Cars, Hydrogen and Climate Change: A Long-Term Analysis with the ERIS Model[*]

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Abstract

The transitions in the global automobile sector in the 21st century are uncertain both in terms of technologies and energy carriers. A key driving force of technological change in the long term could be the need to mitigate GHG emissions. This paper examines the role of the passenger car sector in a GHG mitigation strategy and presents a scenario of the automobile technology choices when a price on greenhouse gas emissions is imposed on the global energy system. The analysis has been conducted with ERIS, a multi-regional energy-systems "bottom-up" optimization model that endogenizes technology learning and allows a detailed technology representation, in addition to capturing competing demands for transportation fuels, including hydrogen. Our results provide some policy insights by illustrating the potential for hydrogen to contribute to climate change mitigation, but show that fuel cell cars are a long-term option for climate policy and hybrid-electric vehicles could be an attractive medium-term option.

***Keywords**:* Technological change, cars, hydrogen, climate change

1. Introduction

The transitions that could take place in the global automobile sector during the 21st century are uncertain. Fuel cell and hybrid-electric vehicles (hereon referred to as FCV and HEV, respectively) could be serious challengers to the currently dominating internal combustion engine vehicle (hereon referred to as ICEV) in the long term. However, how a transition from the ICEV towards the FCV and/or HEV could unfold is unknown.

Also, it is not clear which energy carriers would play a role in the long term. Several energy carriers could substitute for the today's dominant oil products, which have well-known environmental and geopolitical problems. Among others, hydrogen (H_2) has been identified as an attractive alternative for the long run, in particular if used in fuel cells (FCs). However, there are major challenges for its introduction including costs, infrastructure development and deployment of production, storage and end-use technologies.

Combined with these uncertainties is an expectation that transport activity will experience rapid growth over the 21st century as incomes in developing countries rise, with a concomitant increase in energy consumption. In passenger transport, without either a substantial reduction in demand for mobility or a shift towards public transportation (mass transit), both of which

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run counter to current global trends, attenuating this growth in energy demand requires switching to advanced engine technologies.

However, transitions in the energy and transportation sectors may span long periods of time, due to the large inertia of technological systems. In general, the introduction of technologies and energy carriers that are not compatible with the dominating technological regime can be very difficult (Kemp, 1997). Often targeted investments on research and development (R&D), focused demonstration projects and early deployment strategies are necessary to enable emerging technologies to become cost-effective and competitive in the marketplace.

The prospects for H_2 and FCs in the private motor vehicle (PMV, or car) sector are often discussed in the context of the "hydrogen economy", i.e. a global energy system where H_2 becomes one of main final-energy carriers. The "hydrogen economy" is receiving increasing attention as an attractive alternative to achieve sustainability goals in the energy sector (see e.g. Ogden, 1999; Barreto *et al.*, 2003). Fuel cells, with applications in both stationary and transport sectors, are seen as one of the key technologies that could drive a transition towards a "hydrogen economy". The transportation sector appears to offer a particularly promising potential for these technologies although major barriers must be overcome. With a number of hurdles for the penetration of H_2 and FCs, the examination of strategies that could facilitate their introduction has become an important issue.

A key driver of the development of the global energy system in the long term is the need to substantially reduce the emissions of greenhouse gases (IPCC, 2001). Within this context, there has been a substantial debate on the role of H_2-powered FC cars in a strategy to mitigate GHG emissions, particularly on the timing of this option (see e.g. Keith and Farrell, 2003; Azar *et al.*, 2003). It has been argued that mitigation of climate change, among others, could be a reason to support the early introduction of H_2-powered FC cars, especially given the expected rapid increase in personal mobility in the developing world. However, it appears more likely that, in the short term, sectors other than transportation (e.g. electricity generation and non-CO_2 gases) would be the main targets for curbing GHG emissions. Still, in the long term, the transportation sector should also evolve towards a low-emissions configuration. Here, we investigate how the imposition of a cost on greenhouse gas emissions affects the technology choice in the passenger car sector. Specifically, we examine the potential role and timing of FCVs and the influence of the infrastructure barriers in their introduction.

For our long-term analysis we use ERIS (Energy Research and Investment Strategies), a "bottom-up" energy-systems optimization model that allows an adequate representation of technologies and technology dynamics, specifically endogenizing technology learning patterns, and permits the examination of the passenger car sector within the context of the global energy system (Kypreos *et al.*, 2000; Barreto and Kypreos, 2000, 2003; Turton and Barreto, 2004).

The remainder of this paper is organized as follows. Section 2 presents a brief description of the energy-systems "bottom-up" ERIS model used in this analysis. Section 3 describes the construction of the transportation scenario portrayed here and the relevant transport characteristics of the ERIS model, including the technology characteristics and learning patterns assumed. Section 4 describes the results of the analysis, emphasizing the role of technology learning, the impact of constraints on GHGs and the influence of infrastructure for H_2 delivery on the technology choices in the model. Finally, in Section 5 some conclusions and policy insights are outlined.

2. The ERIS model

ERIS (Energy Research and Investment Strategies) is a global multi-regional "bottom-up" energy-systems optimization model that endogenizes technological learning curves (see

Kypreos *et al.*, 2000; Barreto and Kypreos, 2000; Barreto and Kypreos, 2003). Recently, the model has been expanded by the authors (Turton and Barreto, 2004). Several non-electric sectors, covering transportation and thermal needs, and corresponding technologies were incorporated. Also, fuel production technologies are included, specifically for H_2, alcohol and Fischer-Tropsch liquids production. In addition, marginal abatement curves for several non-CO_2 greenhouse gases (EPA, 2003) and forest sinks (IPCC, 2001) were added, increasing the scale and broadening the composition of abatement opportunities available. Abatement opportunities are also afforded by the inclusion of CO_2 capture and storage technologies (David and Herzog, 2000). For a more detailed description of the current version of the model see Turton and Barreto (2004). The reference energy system for this version of ERIS is presented in Figure 1.

