very similar to that of one gallon of gasoline we will consider them equal, as do most publications on this topic. There remains, nevertheless, an adjustment to be made for the difference in kilometers that each car can travel with that same amount of energy. As explained in Chapter Two, there is evidence indicating that fuel cell vehicles are much more efficient than conventional vehicles. Where conventional internal combustion vehicles have an average efficiency close to 30%, hydrogen fuel cell vehicles are believed to be capable of reaching an average efficiency of 75%.

To obtain a price scale factor that truly represents the benefit (kilometers driven) obtained from $1 of hydrogen relative to that obtained from $1 of gasoline we must therefore multiply the price ratio by the efficiency ratio:

$$\left(\frac{hydrogen\_price}{gasoline\_price}\right)\times\left(\frac{gasoline\_car\_efficiency}{hydrogen\_car\_efficiency}\right)$$

As an example, we may consider that if hydrogen was priced at $4.00/kg at the pump and that a hydrogen vehicle was twice as efficient as an internal combustion vehicle, the overall cost ratio for using hydrogen fuel would be 1.66:

$$\left(\frac{4.00}{1.20}\right)\times\left(\frac{1}{2}\right)=1.66$$

3.3. Hydrogen production cost estimates

A survey of the literature was made by searching for production costs estimates for hydrogen. Results were abundant, but many studies do not state clearly the assumptions made to calculate each cost estimate. Comparing estimates from different sources is therefore delicate since many provide great detail in their assumptions and others none at all. In spite of this, a comparison is shown below using very basic differences, which are: whether distribution costs were taken into account or not and which technology the publication was focusing on. The publication year is used to separate estimates, since we expect to see some evolution in price assumptions across time, especially for fuels. As can be seen in Figure 3.1, there is a considerable dispersion in the cost estimates and no time trend is apparent from the following graph.

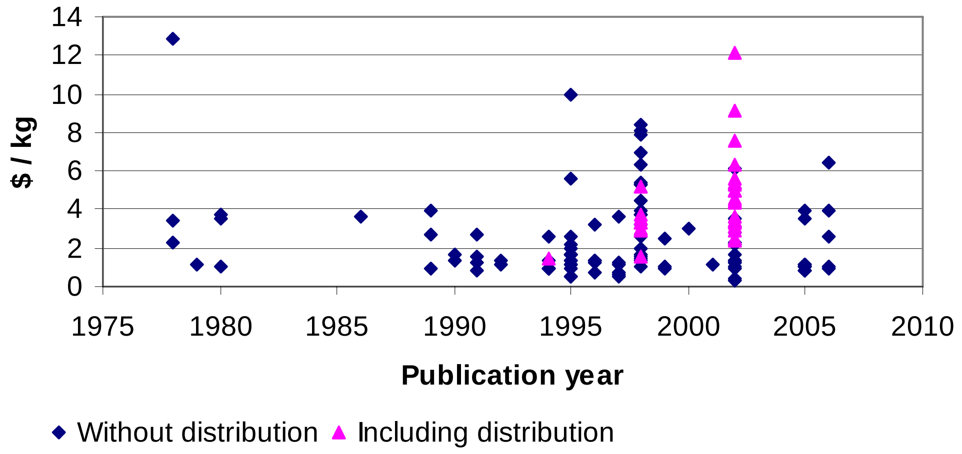

Figure 3.1: Published cost estimates for the production of hydrogen by date of publication.

In Figure 3.1, cost estimates are plotted against the size of the hydrogen production facility. We would expect a downward trend to reflect economies of scale. Nevertheless, there is an unusual concentration of estimates in the lower left corner of the graph made of very low cost estimates to produce small quantities of hydrogen.

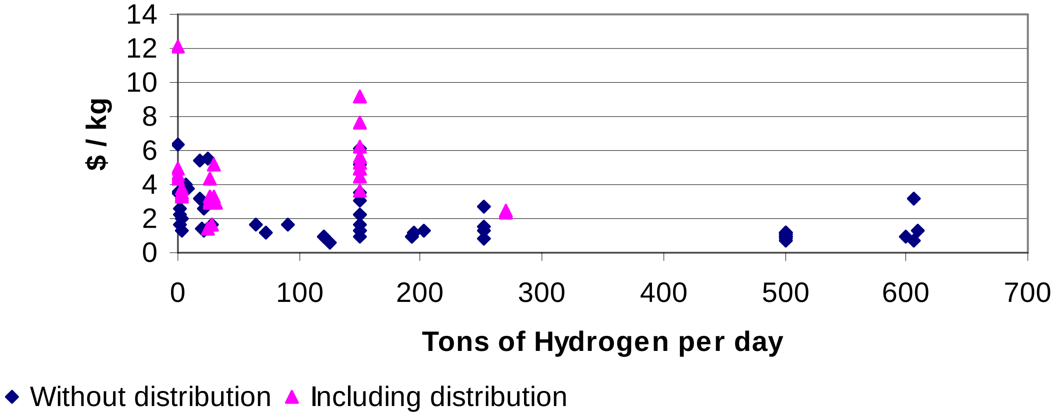

Figure 3.2: Published cost estimates for the production of hydrogen by size of plant.

Figure 3.3 shows the cost estimates for hydrogen production from natural gas only. Plotting the estimates by year of publication, we can see the dispersion in the estimates. Although the increase in cost estimates may be mainly due to fuel price increases, there are also some low cost estimates in recent studies.

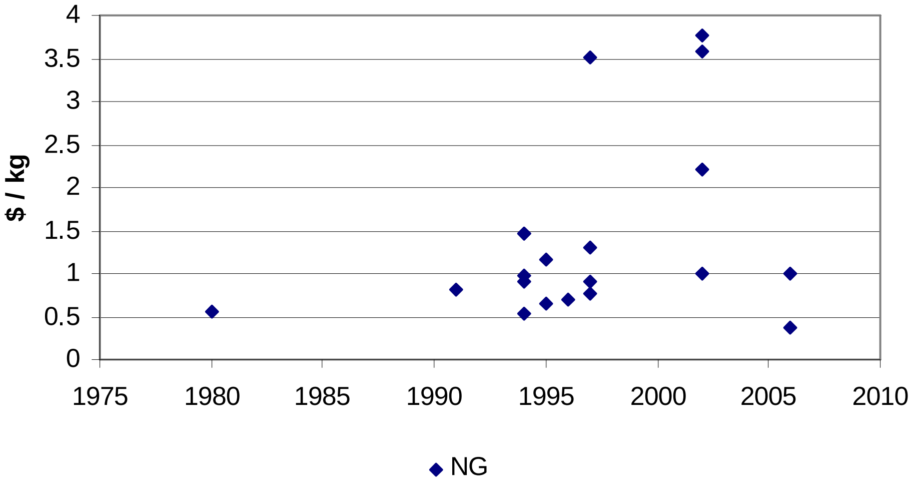

Figure 3.3: Cost estimates for hydrogen from natural gas by publication year.

This same data is reordered by size of the plant that is considered by each publication in Figure 3.2. The expected downward trend is seen in this graph, but we also see some optimistic estimates for small and mid-sized plants.

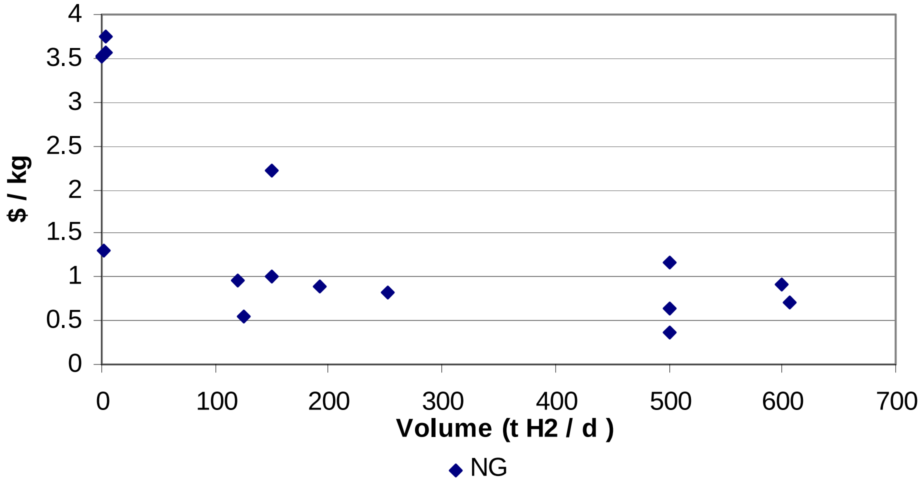

Figure 3.4: Cost estimates for hydrogen from natural gas by size of plant.

The following figures show the same comparison of cost estimates for other technologies.

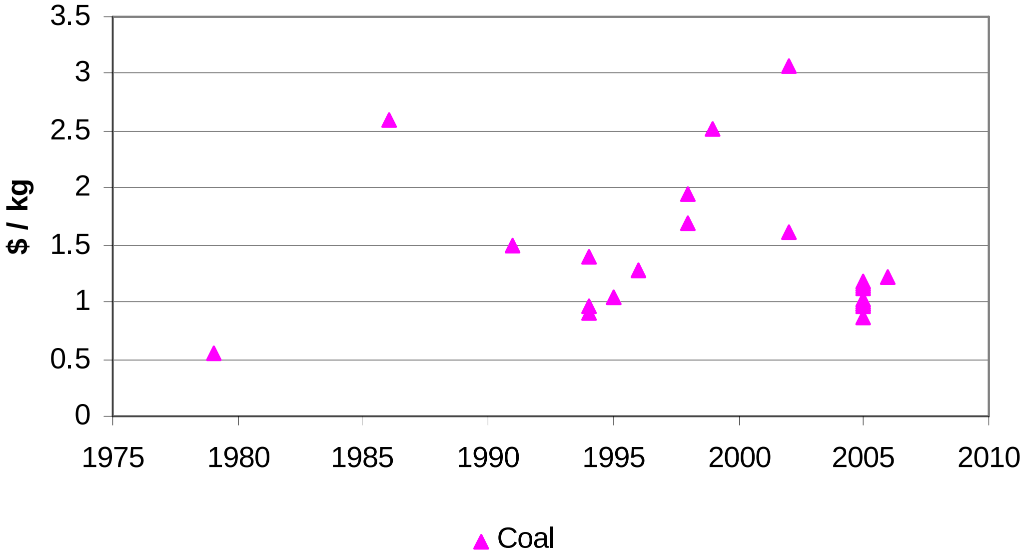

Figure 3.5: Cost estimates for hydrogen from coal gasification by publication year.

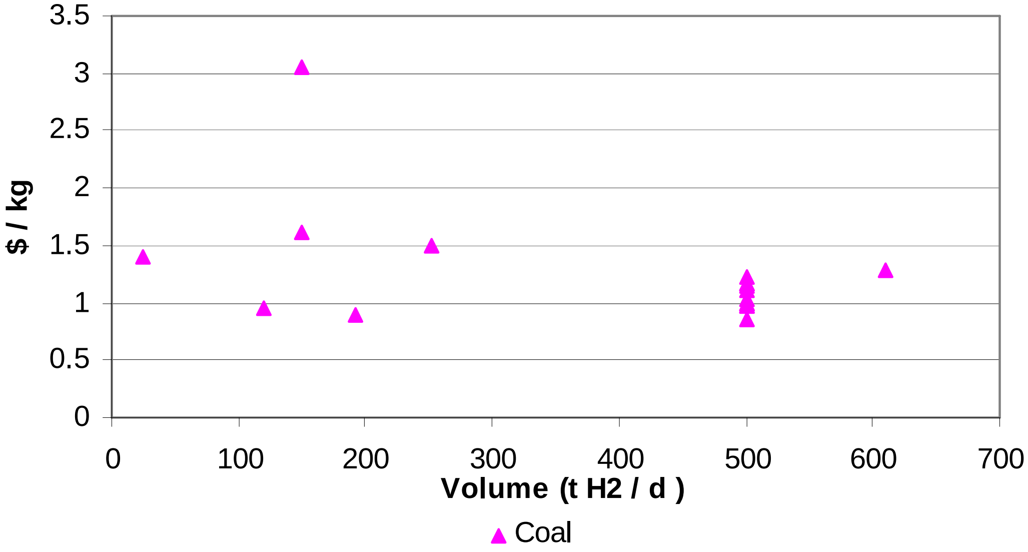

Figure 3.6: Cost estimates for hydrogen from coal gasification by size of plant.