Energy demands, other than for passenger transportation, are taken from the SRES-B2 scenario (Riahi and Roehrl, 2000). B2 is a "dynamics-as-usual" scenario, where differences in economic growth across world regions are gradually reduced and concerns for environmental and social sustainability at the local and regional levels rise gradually along the time horizon.

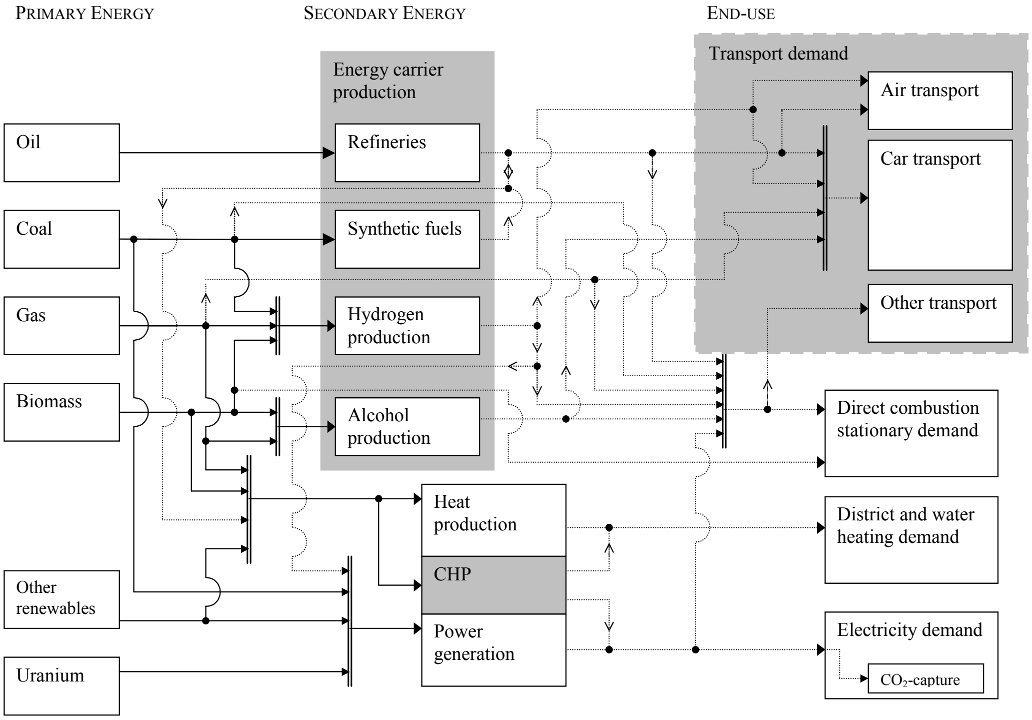

Figure 1: ERIS reference energy system

Note: Boxes represent primary fuels, groups of technologies and demand sectors. Lines indicate flows of fuels used for secondary energy production (plain) and for final demand (dashed). Vertical parallel bars are used to group together multiple fuels or energy carriers used by one group of technologies. Shaded areas group together energy carrier production technologies (in the case of secondary energy), and the transportation sector (in the case of final energy).

Technological learning

The ERIS model incorporates the impact of experience with a new technology on the cost of that technology (also called learning-by-doing) (Argote and Epple, 1990; McDonald and Schrattenholzer, 2001). That is, for those technologies that learn, the specific cost (SC) of a technology is decreasing function of cumulative installed capacity (which is used as a proxy for experience):

$$SC_{te,t} = a' * C_{te,t}^{-b} + floor_{te} \qquad (1)$$

where: $SC_{te,t}$ is the specific cost of the technology; $C_{te,t}$ the cumulative capacity; $floor_{te}$ the technology floor cost; a′, the specific cost at unit cumulative capacity; and, b, the learning-by-doing index.

A mixed integer programming (MIP) formulation of the ERIS model, using stepwise interpolation along the curve defined by equation 1, is used in this study. This avoids the need to use a non-linear formulation of the model, enabling conventional optimization software to find a globally optimal solution to the linearized problem (Barreto and Kypreos, 2000).

For this study, the learning process has been formulated using a technology cluster methodology, following the "key technologies" approach of Seebregts *et al.* (2000). That is, each energy conversion or end-use technology is made up of a number of components, each of which is either subject to improvements through learning or mature (i.e., non-learning). This approach to technological learning allows an energy or end-use technology to benefit from experience gained through the application of another technology that uses a common component. For example, an IGCC power plant may consist of learning components comprising the gasifier and gas turbine, with the remainder of the system assumed to be non-learning. Experience with the IGCC will benefit other technologies that use the gasifier component, such as coal-to-H_2 production, or other technologies that use the gas turbine component, such as gas combined-cycle power plants. In other words, this approach incorporates spillovers into the learning process.

3. Transportation scenario and technologies

3.1 Transport demand scenario

Projections of passenger transportation demand to 2100 were developed using the B2-SRES scenario (Riahi and Roehrl, 2000) and the passenger transportation demand model of Schafer and Victor (2000). The B2 scenario is based on the long-term UN Medium 1998 population projection of 10.4 billion by 2100 (UN, 1998), combined with intermediate levels of economic development where world GDP grows to approximately 11-times 1990 levels by 2100 (IPCC, 2001).

The model of Schafer and Victor (2000) projects total demand for passenger travel (in passenger-km), shares of various modes and vehicle occupancy rates to 2050 for the IS92a/e scenario (Leggett *et al.*, 1992) based on stable time and money share budgets. It was necessary to extrapolate these projections beyond the original income range to cope with a different income and time scenario. Estimates of 1990-2000 vehicle utilization rates were derived from data on vehicle numbers and Schafer and Victor's (2000) models of occupancy and travel demand. These trends were extrapolated based on convergence around 10-16,000 km *per annum* for all world regions except North America, which is assumed to converge to around 22,000 km per annum.

In this demand projection, car transportation is assumed to grow from roughly 9 trillion kilometers of travel in 2000 to around 37 trillion kilometers in 2100 (see Figure 2). Clearly, this growth has major social (in terms of urban planning, mobility), economic (infrastructure, congestion) and environmental (emissions, resource extraction) implications. Figure 4 shows that in this scenario most of the growth occurs in developing regions, with the industrialized regions returning to close to year 2000 demand by the end of the century. It is also worth noting that in this travel demand scenario, aggregate car transportation in developing regions surpasses that in the industrialized world in around 2040-2050.

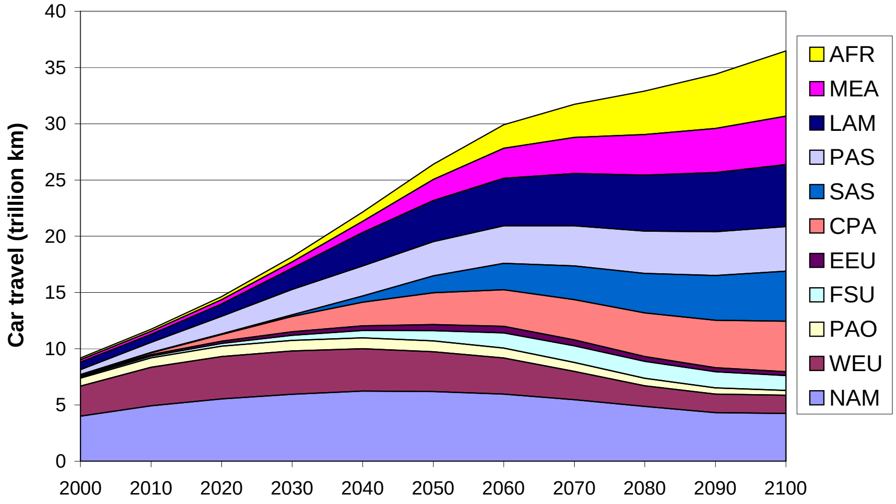

Figure 2: Projected future demand for car travel, 2000-2100

Note: NAM: North America, WEU: Western Europe and Turkey, PAO: Pacific OECD, FSU: Former Soviet Union, EEU: Eastern and Central Europe, CPA: Centrally Planned Asia, SAS: South Asia, PAS: Pacific Asia, LAM: Latin America, MEA: Middle East and North Africa, AFR: Sub-Saharan Africa

The models of Schafer and Victor (2000) were also used to develop estimates of future passenger air transport that were consistent with trends in PMV travel. Global air transport energy efficiency was assumed to converge towards 0.9 MJ/pkm – around a 50 percent improvement in the level of the current most efficient region (PAO), resulting from stock turnover, improvements in aircraft design and higher capacity utilisation. Energy demand growth rates for other transport sectors were derived from the B2-SRES scenario (Riahi and Roehrl, 2000) and applied to 2000 baseline data (IEA, 2003a,b) to generate a projection scenario, incorporating efficiency improvements assumed in the B2 scenario (Riahi and Roehrl, 2000). This travel demand scenario is combined with the energy system model to elucidate possible supply scenarios, which are described below.

3.2 The transportation sector in ERIS

The transportation sector in the modified ERIS is disaggregated into three categories – PMVs (cars), air transportation and all other transportation. The focus of this study is car transportation.

3.2.1 Car transportation

The suite of end-use technologies that compete to supply demand for car travel comprise three different engine technologies and four different fuels (of which ten different combinations have been chosen). Estimates of vehicle technology drivetrain efficiency (used here to refer to overall efficiency of fuel processing, engine, transmission, system control and power regeneration, in the case of HEVs) were derived from Weiss *et al.* (2003), Thomas *et al.* (2000), Weiss *et al.* (2000), Ogden *et al.* (2004) and ADL (2002). The technologies, fuels and relative efficiencies are presented in Table 1. Table 1 also presents abbreviated mnemonics for each technology used for convenience later in this paper (eg. ICC, IGH, AFC).

Three components used in the ten engine-fuel technology combinations studied are assumed to benefit from learning-by-doing. These comprise: the fuel cell (FC); the fuel processor (reformer, R) used with the alcohol and petroleum fuel cell; and the hybrid battery system (B). Non-learning components comprise the internal combustion engine, fuel storage systems, electric motor, generator, transmission and control systems. The relationship between technologies and learning components is also presented in Table 1. The relative drivetrain efficiencies are assumed to remain constant. However, the average efficiency of the base vehicle (ICC) is assumed to improve at 0.2 per cent per annum. This conservative estimate is used to reflect that improvements in vehicle weight, aerodynamics, rolling resistance, engine etc. will be offset somewhat by demand for larger vehicles with more energy-consuming onboard systems as incomes grow. Total drivetrain system costs for mass-produced vehicles were derived from Ogden *et al.* (2004),Weiss *et al.* (2000), Thomas *et al.* (2000) and ADL (2002).