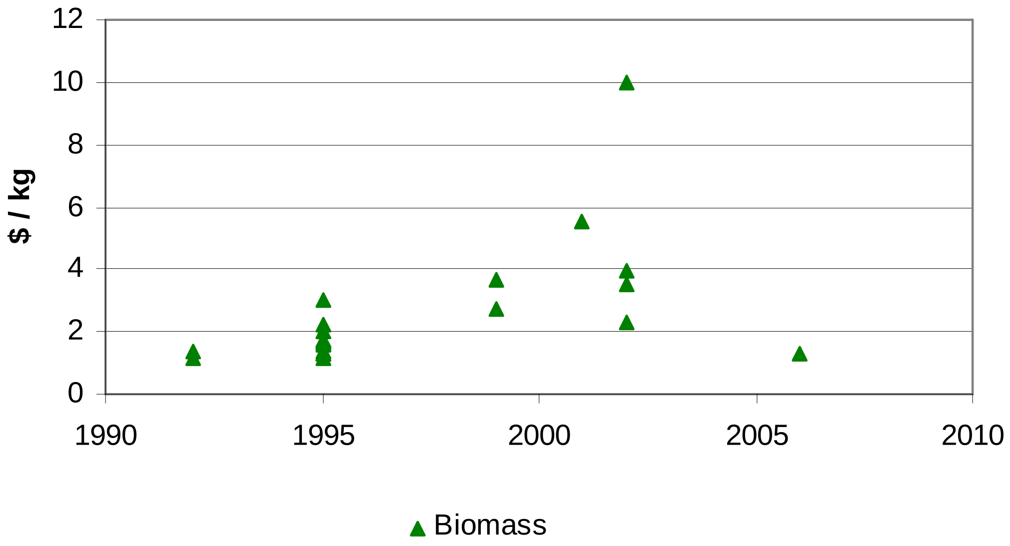

Figure 3.7: Cost estimates for hydrogen from biomass pyrolysis by publication year.

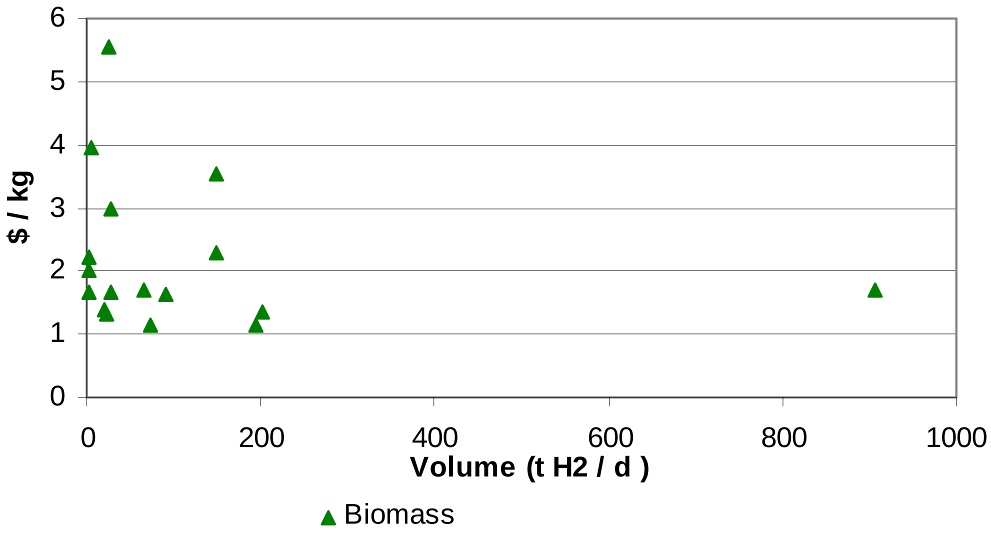

Figure 3.8: Cost estimates for hydrogen from biomass pyrolysis by size of plant.

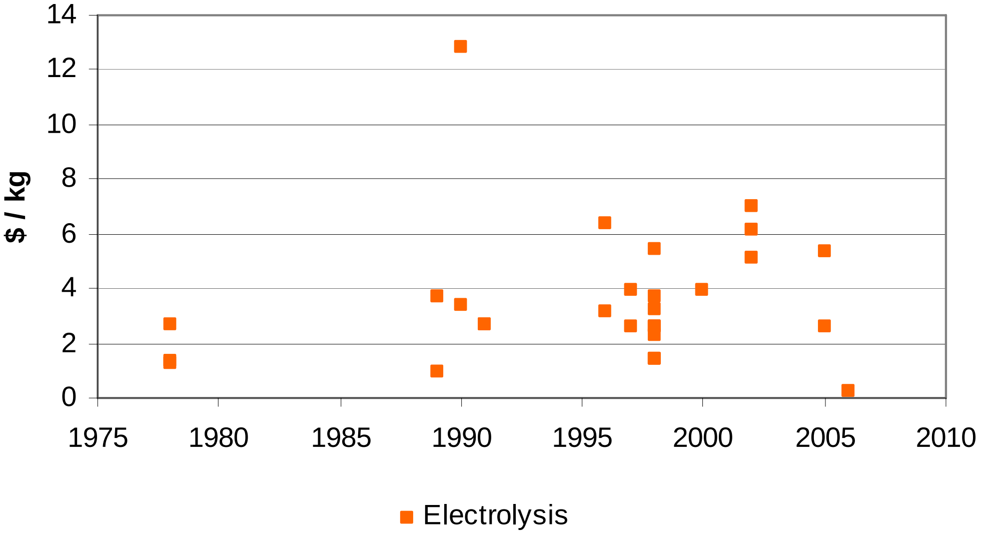

Figure 3.9: Cost estimates for hydrogen from electrolysis by publication year.

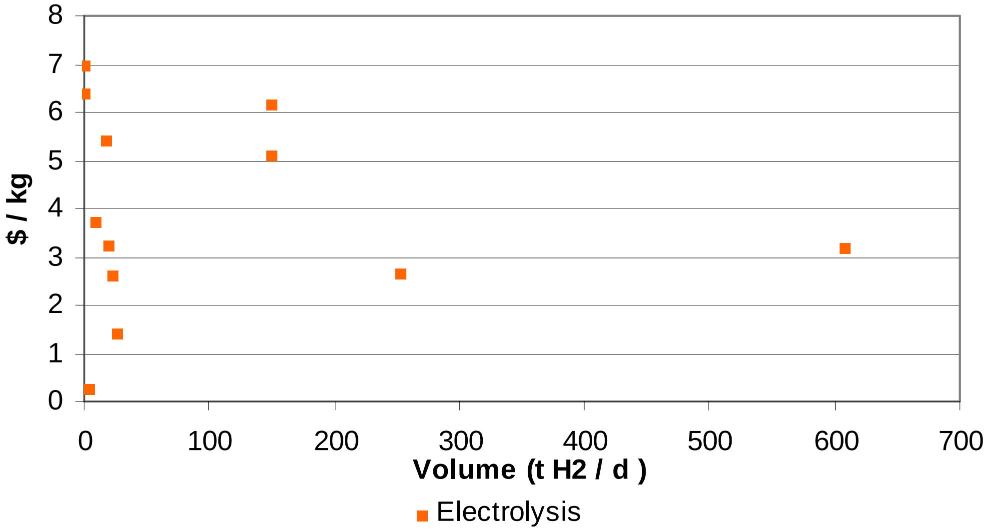

Figure 3.10: Cost estimates for hydrogen from electrolysis by size of plant.

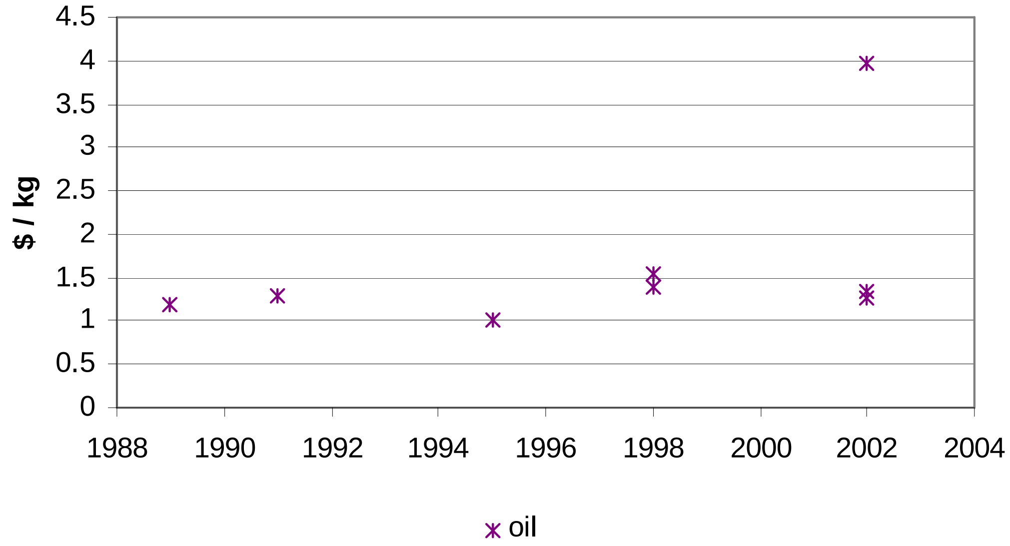

Figure 3.11: Cost estimates for hydrogen from residual oil by publication year.

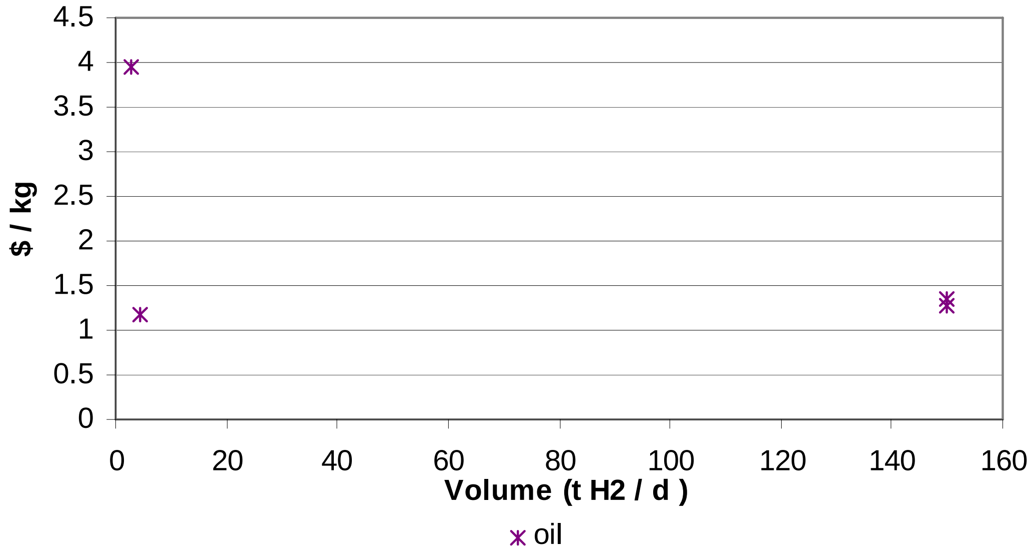

Figure 3.12: Cost estimates for hydrogen from residual oil by size of plant.

The following figure shows all cost estimates in the literature, separated by technology and ordered by size of the plant considered.

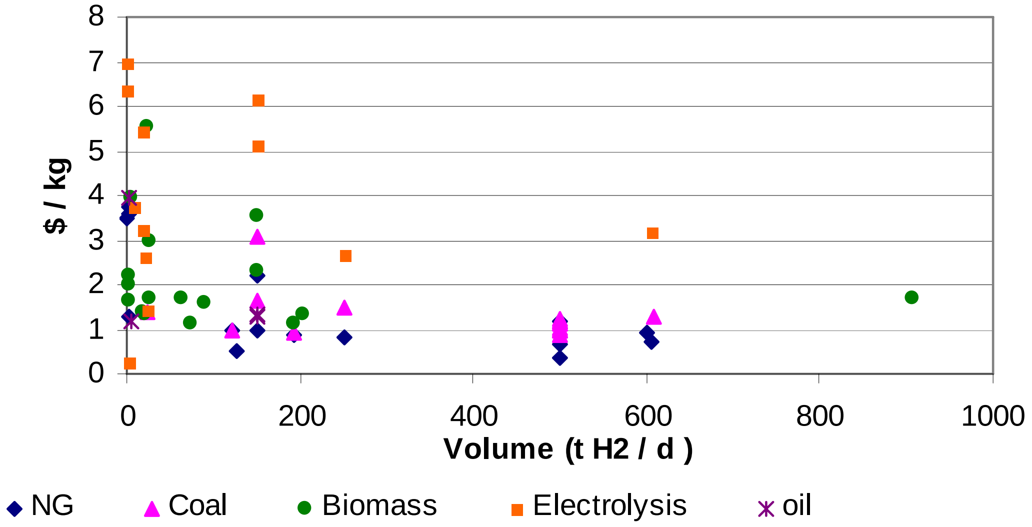

Figure 3.13: Cost estimates for hydrogen with all technologies by size of plant.