Table 1: Relative drivetrain efficiencies of car technologies-fuel combinations (and learning components)

Fuels	**Engine technologies** Conventional ICE	 Hybrid ICE-electric	 Fuel cell-battery hybrid
Petroleum products	***ICC*** 100	***ICH*** 140 (B)	***PFC*** 164 (FC, R, B)
Natural gas	***ICG*** 100	***IGH*** 144 (B)	NA
Alcohols	***ICA*** 96	***IAH*** 136 (B)	***AFC*** 180 (FC, R, B)
Hydrogen	NA	***IHH*** 140 (B)	***HFC*** 220 (FC, B)

Note, for each technology-fuel combination, learning components are listed in parentheses.
FC: fuel cell, R: reformer, B: hybrid battery system

Table 2 shows the starting and floor costs, along with the assumed learning rate for each component. Higher learning rates have been assumed for the less mature components (FC and B). The rates are within the ranges suggested by others (for example, see McDonald and Schrattenholzer, 2001).

Table 2: Starting costs, learning rates and floor costs for car transport technologies

Component	**Starting cost ($/kW for 40 kW FC)**	**Learning rate**	**Floor cost ($/kW for 40 kW FC)**
Fuel cell (FC)	250 (266 AFC) (275 PFC)	15%	45 (62 AFC) (70 PFC)
Reformer (R)	90 (110 PFC)	5%	25 (45 PFC)
Hybrid battery system (B)	$2,500 per vehicle	15%	$700 per vehicle

Note: Currency units are 2000 US dollars.

3.2.2 Air transportation

The model uses a stylized representation of non-car transportation sectors, including air transportation. In this sector it is assumed that petroleum products must supply all demand before 2050. From 2050 onwards it is assumed that H_2 aircraft are a cost-effective alternative, and petroleum and H_2 compete according to fuel cost alone to supply demand for air travel.

3.2.3 Other transportation

As mentioned above, the remaining transportation sectors are represented in a stylized way. These sectors comprise almost entirely land and sea freight. Unlike car transportation where demand is defined in terms of kilometers of travel (see Section 3.1), other transportation demand is defined in energy units, and hence incorporates the impact of efficiency improvements, such as from HEVs, that are already included in the B2 scenario (Riahi and Roehrl, 2000).[2] In contrast, it is assumed that improvements from switching to H_2 FC are not incorporated, which is consistent with the underlying fuel mix in the B2 scenario output. Of the FC options for freight transportation, H_2 FCs are assumed to be the most competitive in line with FC passenger cars, and only this FC technology has been included in the model. Freight vehicles employing H_2 FCs are conservatively assumed to be 50 percent more efficient than similar vehicles employing ICE-based drivetrains.

3.3 Fuel production sector in ERIS

ERIS accounts for competing demands for fuels and constraints on resource availability that affect the cost of fuels. Total global resource constraints and resource extraction costs are derived from Rogner (1997), with a number of different resource supply categories available for each fuel, but at increasing cost. Competing demands manifest through the reference energy system (see Figure 1). In addition to the cost of fuel extraction, ERIS includes fuel production, processing, transmission and distribution costs.

In the case of transmission and distribution (T&D) for H_2 and natural gas (both of which are assumed to require a pipeline network), ERIS uses a binary decision variable, combined with a minimum T&D capacity threshold[3] to reflect that it is necessary to build a minimum amount of infrastructure regardless of the quantity of fuel delivered. This means that the marginal cost of delivering small quantities of gaseous fuels is high, but the cost decreases and eventually stabilizes with increasing demand.

The incorporation of a detailed car transport sector into the ERIS model requires a detailed representation of energy carrier production technologies. Accordingly, energy carrier production technologies for H_2 (from coal, gas and biomass), alcohol (from gas and biomass) and petroleum products (from oil and coal) were incorporated into the model.

Hydrogen produced with electrolysis is not included as a production option because it is assumed to be too expensive. This assumption follows logically from other assumptions about the cost of electricity generation technologies compared to H_2 production technologies using the same feedstock, and transmission and distribution costs for either carrier.[4] This is the case across all fuels, including renewables, and is maintained even under extreme technological learning assumptions that favor electricity generation. The operating characteristics of H_2

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[2] It should be noted that characteristics of the freight driving cycle make hybrids vehicles relatively less competitive compared to passenger vehicles.

[3] Equivalent to 40 GW per world region, with an assumed T&D plant factor of 0.5 for H_2 and 0.7 for gas.

[4] It should be noted that H_2 production using electrolysis may occur in some small niche markets, such as in geographically isolated areas without indigenous fossil fuel or biomass sources but with access to other renewables.

production and electricity generation mean that H_2 production is more efficient and also more amenable to CCS, meaning that GHG taxes favor H_2 production over electricity generation.

Details on the cost of the H_2, alcohol and synthetic fuel production technologies were obtained from a number of sources. Of the components used in these technologies, two are assumed to become more cost competitive with additional experience: gasifiers and the steam methane reformer. The gasifiers are used in coal-to-liquids (Fischer-Tropsch) synthesis, production of H_2 from coal and biomass and production of alcohols from biomass (in addition it is also used in advanced coal (IGCC) electricity generation). For the steam reformer (combined with a Pressure Swing Absorber (PSA)), we have assumed the same relative learning potential as for transport-based steam reformers. This component is used in H_2 and alcohol production from natural gas (and in the stationary gas FC-based electricity generation).

4. Results

We present three sets of scenarios:

- a baseline scenario where no technology or greenhouse policy instruments are implemented (with and without technological learning);
- a series of climate change mitigation scenarios where progressively higher carbon-equivalent (C-e) taxes are imposed on anthropogenic greenhouse gas emissions; and
- a pro-H_2 scenario where it is assumed that, in addition to a low C-e tax, there is strong support for the development of H_2 delivery infrastructure, thereby reducing the transmission and distribution costs of this fuel. Hydrogen delivery infrastructure was chosen as the target as this is one of the barriers most often cited to wider uptake of this fuel in small-scale applications such as PMVs.