We can see two distinct cost groups. The more expensive one includes electrolysis and biomass pyrolysis. Natural gas, coal and residual oil are the feedstocks for the cheaper group of technologies. It is noteworthy that these cost estimates do not include transportation or distribution costs. Since few published articles include an analysis of the distribution system and costs all estimates have been normalized to the production cost only. As will be seen in the next section, transportation and distribution costs represent an important part of the total cost.

As can be seen from the previous figures, there has not been a significant trend over time; there is a wide range of cost estimates even when controlling for feedstock and while there may be some economies of scale, it is not clear from the studies that scale would reduce the cost significantly.

3.4. Detailed cost estimates in selected studies

A problem with many studies is that they include insufficient detail to understand the assumptions that result in different estimates. Two studies provide the detail that was necessary to develop a deeper understanding needed to model the hydrogen production. The first is a study by National Renewable Energy Laboratories (NREL) carried out by Simbeck and Chang of SFA Pacific, Inc. This 2002 study reviewed all hydrogen production technologies and hydrogen transportation methods. This study concluded that steam methane reforming is the cheapest technology to produce hydrogen and that liquid hydrogen via tanker truck is the most economical way to transport and distribute, therefore when pipeline distribution is considered, hydrogen costs are significantly higher. This is because of the high capital investment needed for a pipeline.

The second study that is used for this work was developed by the National Academy of Science in 2004. The cost estimates put forth by this study are significantly lower than the estimates from the previous study. This is despite the fact that fuel prices, especially natural gas, had risen significantly between 2002 and 2004.

A comparison by technology and distribution type is made in Figure 3.14. The red line across the graph indicates the gasoline price adjusted for efficiency, assuming fuel cell cars are twice more efficient than internal combustion vehicles. This figure also breaks down each estimate into the main 4 costs components, which are fuel, electricity, capital and labor.

The labeling of the columns represents the following combinations:

- NG-SEQ NAS: Natural Gas with carbon sequestration distributed by pipeline reported by NAS study.
- NG Pipe NAS: Natural Gas without carbon sequestration distributed by pipeline reported by NAS study.
- NG-Pipe NREL: Natural Gas without carbon sequestration distributed by pipeline reported by NREL study.
- NG-Cryo NREL: Natural Gas with out carbon sequestration distributed in liquid form by tanker trucks, reported by NREL study.
- The next four columns represent the same estimates using Coal feedstock.

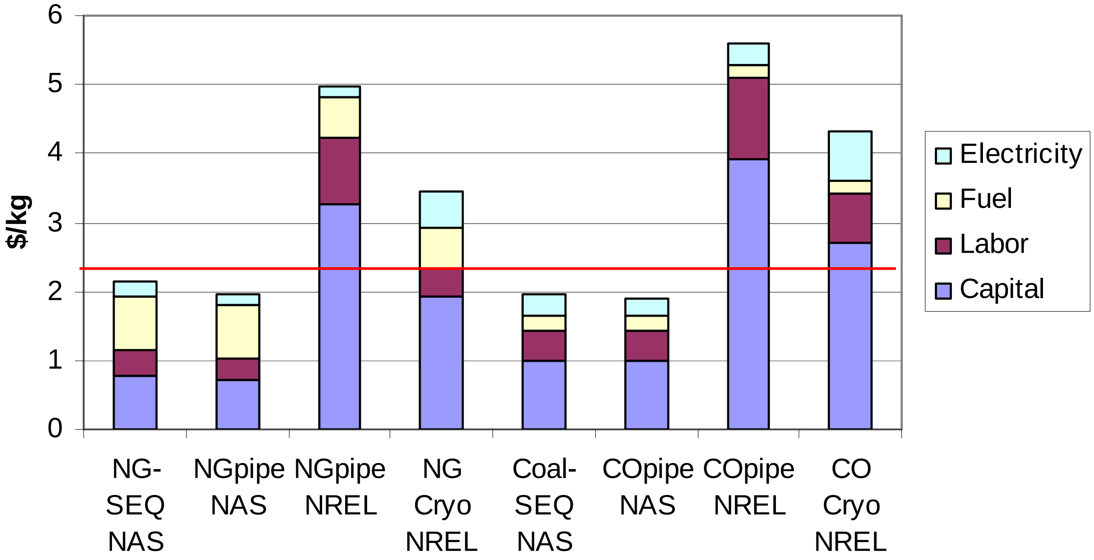

Figure 3.14: Cost estimates NREL, 2002 and NAS, 2004 by inputs.

In addition to the strong differences between the studies, Figure 3.14 shows that capital costs are the main driver of cost for all technologies. Figure 3.15 presents a similar comparison with a break down by production, distribution and dispensing costs. It is noteworthy that distribution costs for a pipeline distribution system are considerable. The line across this graph represents the current cost of production for industrial hydrogen. This line can be compared to the production cost estimates, since most hydrogen is currently produced next to the client site and consumed without the need for transportation and distribution.

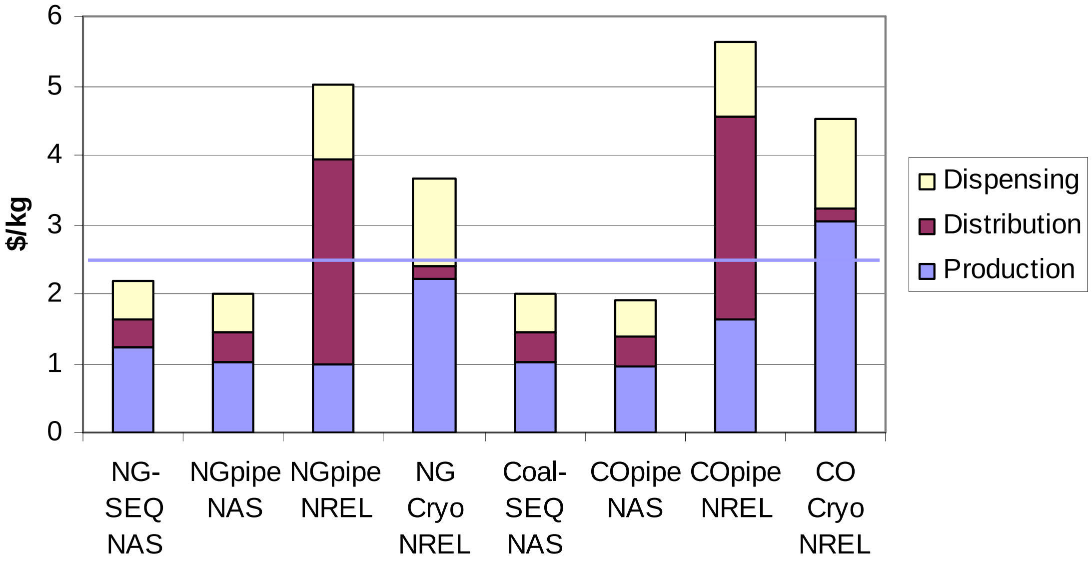

Figure 3.15: Cost estimates NREL, 2002 and NAS, 2004 by stage.

4. Household transport in the EPPA Model

This section presents the EPPA model, which is the basis for the work developed here. It explains in detail how the transportation sector is modeled and the changes that were made to the model in order to introduce a hydrogen based transportation sector.

4.1. The EPPA Model

The Emissions Prediction and Policy Analysis (EPPA) model is a recursive-dynamic multi-regional general equilibrium model of the world economy (Paltsev et al., 2005). It was developed by the Joint Program on the Science and Policy of Global Change at MIT. It is built on the GTAP 5 dataset and on additional data for emissions (Dimaranan and McDougall, 2002). It is a standalone model designed to provide projections for economic growth and anthropogenic emissions of greenhouse related gases and aerosols. It allows evaluating of the impact of emission constraining policies on economic growth across different sectors. The EPPA model is also the component that represents the human systems in the MIT Integrated Systems Model (IGSM).

It was made using the Mathematical Programming Language Subsystem for General Equilibrium (MPSGE; Rutherford, 1995; Rutherford, 1999), which is a subsystem of the Generalized Algebraic Modeling System (GAMS) modeling language (Brooke, Kendrick and Meeraus, 1996).

The EPPA model calculates the general equilibrium of the world economy across the 16 regions and 16 sectors shown in Table 4.1. Each production sector is modeled as a production function that takes some inputs and produces one output which is directly consumed by households, consumed as an intermediate good by another sector or exported. Inputs are normally capital, labor, energy resources and intermediate goods from other sectors.

It is calibrated to the GTAP 5 dataset with a reference year of 1997. Thereafter, the model solves for a series of static equilibria through 2100 in five-year time steps, starting in 2000. This solution is based on the following three basic principles:

- *The zero profit condition*, which requires that every sector producing any output must earn zero profit. The economic definition of profit differs from the common notion of profit by taking into account the cost of opportunity.
- *The market clearance condition*, which requires that for every good, supply and demand must balance.
- *The income balance condition*, which requires that for every agent, the value of income must equal the value of factor endowments (i.e. labor and capital) and tax revenue.

The dataset entered for the base year (1997) complies with these three conditions and for the subsequent periods, the model calculates an equilibrium in which the conditions are met for every sector, good and agent. Each of the 16 production sectors is modeled as nested constant elasticity of substitution (CES) production functions. CES production functions include Cobb-Douglas and Leontief production functions, which are special cases of the CES. Figure 4.1 shows the production structure of a typical sector. In this structure a horizontal line indicates a Leontieff relation, in which inputs are not substitutable and their shares are fixed. The non perpendicular bundles indicate that substitution is possible with an elasticity that is represented by the symbol shown next to the node. Consumption is also modeled using a CES utility function. Figure 4.2 shows the structure of the household utility function.

This work is based on the fourth version of the EPPA model, which, compared to previous versions, has new features that make the introduction of a hydrogen based transportation sector possible. Among the most important of those features are the following:

(1) The disaggregation of the services (SERV) and industrial transportation (TRAN) sectors from the "other industries" sector (OTHR);

(2) The disaggregation of transportation into industrial transportation and household transportation treated as part of household consumption;

(3) The disaggregation of the household transportation sector into purchased transportation and own-supplied transportation;

(4) The introduction of a sector producing liquid fuel from biomass.