4.1 Technological learning in transportation technologies

Figure 3 and Figure 4illustrate the impact of learning-by-doing on the future choice of car technologies. Figure 5 presents a case where there is no learning-by-doing in any of the components used in transportation technologies. Learning-by-doing is assumed to occur however for components used only in stationary applications, such as gas turbines, gasifiers, stationary FCs, and advanced nuclear power generation. Figure 6 illustrates the impact of also allowing transportation components, comprising the mobile FC, reformer and hybrid battery system, to learn from experience.

Based on the assumptions used here and in the absence of technological learning, ICEVs remain the dominant technology, although there is a shift towards increasing use of gas (see Figure 3). A very small number of natural gas HEVs enter the market. Incorporating the impact of learning from experience into the projection (see Figure 4) results in the introduction of several technologies that were previously unable to compete. HEVs, in particular experience a relatively rapid uptake and dominate by the end of the century. FCVs, on the other hand, account for less than 1 percent of the market by 2100. The direct H_2 FCV accounts for this entire uptake, it being the cheapest FC technology.

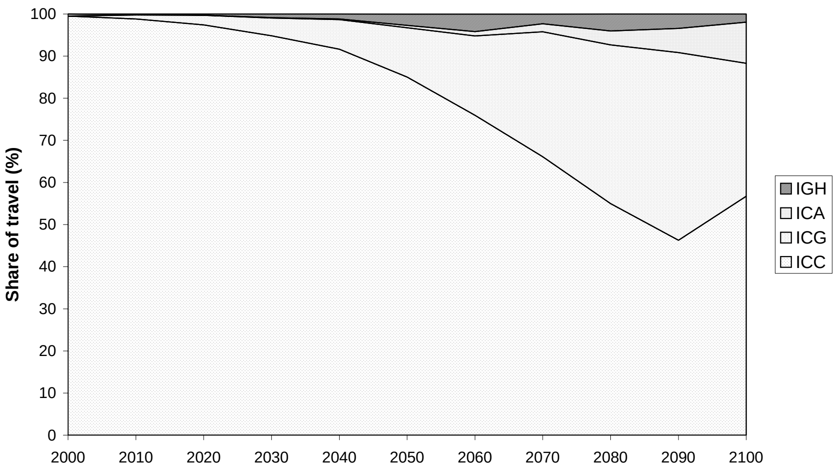

Figure 3: Share of global car travel by drivetrain technology and fuel, without learning in mobile FC, reformer and battery system, 2000-2100.

Note: dotted shading indicates ICEVs, and diagonal shading indicates HEVs; see Table 1 or 2 for a detailed description of the technology abbreviations.

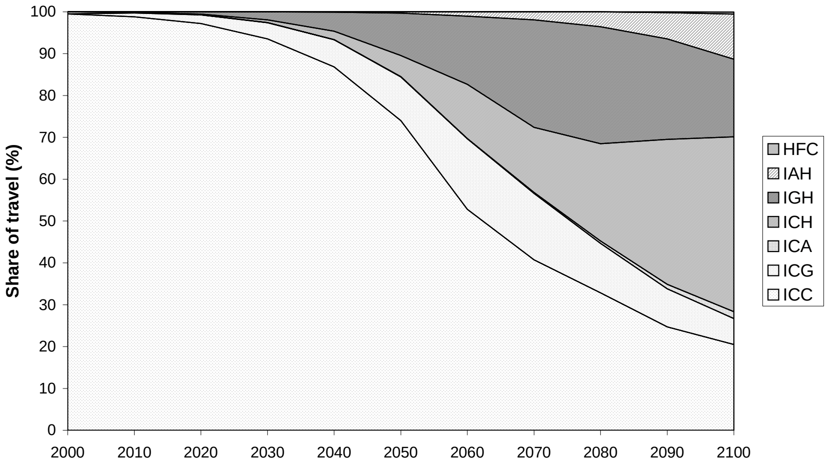

Figure 4: Share of global car travel by drivetrain technology and fuel, with learning-by-doing in mobile FC, reformer and battery system, 2000-2100

Note: dotted shading indicates ICEVs, diagonal shading indicates HEVs, and the H_2 FCV indicated with either medium shading; see Table 1 or 2 for a detailed description of the technology abbreviations.

Even though FCVs play a minor role in this scenario, Figure 5 shows that a significant amount of H_2 is being produced, almost entirely from the gasification of coal. This quantity of H_2 is equivalent to about 7.5 percent of non-electric final demand, but would be sufficient to supply a global PMV fleet comprising three-quarters H_2 FCVs. However, in our scenario, H_2 is a convenient and flexible energy carrier that many sectors are likely to demand in the long run, particularly since the cost of other fuels is assumed in these scenarios to increase as cheaper resource categories (see Rogner, 1997) are exhausted.

Based on the assumptions used here, it may be more efficient to use H_2 in non-car transportation – road and sea freight, and air – where there are fewer effective fuel and technology substitutes. In the case of air transportation where all demand must by supplied by petroleum products up until 2050, H_2 captures around 10.5 percent of the market by 2100. In the freight (or other) transportation market H_2 achieves a lower penetration (3 percent), which represents a significantly larger amount of fuel than is used in PMV transportation.

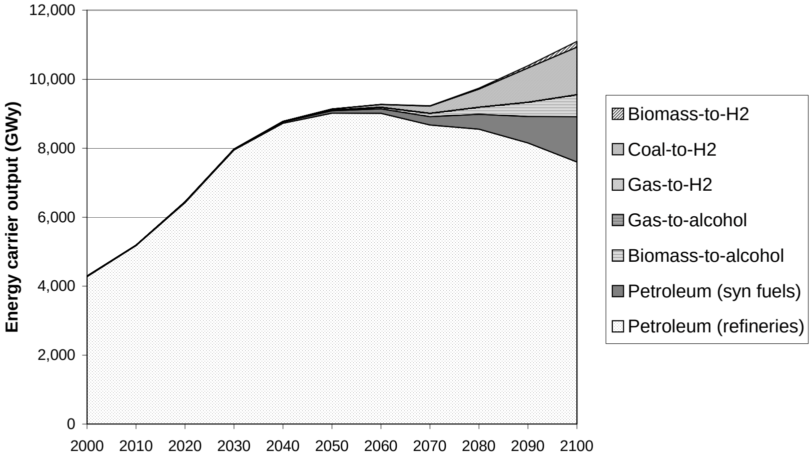

Figure 5: Global energy carrier production (secondary energy), with learning in transport technologies, 2000-2100

The penetration of H_2 in these sectors is not inconsistent with the level of uptake observed in passenger transport, because these sectors exhibit a much higher rate of vehicle utilization which tends to increase running costs relative to capital costs, making improvements in efficiency more valuable. In addition, these sectors are more suited to a more centralized refueling network, which is expected to evolve prior to the highly diffuse network required to make H_2 sufficiently convenient for the passenger car market. Lastly, there is more space for on-board storage and hence cheaper storage options. However, these results must be viewed with caution because of the highly stylized characterization in the ERIS model of the air and freight sectors.

The majority of the H_2 produced in this scenario (around 68 percent) is used in the stationary energy sector to supply thermal needs. Stationary combustion of H_2 to provide for thermal demand avoids many of the drawbacks of using H_2 as a transport fuel. For a start, combustion technologies are far cheaper than FCs (and are just as suitable for supplying thermal needs), and the need for costly and bulky storage is also avoided. In some stationary applications, particularly in the industrial sector where demands are concentrated in a small number of locations, transmission and distribution costs may also be lower.

4.2 Climate change mitigation policies

We now examine how imposing a cost on GHG emissions affects the choice of car transportation technologies by way of imposing various levels of carbon-equivalent (C-e) taxation. The use of a C-e tax allows non-CO_2 abatement opportunities to compete with energy system abatement, forest sinks and carbon capture and storage (CCS).

Figure 6 shows the impact of emissions taxes ranging from \$0-1000/tonne C-e on the uptake of FCVs, based on the assumptions used in this analysis. Figure 8 presents for each tax rate the share of passenger car travel supplied by FCVs and the quantity of H_2 produced globally at the end of the 21^{st} century. The level of H_2 production is reported to examine the relationship between this fuel and FCV uptake, and the effectiveness of abatement policies in promoting the use of H_2. The impact of the C-e tax on atmospheric CO_2 concentrations in

2100, as calculated using the simple climate model MAGICC (Wigley and Raper., 1997) is also presented in Figure 6.[5] The $0/tC-e case, where FCVs capture roughly 0.5 percent of the market by 2100, is the same as discussed in Section 4.2 and presented in Figure 4 and Figure 5. This scenario results in an atmospheric CO_2 concentration of 850 ppm in 2100, with emissions peaking at 29.3 Gt C-e (CO_2, CH_4 and N_2O, only) in 2090.

The plot of FCV share in Figure 6 can be divided into three different regions based on changing responses to a GHG emissions tax. By contrast, increasing GHG tax rates have a far more consistent impact on atmospheric CO_2 concentrations.

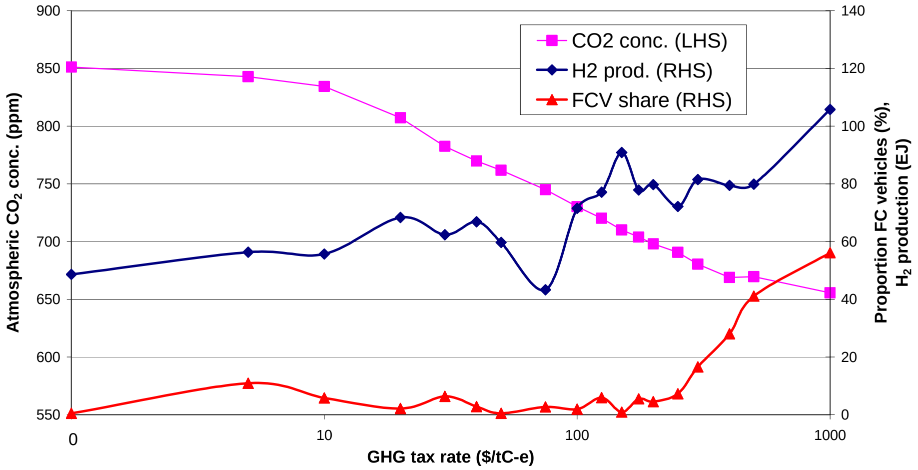

Figure 6: Impact of greenhouse gas tax on FCV uptake, H_2 production and CO_2 concentration, 2100

The first region in Figure 6 covers low GHG tax rates ($5-40/t C-e) which appear to provide a low and inconsistent incentive for the uptake of FCVs, although these rates are generally supportive of increased H_2 production, particularly from biomass. In the scenario examined here, this H_2 is not consumed to any great extent in PMV transportation, for many of the reasons discussed previously. In other words, although supportive of H_2 production low GHG taxes do not appear to significantly advantage FCV technologies relative to ICEV and HEV technologies.