Table 4.1: Regions and sectors of EPPA

Agriculture	United States
Energy Intensive	Canada
Transportation	México
Other Industry	Japan
Services	Australia &New Zeeland
Electricity	Europe
Conventional Crude Oil	Eastern Europe (Transition's economies)
Oil from Shale	Former Soviet Union
Liquid Fuel from Biomass	Asia
Refined Oil	China
Coal	India
Natural Gas	Indonesia
Gas from Coal	Africa
Own-Supplied Transport	Middle east
Purchased Transport	Latin America
Other Goods & Services	Rest of the world

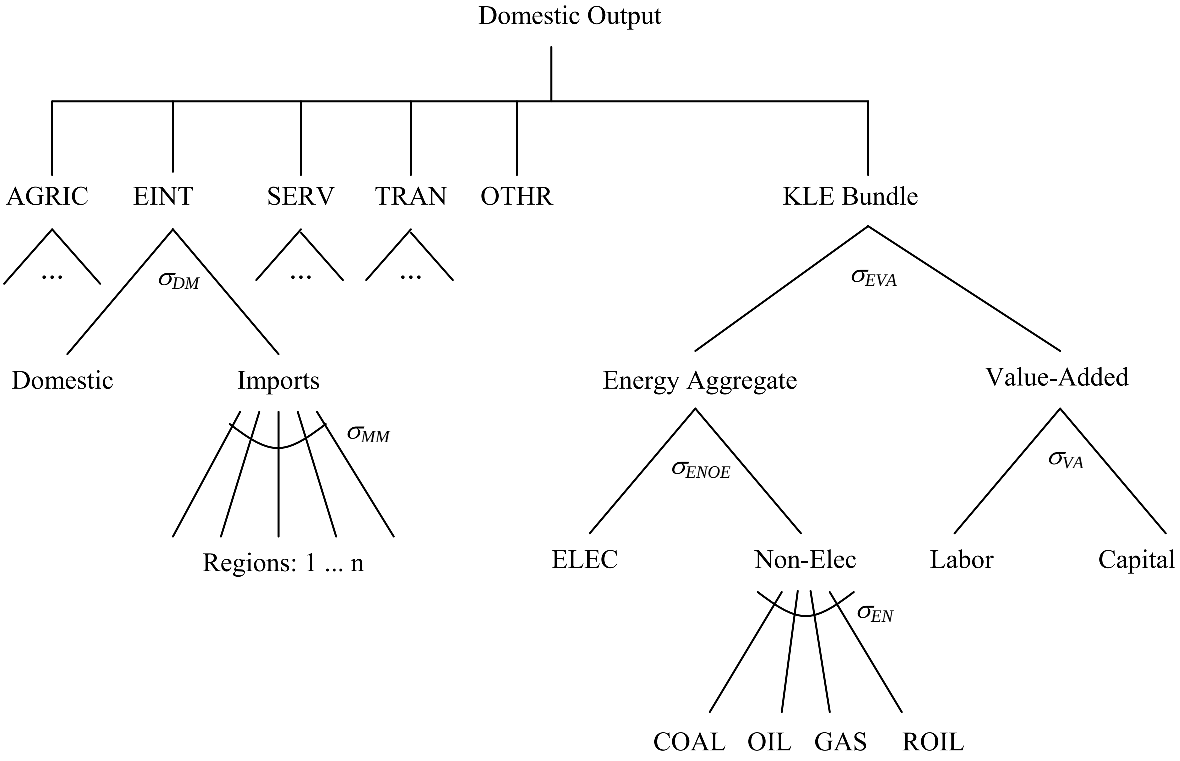

Figure 4.1: A typical sector production structure in the EPPA Model

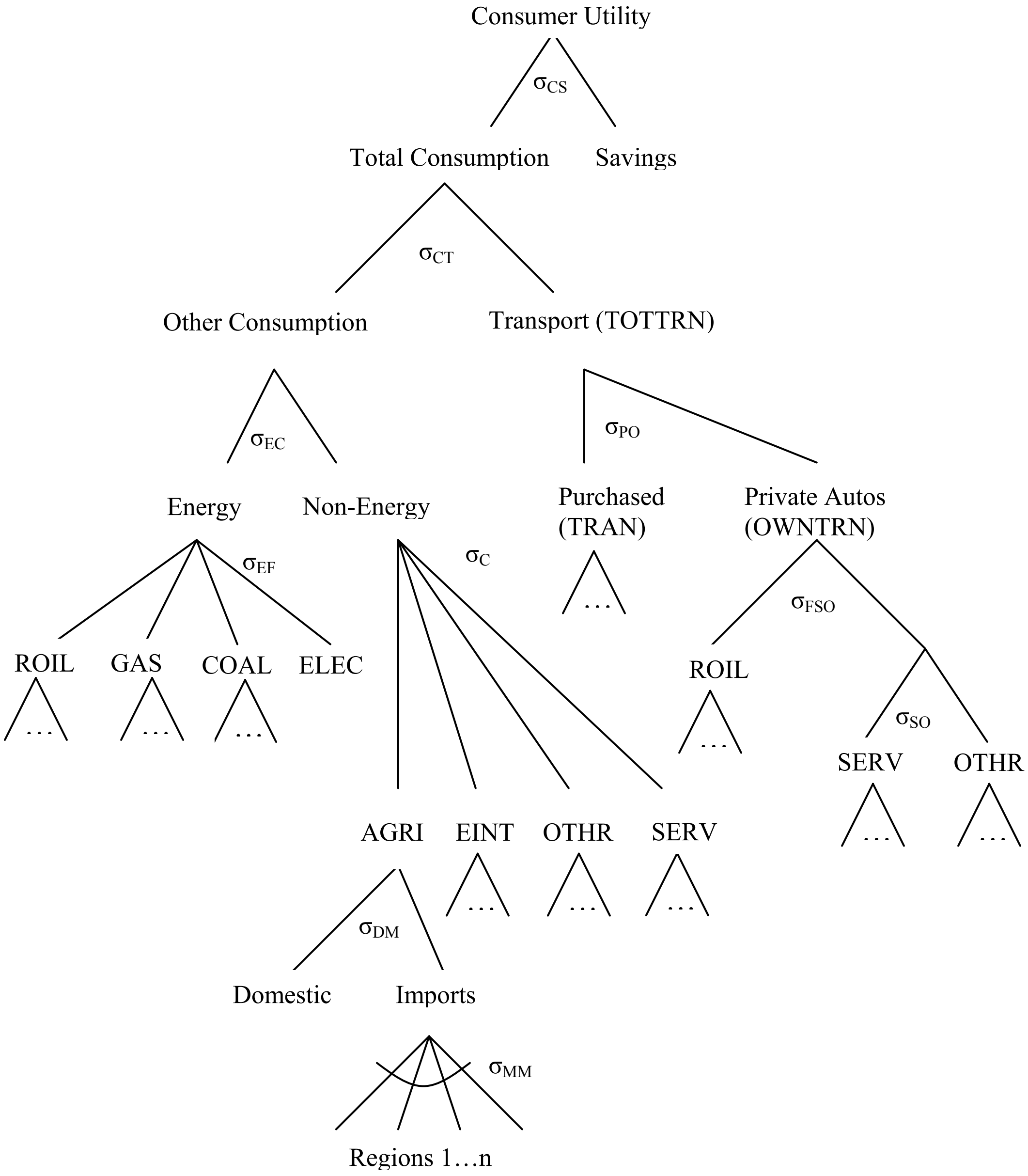

Figure 4.2: Household utility function.

4.2. Household transport sector

As mentioned above, a sector in a general equilibrium model is defined by a series of inputs that get combined according to a production function to produce an output. It is therefore necessary to specify what those inputs are, what the production function is, and what the share of each input is for the base year. This section describes the household transportation sector in such a manner.

Structure of the sector

As shown in Figure 4.2, transportation is part of household consumption. TOTTRN represents the total transportation expenditure of households. The fourth version of EPPA disaggregates household transportation (Paltsev et al., 2004) into purchased transportation (TRAN) and own-supplied transportation (OWNTRN), which includes private autos. This disaggregation is represented in Figure 4.3. Purchased transportation includes all transportation and delivery services that are provided by firms, including air, rail and maritime travel, purchased ground transport (bus systems for example) and all type of delivery services. Own-supplied transport includes privately owned vehicles that are operated directly by households.

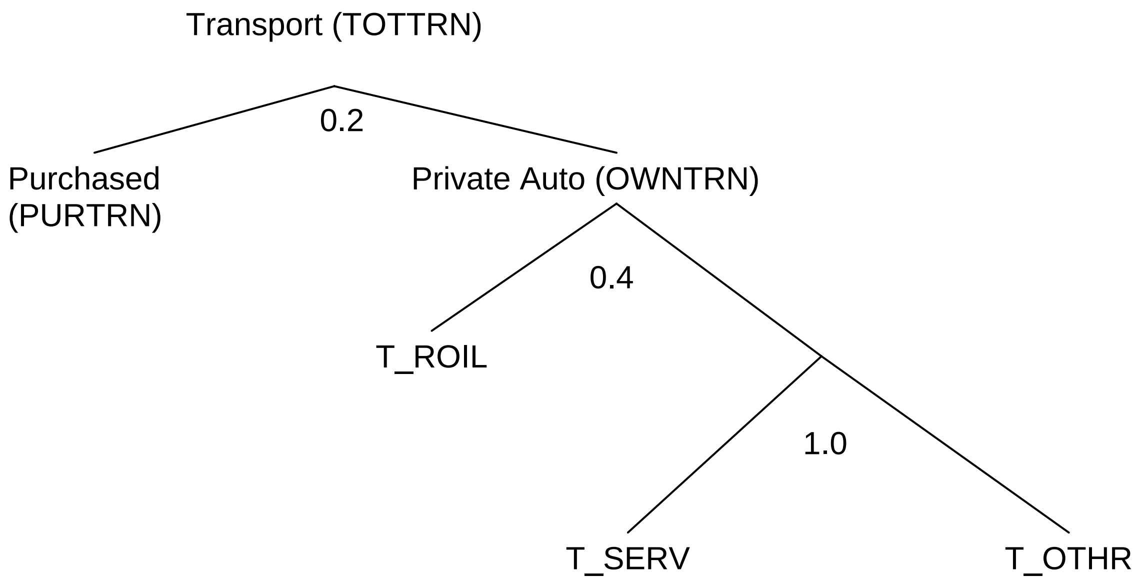

Figure 4.3: Household transportation.

The own-supplied household transport uses the intermediate outputs of three sector: refined oil (ROIL), services (SERV), and other industries (OTHR; Paltsev et al., 2004). The ROIL input represents the cost of fuel for private automobiles. The OTHR share represents the cost of purchasing the automobiles. This is because the automotive industry is included in the "other industries" sector in the model. The SERV share represents all non-fuel operational costs. Among these are the costs of insurance, financing, and maintenance, such as oil and tires.

The elasticities of substitution are shown at the nodes of Figure 4.3. The elasticity of substitution between purchased transport and own-supplied transport is 0.2.

The elasticities of substitution within own-supplied transportation are larger because there is more possibility of substitution among these inputs. First, we consider the substitution between SERV and OTHR. An elasticity of one seeks to reflect the possibility of shifting from an inexpensive but high maintenance car to a more expensive vehicle that requires less operational costs. Similarly, the elasticity of 0.4 between the ROIL input and the OTHR/SERV bundle reflects the possibility of spending more on an efficient vehicle and giving it more maintenance to reduce the fuel needs.

b) Input shares

The input shares for the whole household transportation sector have been calculated from available data. Paltsev et al. (2004) explains how information about these shares is obtained mainly from the GTAP, OECD and IEA to calibrate the model in the base year. These shares vary across regions because different inputs may have different prices, may be taxed differently or households may have different consumption patterns. It is nonetheless noteworthy that for 1997 (the calibration year for the model) the total value of all inputs for the sector must equal the value of the output (i.e. comply with the zero profit condition). As will be explained further in this document, this is not necessarily the case for sectors that are not active in the calibration year.

Figure 4.4 shows the shares of these three inputs for the US and for Europe. There is a big difference in the share of ROIL. This is mainly due to taxing of fuels in European countries. The EPPA model uses a tax rate of 470% on refined oil fuels for Europe. This tax rate induces a lower consumption of fuel per kilometer driven, but due to the high tax-inclusive price, that smaller amount of consumed fuel represents a greater proportion of the total cost per kilometer driven. In the EPPA model, as in the GTAP dataset, refined oil fuel is not taxed in the US.

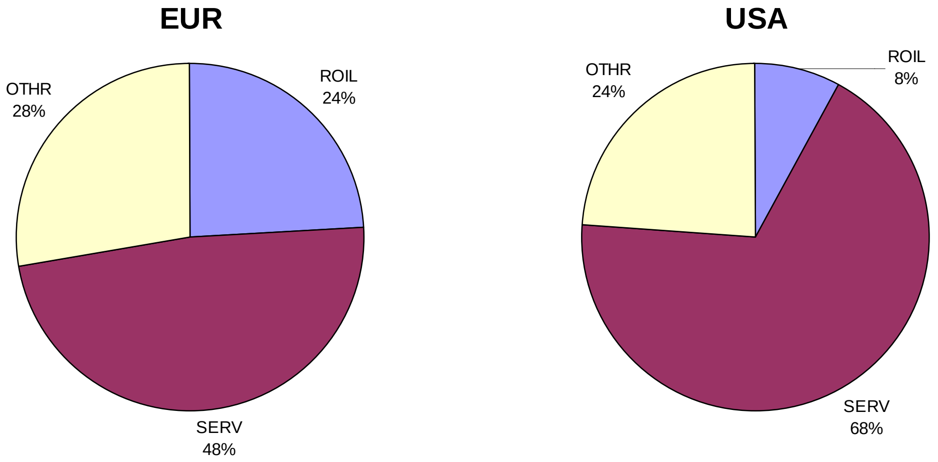

Figure 4.4: Inputs to household transport sector in the USA and Europe.

5. Modeling hydrogen transport

In order to model hydrogen based household transport in EPPA, an independent transportation sector that is based on hydrogen was introduced. This sector is in direct competition with the own-supplied household transportation mentioned in the previous section. I also introduced two hydrogen producing sectors that provide fuel to this new transportation sector.