At intermediate C-e tax rates ($50-150/t C-e) FCVs are consistently unattractive, with these tax levels tending to favour HEVs. Across this intermediate range of tax rates hydrogen production at first decreases to below the level observed under a zero tax before more than doubling. The decline shown in Figure 6 at around $75/tC-e occurs because coal-to-H_2 production becomes more expensive, and drops to 2/3^{rds} of the level in the zero-tax scenario, whilst carbon capture and storage (CCS) is not, for the most part, a competitive abatement option. These increasing tax rates continue to favor a shift to biomass-to-H_2 production, although this is a costly technology and uptake is slow. At the higher C-eq tax rates within this range CCS from H_2 production is competitive, resulting in the observed doubling in H_2 production between $75 and $150/tC-e, mostly as a result of coal-to-H_2 production increasing by more than 130 percent. Interestingly though, this additional H_2 production does not coincide with any increase in the use of FCVs, implying that under our assumptions it is more cost-effective to use the H_2 in other sectors, for many of the same reasons discussed in the baseline scenario.

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[5] Using mid-range estimates for climate sensitivity, 1980s-mean net deforestation and aerosol forcing parameters, and defaults for other parameters.

The third region in Figure 6 covers the high GHG tax rates ($200/tC-e plus), which under the assumptions modeled here are necessary to provide a consistent and increasing incentive for the uptake of FCVs (see, for example, Ogden *et al.*, 2004). Only at these high tax rates do the efficiency benefits of FCV technologies begin to outweigh the cost barriers, which have up until now tended to favor the less energy-efficient use of H_2 in direct stationary applications. In fact, there is a clear redirection of H_2 as we move from $150/tC-e to $250/tC-e, with H_2's share of direct stationary combustion falling sharply from 17 to 4 percent, while the H_2 FCV share of PMV travel increases from less than 1 to more than 7 percent (and other uses of H_2 do not change significantly). Simultaneously, petroleum is redirected from transport to stationary applications, and the overall increased energy efficiency (owing to the use of FCVs) allows final demands to be met with less H_2 (and less primary fuel overall). This partly explains the somewhat inconsistent impact of high GHG tax rates on H_2 production shown in Figure 6.

However, in this scenario the supply of H_2 is also influenced by the cost premium of biomass-to-H_2 technology and an assumed constraint on the availability of CCS from H_2 production, reflecting the limited suitability of some H_2 production sites for CCS. This constraint begins to have a noticeable impact at tax rates above $150/tC-e. On the other hand, it is also above this rate that H_2 production from biomass (which is also amenable to CCS) replaces production from coal – with the assumptions modeled here, moving from a GHG tax of $150 to $250/tC-e results in a halving of coal-to-H_2 production and a 60 percent increase in biomass-to-H_2 production.

The result seen in Figure 6 is a combination of more expensive H_2 production and more efficient consumption, manifesting as a decrease in production from a peak at $150/tC-e to a long trough extending from $200-500/tC-e. At $500/tC-e and above FCVs are highly competitive because of their efficiency and ability to utilize (via H_2) biomass, a carbon-free and abundant primary feedstock. However, at these taxation levels flexible zero- and low-emissions fuels such as H_2 are increasingly competitive in almost all sectors.

The above results imply that the application of broad abatement instruments (such as a carbon tax, or emissions trading) alone is insufficient to bring about a consistent transition to FCVs, except at very high levels (for a discussion see, for example, Keith and Farrell, 2003). Nor is promoting the use of FCVs in passenger car transportation necessarily a cost effective way to abate greenhouse gas emissions, except where deep cuts in emissions are required or over the very long term.

4.3 Infrastructure policy

Since broad-based abatement instruments are an ineffective and costly way to bring about an increase in the number of FCVs, it seems sensible to examine policies that are more FC-specific to see whether they are a more effective alternative. Accordingly, we examined a policy where in addition to a small C-e tax, governments support the development of a H_2 transmission and distribution infrastructure by paying part of the capital cost of developing the pipeline network. The need to develop expensive transmission and distribution infrastructure to make H_2 available and convenient is often cited as one of the major barriers to the widespread utilization of H_2 in transportation. This distribution network must be developed initially in the absence of any demand for H_2. The model used here has attempted to incorporate the costs of this and other transport fuel transmission and distribution infrastructure, including the need to develop a minimum network irrespective of the quantity of fuel delivered.[6]

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[6] Technically, this was modeled using a binary decision variable to reflect the use of hydrogen, coupled with a minimum capacity requirement of 40 GW (or 20 GWy of H_2 distributed) per region.

This enables us to investigate how significant a barrier the infrastructure costs are to the uptake of advanced transportation technologies, given that the vehicle costs alone may make these technologies uncompetitive. This may be particularly useful for policymakers interested in the effectiveness of different possible approaches to promoting H_2 as a transport fuel.

Accordingly, a scenario was examined in which the capital cost premium of H_2 transmission and distribution infrastructure over that of petroleum is funded externally – for example, by a government pipeline and reticulation program. The impact of such a program on the overall cost of H_2 FCVs is small, with transmission and distribution capital costs accounting for only roughly 3 percent of the per kilometer cost of the H_2 FCV drivetrain and fuel costs. However, these capital costs bring an advantage over the nearest cheaper competitors.