This section explains the structure of the hydrogen producing sectors, the whole structure of the new household transportation sector, and the definition of markups, which is the way I model the cost differences between the conventional transportation sector and the hydrogen transportation sector.

5.1. Structure of the hydrogen fuel sector

The production of hydrogen is modeled by two independent and competing sectors. The first produces hydrogen from natural gas based on the steam methane reforming technology, and the second produces hydrogen from coal based on the coal gasification technology. Both of these sectors are equipped with carbon capture and sequestration and are set to capture 90% of their carbon emissions. The structure of the sector is shown in Figure 5.1. This structure is the one designed (Paltsev et al., 2005) for the generation of electricity with carbon capture and sequestration. This structure is well adapted to the production of hydrogen for similar reasons to those put forth by Paltsev et al. (2005), like the flexibility given by separating the distribution and capture inputs from the production inputs. It is also adequate to use this structure since the hydrogen sector is identical to a part of the electricity generation sector1 described by this structure elsewhere in the EPPA model.

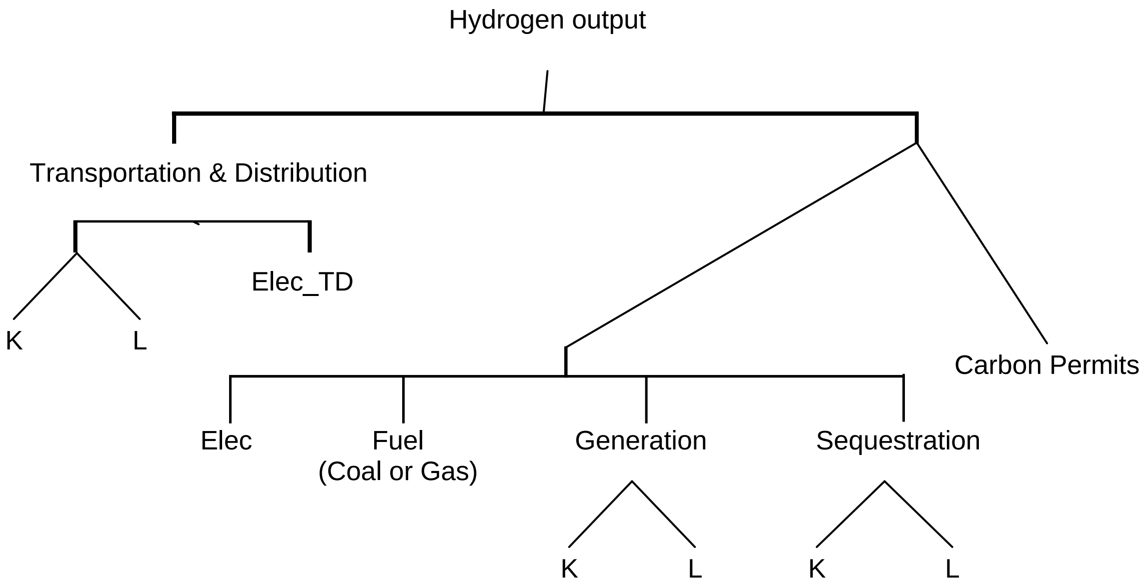

Figure 5.1: Structure for the hydrogen production sector.

5.2. Structure of the modified household transportation sector

Figure 5.2 shows the structure of the household transportation sector after introducing the hydrogen based transportation sector. The hydrogen transportation sector competes with the conventional own-supplied transportation sector, acting as a perfect substitute for it. This is reflected in the infinite elasticity of substitution. Although hydrogen vehicles do not currently provide the same level of service as conventional

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[1] The electricity generating technologies that this structure seeks to model in reality produce hydrogen as an intermediate product and then use it to generate electricity.

vehicles, the relative prices that will be used for the vehicle in this work, assume that, along with cost reduction for vehicles, other issues of vehicle performance will also be solved. The hydrogen vehicles are assumed to be equivalent in all performance aspects to the conventional vehicle.

The structure of the hydrogen transportation itself is identical to the conventional transportation, aside from changing the gasoline input for the hydrogen fuel input. This structure was chosen not only for simplicity but for lack of information leading to the conclusion that hydrogen vehicle technology would have different elasticities of substitution or production structure. In the absence of this information, the best approximation we have for the trade-offs among inputs is that of conventional transportation. Nevertheless, the same production structure does not imply the same input shares as the conventional transportation sector. These shares are in fact determined by the markups that are explained in the next section.

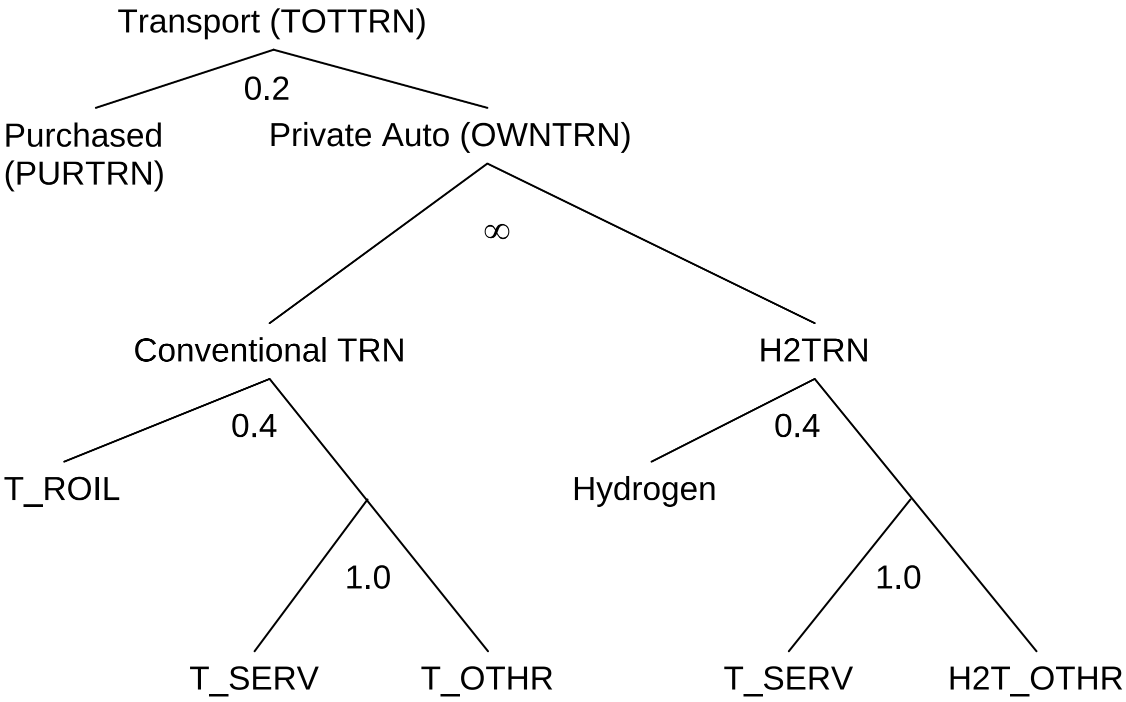

Figure 5.2: Structure of the new household transportation sector.

5.3. Shares and markups

A convention used in the EPPA model is to determine a set of factor shares that sum to 1.0, and then to apply a "markup," which is a multiplication factor that reflects the cost (in the base year) of the advanced technology relative to the one against which it competes. If the markup is larger than 1.0 it reflects that the technology is more expensive than the benchmark technology.

In modeling hydrogen transportation two markups have been used. The first markup represents the cost of hydrogen fuel relative to the cost of gasoline to drive a kilometer. This markup takes into account the efficiency adjustment explained in section 3.2. Hereafter this markup is called the hydrogen markup.

The second markup represents the cost of a fuel cell vehicle relative to the cost of a conventional vehicle. Hereafter this markup is called the vehicle markup. Current estimates for this markup are between 10 and 20.

The markups describe the relative prices in the base year. The relative price of hydrogen varies as time goes forward due to the increase in gasoline price and changes in the feedstock cost (i.e. coal) for hydrogen production. On the other hand, the changes in the price of the OTHR sector goods affect the price of conventional and hydrogen vehicles in the same way. Therefore, the relative price of hydrogen vehicles remains at the markup value, even though the price of the OTHR sector good changes.

6. Scenario Analysis

This chapter presents the results obtained in this work by comparing different scenarios. As explained previously, this work is concerned with the starting date and conditions at which hydrogen transport becomes economical and starts penetrating the market. The penetration rate and the time necessary to completely overtake the transport sector are out of the scope of this work. This rate of penetration has been analyzed and described by other studies, based on different assumptions. The first section of this chapter analyzes the tradeoff between fuel and vehicle cost at the point of penetration of hydrogen transport. The time at which the sector will start penetration based on the initial cost ratios is analyzed in section 6.2.

As explained in section 5.3, hydrogen transport is modeled with two markups that represent vehicle cost and hydrogen cost. These two markups determine the relative price of hydrogen and fuel cell vehicles compared to conventional transport in 1997. The relative price of hydrogen varies over time because the price of gasoline grows faster than the price of hydrogen; therefore the relative price decreases over time. The relative price of the hydrogen vehicle does not vary over time and will maintain the initial markup for the whole century. A complete model simulation was done for each combination of these two markups to see the entry period and conditions.

6.1. Description of scenarios analyzed

The objective of this analysis is translated in to the following two specific questions:

- At which combinations of relative prices for the hydrogen vehicle and the hydrogen fuel does the sector start penetrating?
- In which decade will the sector start penetrating the market, given some initial markups, and taking into account that the hydrogen relative price will decrease with time (as oil price increases)?

The answers to these questions are compared across a set of different scenarios. The scenarios are designed to identify the effects of the most relevant drivers of hydrogen transport sector penetration, which are the following:

- Tax treatment of hydrogen fuel relative to gasoline;
- Availability of other alternatives such as ethanol;
- Climate change mitigation policies.

To analyze the impact of tax treatment we consider the possibility of taxing gasoline at the current rate but not taxing hydrogen, taxing both fuels or not taxing either. To consider the impact of ethanol fuel as a competing option, we compare the results with and without the existence of this fuel. To determine the impact of climate change mitigation policies, the case in which CO_2 concentrations would be stabilized at 550ppm was considered. Although this possibility seems hard to reach in today's political context, it is a policy that has been extensively discussed and provides an appropriate example of a carbon constraining policy.

The method by which the model constrains carbon emissions is by fixing the total emissions and allowing for trading in carbon emission permits across sectors to determine a price for them.

The scenarios that were specifically analyzed to isolate the desired effects are the following:

(i) Taxes are imposed (at current rate) on gasoline and hydrogen (Europe);
(ii) No taxes are imposed on gasoline or hydrogen (USA and Europe);
(iii) Taxes are imposed (at current rate) on gasoline but not on hydrogen fuel (Europe);
(iv) Same conditions as scenario (i) with a carbon emissions constraining policy that stabilizes CO_2 concentration at 550ppm (Europe);
(v) Same conditions as scenario (ii) with a carbon emissions constraining policy that stabilizes CO_2 concentration at 550ppm (USA and Europe);
(vi) Same conditions as scenario (iii) with a carbon emissions constraining policy that stabilizes CO_2 concentration at 550ppm (Europe);
(vii) Same conditions as scenario (iv) without the presence of the ethanol sector (Europe);
(viii) Same conditions as scenario (v) without the presence of the ethanol sector (USA & Europe);

(ix) Same conditions as scenario (vi) without the presence of the ethanol sector (Europe);

These scenarios are analyzed for the Europe and USA regions since these are the regions that account for the largest proportion of transportation emissions. They are also the regions that report data for the transport sector in the most accurate way and can therefore be used for more reliable simulation.

The differentiated tax treatment of hydrogen and gasoline is only relevant for Europe since the USA is modeled as having no tax on gasoline. This is why scenarios (i), (ii), and (iii) are equivalent in the USA. For the same reason, scenarios (iv), (v), and (vi) are also equivalent.

6.2. Vehicle-fuel cost tradeoff

There is a tradeoff between the hydrogen-vehicle cost and hydrogen cost in the sense that as one rises the other has to be lower for the sector to enter the market. From each model simulation, the price of hydrogen relative to the price of gasoline in the period in which hydrogen transport starts penetrating was obtained. For each different vehicle markup, there is a different price of hydrogen at the period of hydrogen sector entry. A way to observe the tradeoff is by plotting the relative price of hydrogen needed for entry against vehicle markup. This yields a downward slope curve since higher hydrogen vehicle prices make lower hydrogen prices necessary for the sector to enter. Figure 6.1 presents the plot of this tradeoff for scenario (ii) in the USA and for scenarios (i), (ii), and (iii) in Europe.