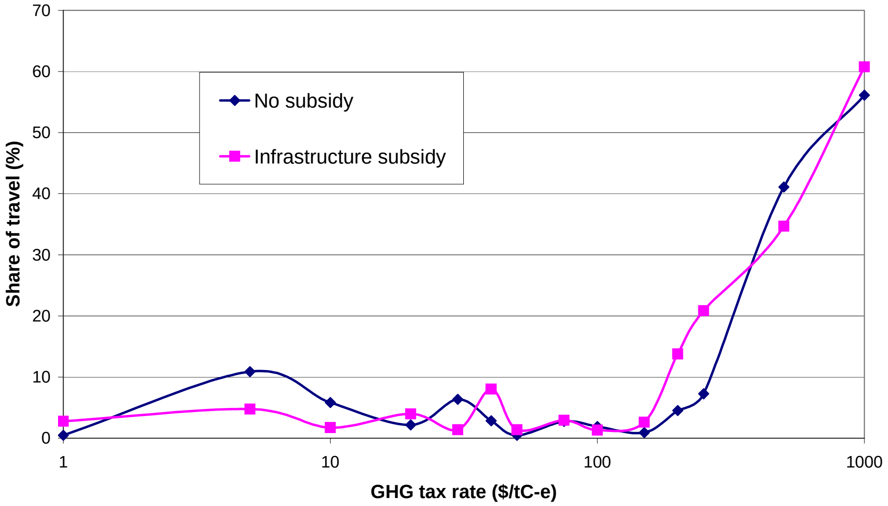

Figure 7: Impact on share of FCVs of infrastructure policy at different GHG tax rates, 2100

The impact of a H_2 infrastructure program alone (i.e. with a 0 U$/tC-e tax) is to raise the share of FCVs in 2100 from roughly zero to 3 percent. However, because of the inconsistent response observed at low GHG tax rates in Section 4.3 this result cannot be viewed as significant. This is illustrated in Figure 10, which compares the impact of the GHG tax with and without the support for H_2 T&D infrastructure. Figure 7 shows that supporting H_2 T&D infrastructure does not have a major impact on the uptake of FCVs across a range of C-e tax rates, except around $200-$250/tC-e where it appears to accelerate market penetration. At tax rates above $250/tC-e, supporting H_2 T&D infrastructure does not appear to promote additional FCV uptake. However, it should be noted that supporting H_2 T&D does have a generally positive impact on H_2 consumption, which is on average 30 percent higher under the infrastructure policy across the C-e tax rates examined.

These results imply that if the policy goal is to promote FCVs, then some other highly specific policy instrument is required. Many possibilities exist, including targets or standards for vehicle manufacturers or distributors, government procurement programs, direct financial incentives through tax credit schemes or feebates regimes, etc. However, the results of the analysis in Sections 4.2 and 4.3 imply that it is unlikely that FC-specific policies become cost-effective ways of pursuing climate change mitigation or promoting development of a H_2 economy.

5. Conclusions

This paper has presented an examination of the potential role that hydrogen and hydrogen-based fuel cell cars could play as part of a long-term strategy for the mitigation of GHGs in the global energy system. The analysis has been conducted with the "bottom-up" energy-systems optimization ERIS model, taking into account the effects of technology learning, the imposition of taxes on GHG emissions and of policies to support the development of hydrogen infrastructure. Ours is a "what if" scenario that explores the implications for new transportation technologies of a continuation of current trends in passenger transport, many of which appear unlikely to change in the medium term. This scenario is useful in the context of examining the energy system changes necessary to achieve deep cuts in GHG emissions when demand is inflexible. Our results illustrate the potential for hydrogen to contribute to climate change mitigation, but show that fuel cell cars are rather a long-term option for climate policy.

Assuming that car transportation technologies do not benefit from experience leads to the unsurprising result that new and expensive technologies are not used. Only with extremely high resource costs is this likely to change. On the other hand, assuming learning in car technologies and fuel production has a significant impact on technology uptake. Since FC technologies are still in their infancy, it can be reasonably expected that they have a promising learning potential in the long term.

However, in the case of learning, our perfect-foresight, least-cost optimization approach implies that, actors are aware of the rate and extent of the benefits gained from experience using a new technology. Therefore, they make optimal and early investments. However, in many cases new technologies are risky and first-movers may face higher costs, which tends to delay the uptake of technologies. This market failure necessitates policy intervention to promote sufficient technology utilization to achieve the optimal learning potential and hence least cost (see, for example, Ogden *et al.*, 2001). One possible way to effectively stimulate the learning process is to establish international public-private partnerships to share costs and risks of R&D, demonstration and deployment programs (RD3) (for example, see PCAST, 1999). Other policy interventions could include "buy-down" strategies, infrastructure development, other R&D support and pollution taxes.

However, we have seen that GHG taxes may not be effective in promoting FCV uptake even when there is perfect foresight. GHG mitigation policies, applied in the scenarios examined here as a comprehensive GHG tax, have an inconsistent impact on the uptake of FCVs in car transportation. Only high GHG tax rates ($200/t C-e and above) provide an adequate and consistent incentive to FCVs. From a policy perspective this indicates that promoting FCVs is not a cost-effective way of reducing GHG emissions except in the long term or where deep cuts in emissions are required. In other words there are many cheaper alternative abatement options across all sectors, including in PMV transportation where the use of HEVs and a shift to gas or alcohol is preferable from the point of view of cost-effectiveness.

Although subsidizing the capital costs of H_2 transmission and distribution infrastructure does not necessarily lead to increased uptake of FCVs, it does result in additional H_2 production, and the development of a more extensive T&D network which reduces the additional cost of shifting to FCVs. That is, it provides some elements in a coordinated market strategy for the eventual introduction of FCVs. It also results in broad abatement instruments becoming more effective at promoting H_2 and H_2-using technologies.

It is important to stress that our results and findings depend on the modelling assumptions outlined in this paper, about which there are a number of uncertainties. In particular, technological uncertainty is potentially significant and the possibility of technology breakthroughs cannot be ruled out. Specifically, faster technological development that leads to a rapid decrease in the costs of FCs may accelerate the uptake of FCVs and allow them to capture a larger share of the transportation market.

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