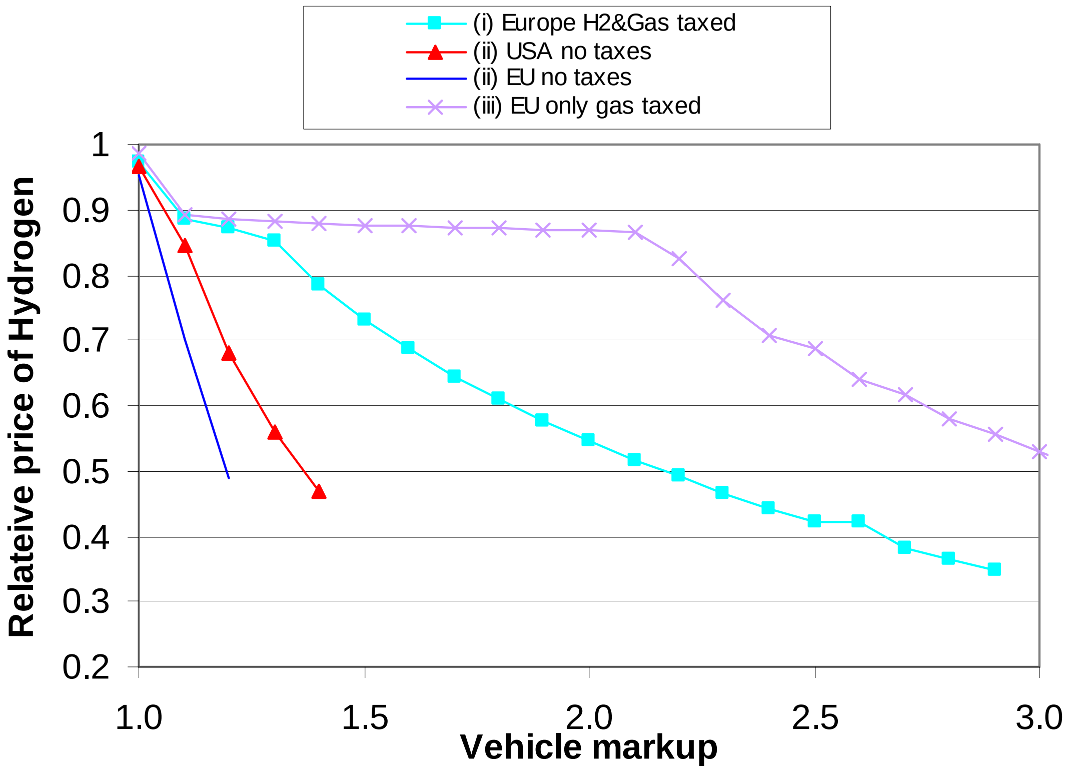

Figure 6.1: Relative hydrogen price at the moment of sector entry

First we can observe that USA and Europe show a similar behavior in scenario (ii), in which there are no taxes on either fuel. The curves for this scenario have a very strong downward slope. This translates the fact that as the vehicle markup grows, the price of hydrogen needs to fall sharply in order for the sector to penetrate. We can also see that at a vehicle markup of 1.5 (i.e., fuel cell cars 50% more expensive than conventional) or higher the sector does not penetrate at all before 2100.

If we compare scenario (i) and scenario (ii) for Europe we can see the strong effect of taxes. The curve for scenario (ii) has a much flatter slope and reaches much higher vehicle markups. We can see that taxing both gasoline and hydrogen at the same rate is more favorable to hydrogen penetration than not taxing either.

When comparing scenario (ii) with scenario (iii) for Europe, a higher curve is expected since it reflects the more favorable conditions of scenario (iii), in which only gasoline is taxed. Nevertheless, the flat part of the curve is an unexpected effect of the general equilibrium model.

There remains the question of perennity of European fuel taxes. It may be unrealistic to suppose that the European governments can forgo the revenue they collect from fuel taxes. It is therefore not possible to imagine that they would avoid taxing hydrogen when it represents a large proportion of the transport sector. 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 smaller tax rates and they would probably face increasing pressure to lower the rate. Although these possibilities are not represented by any specific scenario they are combinations of the ones that are analyzed here and their outcomes can be interpolated from this analysis.

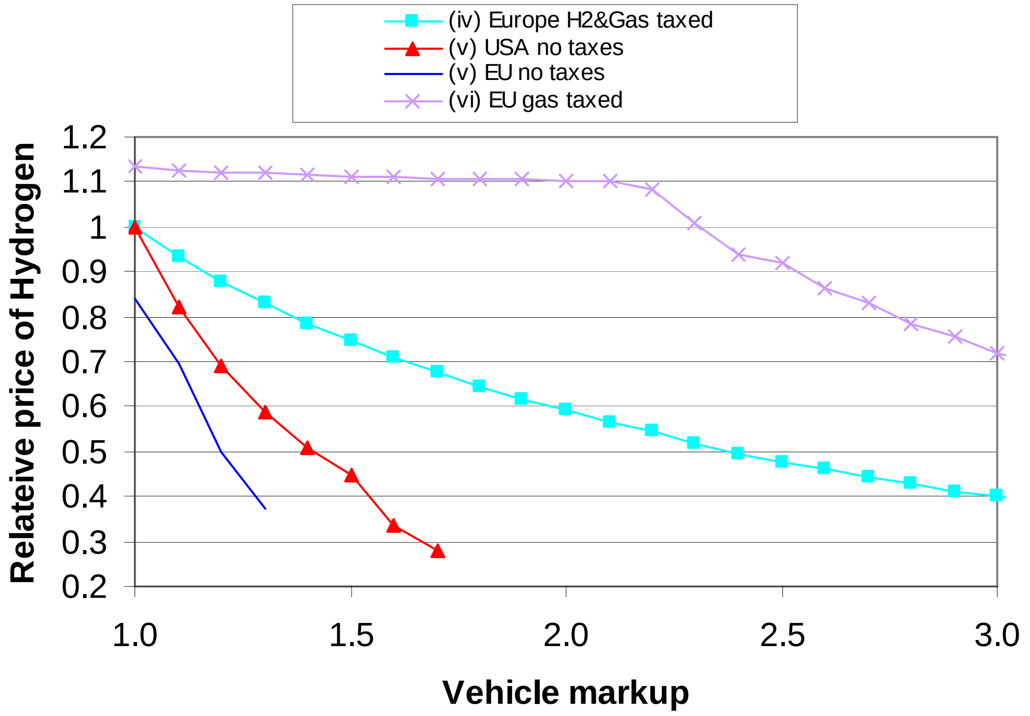

Figure 6.2: Relative hydrogen price at the moment of sector entry with a climate policy

Figure 6.2 shows a similar graph for the same scenarios but including a carbon constraining policy (550ppm stabilization as described in section 6.1). We can see little change from the previous figure. This is as expected because a carbon constraining policy only accelerates the increase in oil-price by imposing a cost on carbon emissions. This does not affect the conditions at which the hydrogen sector penetrates; it simply makes them take place sooner. Finally, we can see a very similar graph in Figure 6.3 that shows the entry conditions for the same scenarios with carbon constraining policy and without the presence of the ethanol sector. The same reasoning explains the little change from the two previous graphs.

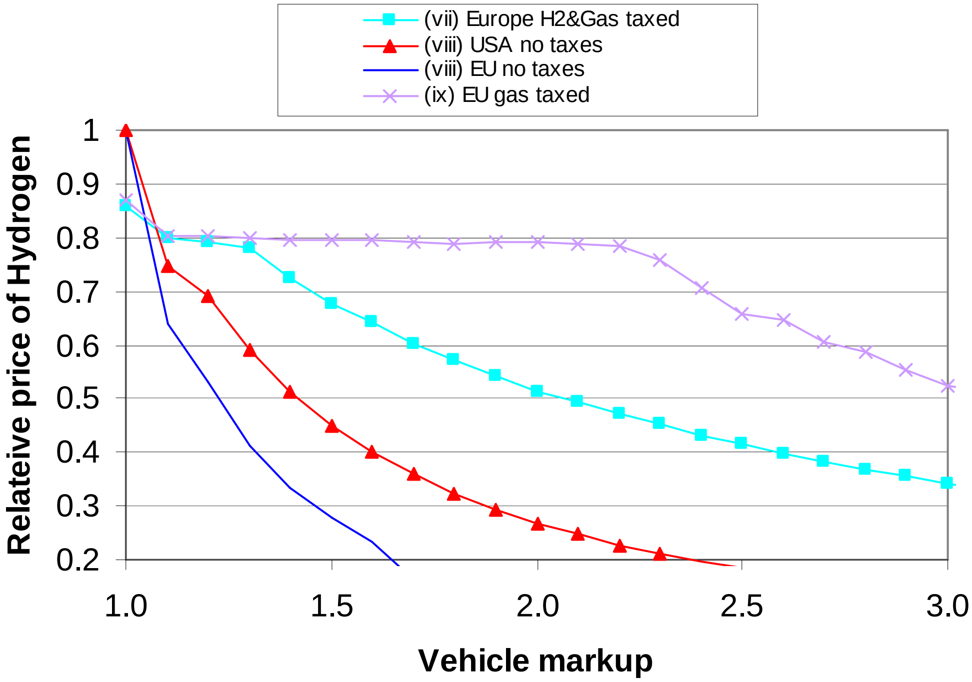

Figure 6.3: Relative hydrogen price at the moment of sector entry with a climate policy and without ethanol competition.

6.3. Penetration time of hydrogen transport

One of the most relevant questions about hydrogen transportation concerns the time at which it will be possible to have commercial penetration. This depends strongly on which are the markups as well as the factors that were analyzed in the previous section.

The procedure followed to answer this question consists of running the EPPA model for the whole century for each combination of the two markups. For each of these runs, the period of hydrogen entry for each region was captured. Figure 6.4 shows the data that results from such a procedure; each point represents one model run and its color indicates the date of hydrogen entry. This data is organized to produce a plot shown in Figure 6.5, which shows the decade in which the hydrogen sector would start penetrating the European market depending on what the markups are in the reference year for scenario (i).

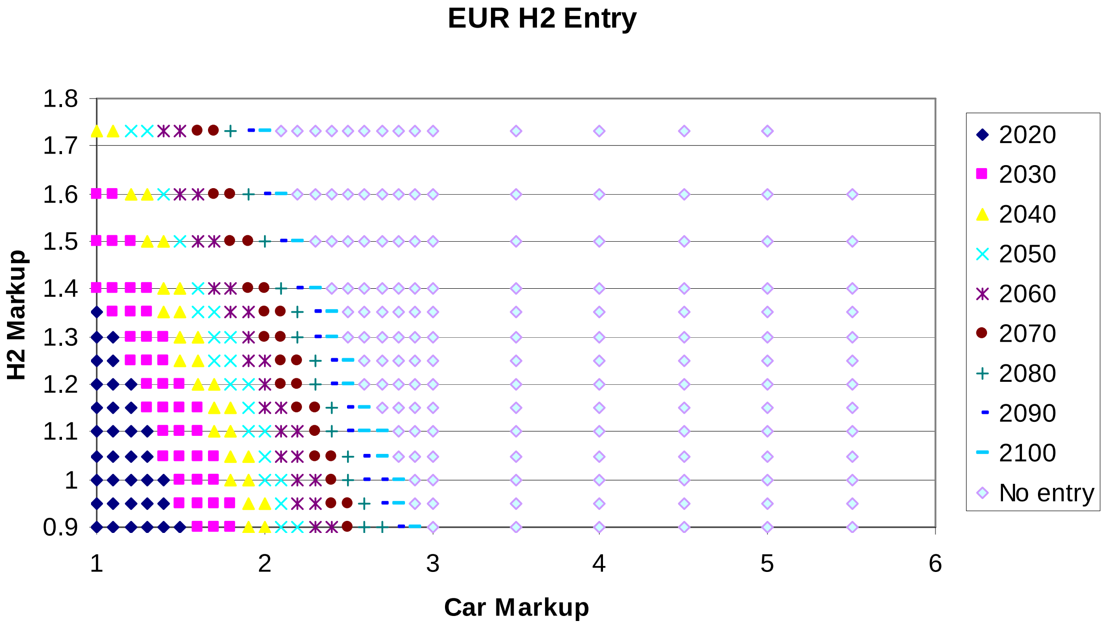

Figure 6.4: Entry for each run representing a combination of markups

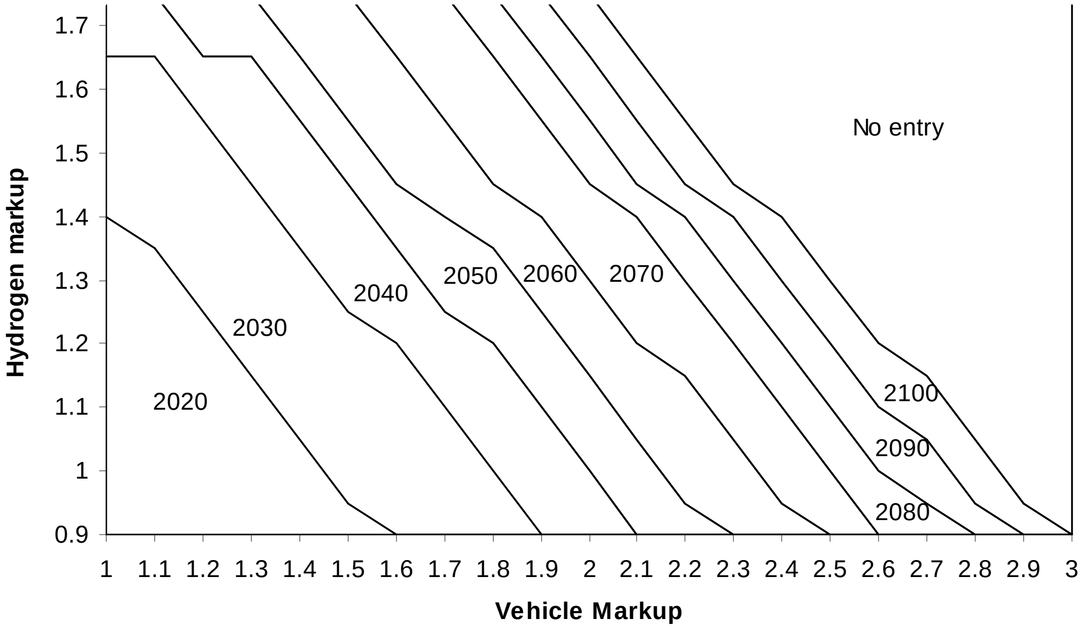

Figure 6.5: Entry decade in Europe for scenario(i)

To interpret Figure 6.5, it can be said that one of the possible conditions at which there could exist hydrogen transportation in 2040 are:

- That technological progress lowers vehicle costs to a proportion of 1.7 relative to conventional vehicles before 2040 (allowing sufficient lead-time for the design and production of vehicles), and
- That the relative price of hydrogen before gasoline price increases (which are already taken into account in the model) is 1.3 with respect to gasoline.

Figure 6.6 shows the penetration timing for the USA for scenario (ii). We can see that, if the vehicle markup is larger than 1.5 (i.e., hydrogen vehicle price is above 50% more expensive than conventional vehicles) the hydrogen transport sector does not enter at all in the 21st century. The same behavior is seen for Europe in Figure 6.7, for this no-tax scenario.

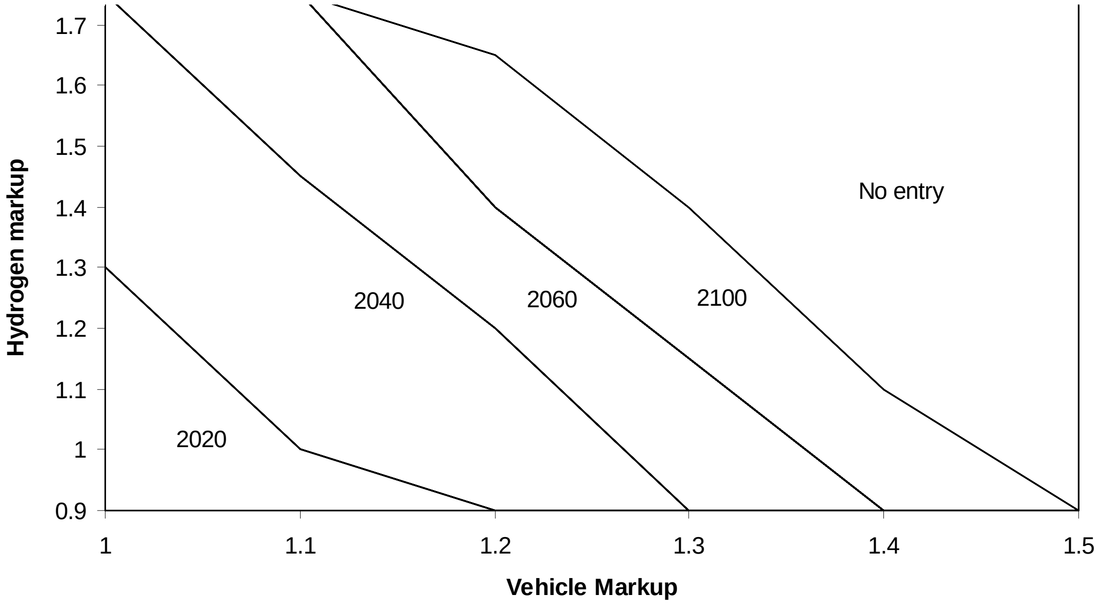

Figure 6.6: Entry decade in the USA for scenario(ii)

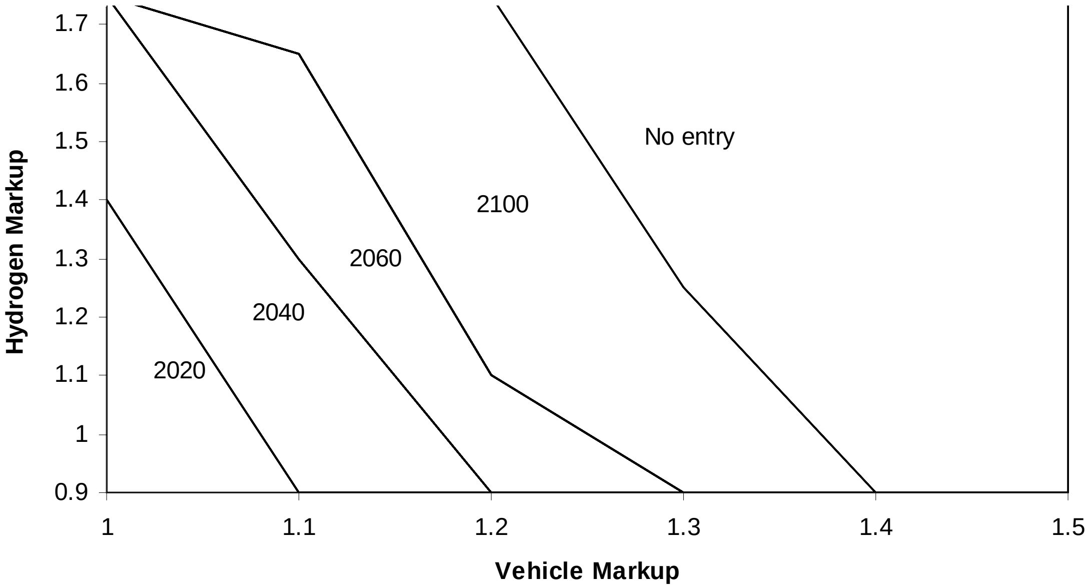

Figure 6.7: Entry decade in Europe for scenario(ii)

If Europe continued taxing gasoline as high as it does today and hydrogen fuel was not taxed (scenario iii), this would give hydrogen transport an even more favorable environment. Whereas in scenario (i) the maximum vehicle markup allowing hydrogen transport to enter before 2100 was three, it is now four, as can be seen in Figure 6.8.

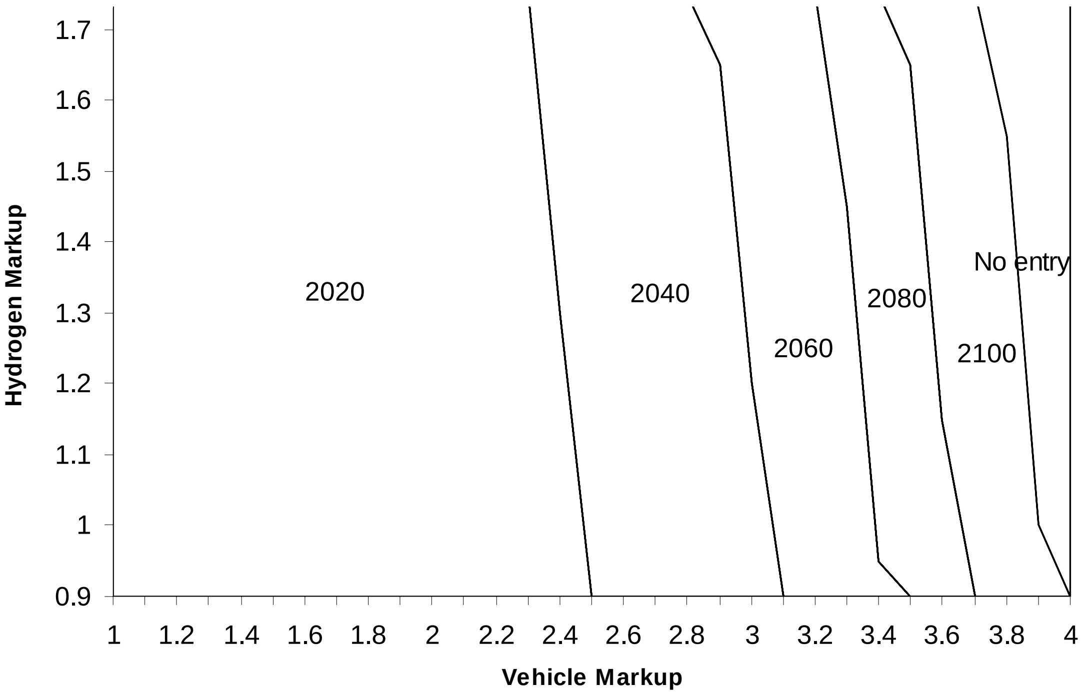

Figure 6.8: Entry decade in the Europe for scenario(iii)

Figure 6.9 shows the penetration timing for Europe in scenario (iv), which is similar to scenario (i) but with a carbon constraining policy.

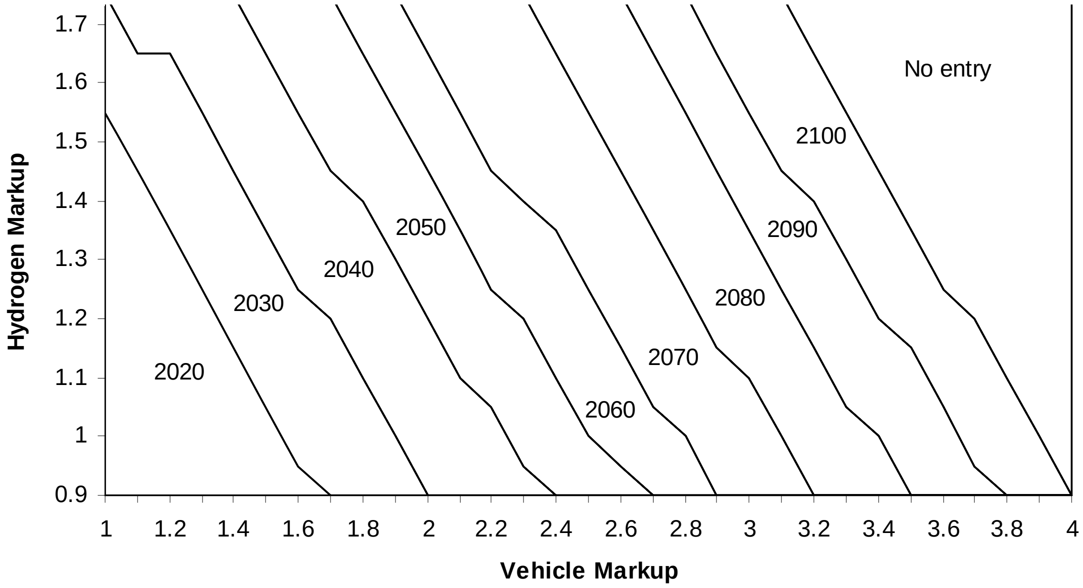

Figure 6.9: Entry decade in the Europe for scenario(iv)

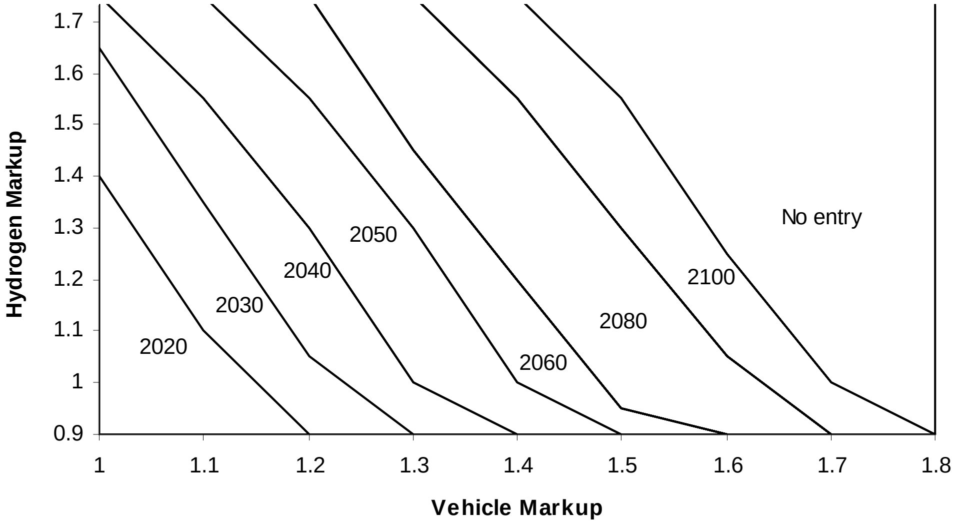

Figure 6.10: Entry decade in the USA for scenario(v)

Figure 6.10 shows the effect of a carbon constraining policy on hydrogen entry in the USA. As we can see there is a favorable effect since the maximum markup for entry moved from 1.5 to 1.8. Nevertheless, this effect is small. Unless hydrogen vehicle costs are reduced by an order of magnitude, there would be cheaper ways and technologies to constrain emissions.

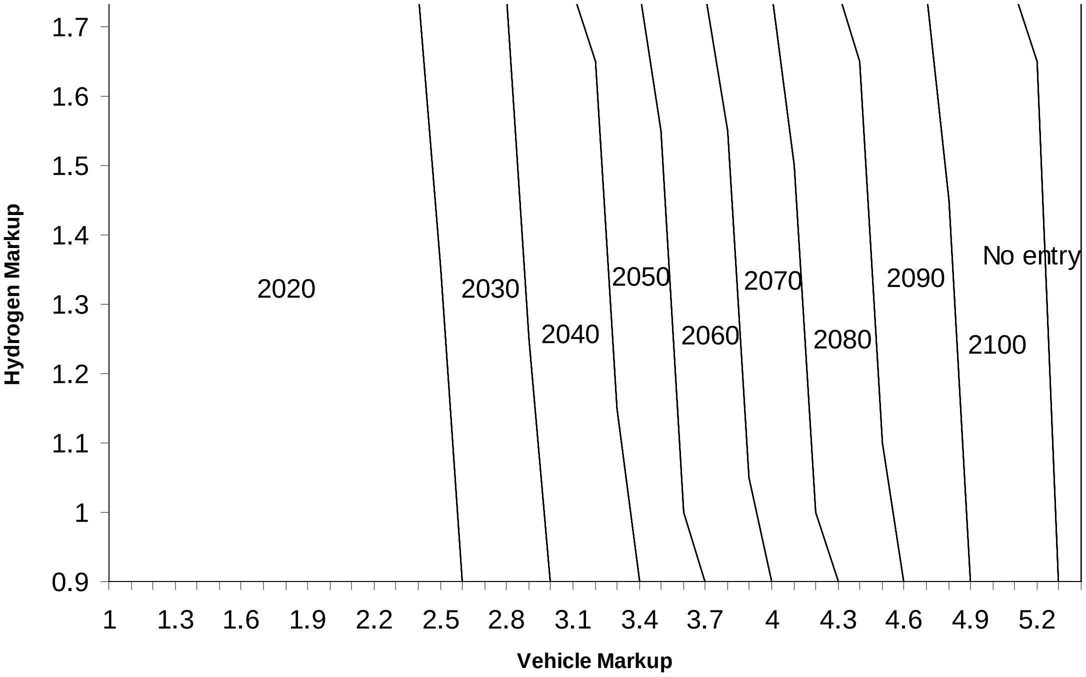

Figure 6.11: Entry decade in the Europe for scenario(vi)

We can observe (Figure 6.11) that by taxing gasoline, not taxing hydrogen and simultaneously imposing a carbon emission constraining policy, the situation becomes very favorable. 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 normal vehicles.

In the scenarios that omit the ethanol sector the conditions for hydrogen transport improve considerably showing that the competing effect of this sector is very important.

Figure 6.12 shows scenario (viii) for the USA, where the hydrogen sector can enter the market even at vehicle markups of three.

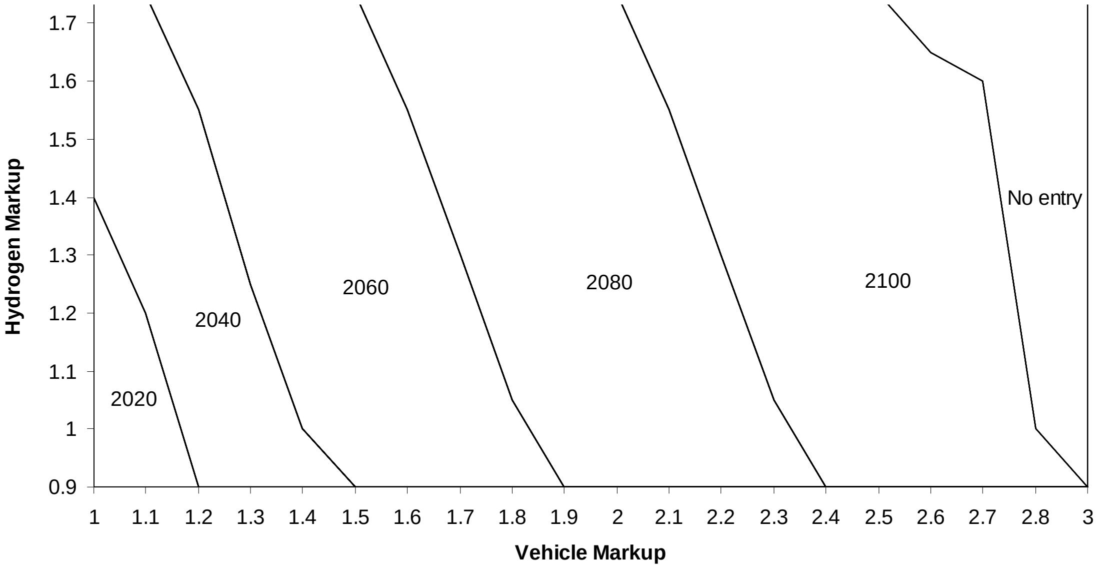

Figure 6.12: Entry decade in the USA for scenario(viii)

The case of Europe when both fuels are taxed or when only gasoline is taxed is much more favorable. The scenario where both fuels are taxed allows entry of the sector before the end of the century for vehicle markups of up to seven, and by 2050 with markups of up to three.

6.4. Reduction of emissions

This section describes the type of impact on GHG emissions of the entry of hydrogen into household transportation in the USA. Figure 6.13 shows the GHG emissions in the US in the “business-as-usual” scenario without hydrogen and with hydrogen entering in 2050.

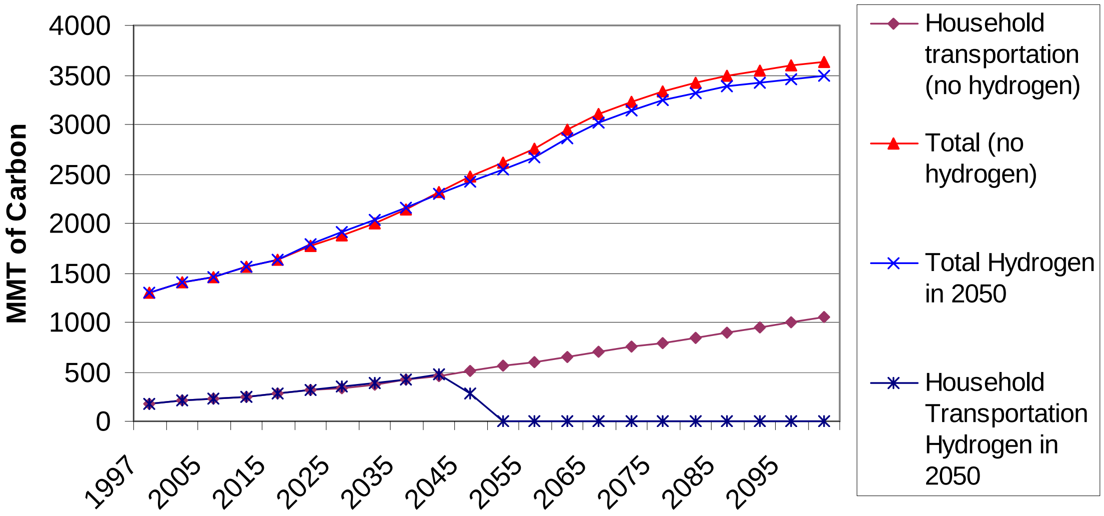

Figure 6.13: Reduction in GHG Emissions in the USA with Hydrogen Transportation in 2050

As can be seen, the reduction in emissions is negligible (less than 4% by 2100). This is because although hydrogen would not have any emissions, the emissions from hydrogen production would be released unless some policy to enforce sequestration is enacted. This shows that, if there is not climate policy, even if hydrogen vehicle technology becomes inexpensive, there will be no effect on emissions. The only effect that hydrogen transport would have is to displace the emissions from the vehicles to the hydrogen production plants. The sudden drop in household transportation emissions shows the entry of hydrogen vehicles in 2050, since this work include the effects of fleet turnover. This does not affect the comparison of emission levels in 2100.

7. Conclusions

This work analyzed the behavior of a hydrogen transport sector within a general equilibrium model of the economy. The results of numerous simulations are presented by comparing different scenarios and isolating the effects of the most important factors. The main conclusions that are drawn from this analysis are the following:

- Under market conditions and in the absence of climate policy that would price carbon, hydrogen fuel cell vehicles penetrate the USA market when the cost of vehicles is no more than 1.30 times the cost of conventional vehicles, and assuming hydrogen can be produced at 1.30 times the 1997 price of gasoline. Even if this cost target is reached and hydrogen vehicles enter the market, CO2 emissions for the US are reduced only very slightly because coal is used to produce the hydrogen and there is no incentive to sequester the carbon when the hydrogen is produced.

- The existing fuel tax structure in Europe strongly 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 assuming the tax rate is per unit of energy, this implies a lower tax per vehicle mile traveled. 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 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 European governments would lose all fuel tax revenue.

- A carbon constraining policy is favorable to hydrogen transportation to some extent. It increases the maximum vehicle markup that makes entry possible by 0.5 to 1.0 in scenarios with fuel taxes in Europe. In the USA, it only increases the maximum markup by 0.3, to a maximum markup of 1.7.

- If ethanol technology is not available and does not compete with hydrogen transportation technology, the favorable effect is much larger. It increases the maximum vehicle markup in the USA by 0.8. If the 550ppm stabilization policy is imposed and ethanol is not available, hydrogen transportation can penetrate the USA market with a vehicle markup of up to 3.0. This is the most favorable scenario considered for hydrogen transportation in the USA.

To put these results in perspective we must recall that current vehicle markups are between ten and 20. This means that without a strong gasoline tax policy, hydrogen would not play a significant role in the USA in the 21st century unless there is a decrease in vehicle cost of more than ten times.

This work has not dealt with some factors that are important for hydrogen transportation to penetrate the market such as the intermediate steps in building a hydrogen-dispensing infrastructure. It does not take into account current technological challenges that prevent hydrogen fuel cell automobiles from being service-equivalent to conventional cars such as range, power, and maximum speed. The cost of overcoming these challenges is considered to be included in the vehicle markup. As a result, the conclusions presented here should be considered as somewhat favorable for hydrogen. An exhaustive analysis of issues that were left out would yield more pessimistic conclusions for an eventual hydrogen transport sector.

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