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The diffusion of fuel cell vehicles and its impact on the demand for platinum group metals: research framework and initial results

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A fuel cell is an electrochemical engine that converts the chemical energy of a fuel, such as hydrogen, and an oxidant, such as oxygen, directly into electricity. The emerging fuel cell industry may represent a major opportunity for the global platinum mining industry. This is because low temperature fuel cell systems use platinum group metals as catalysts. Fuel cell vehicles may become the most important driver of future platinum demand within years of their commercialization.

A great number of factors impact on and drive the diffusion of fuel cell vehicle innovation. Such drivers range from energy security to environmental concerns and the technological development of fuel cells and systems. Such factors and drivers of fuel cell vehicle diffusion are combined with the generic 'body of knowledge' on 'technology forecasting' and 'diffusion of innovation' to design a framework that provides a holistic approach to the analysis of this complex enterprise.

An attempt is made in this paper to address the following questions: Which types of fuel cells require platinum group metals? Which types of fuel cells will achieve dominant design status? Will fuel cell vehicles diffuse successfully? How big will the impact of successful fuel cell vehicle diffusion be on future platinum demand? How well do fuel cell vehicles compete with incumbent technologies such as spark-ignited and compression-ignited internal combustion engine-driven vehicles? How soon will oil depletion start to drive the diffusion of fuel cell vehicles? How important is hydrogen as a fuel? What impact does the inadequate hydrogen fuelling infrastructure have on fuel cell vehicle diffusion?

The paper contains some initial results of a research project that has the aim of producing a schedule of future platinum demand generated from fuel cell vehicles.

Keywords: diffusion of fuel cell vehicles, technology forecasting, platinum demand forecasting.

Introduction

A fuel cell is an electrochemical engine that converts the chemical energy of a fuel, such as hydrogen, and an oxidant, such as oxygen, directly into electricity. The main question that this paper focuses on is how soon and to what extent the commercialization and diffusion of fuel cell vehicles (FCVs) will start to impact significantly on future platinum demand. Global platinum demand may increasingly be affected in future by the degree to which fuel cell technology will become embedded in vehicles, distributed electricity generators and various electronic devices, e.g. notebooks. Of all the various fuel cell applications, the biggest amount of platinum will probably be used in FCVs. The focus is therefore on forecasting the diffusion of FCVs. Mike Mtakati, a spokesperson for Anglo Platinum, said that fuel cell technology could in the long term become the dominant driver of the South African platinum industry (cartoday.com, 5 Feb. 2003). Platinum and other platinum group metals such as palladium are already used in many of today's motor vehicles. The platinum loading on a fuel cell catalyst is, however, currently greater than that on a platinum-based autocatalyst. Johnson Matthey estimates that, once proton exchange membrane fuel cell (PEMFC) technology is mature, a medium-sized passenger car will require 10 grammes of platinum for its fuel cell. This is equivalent to about 320 000 oz of demand for every million vehicles (*SA Mining, Coal, Gold and Base Minerals*, Oct. 1998, p. 35).

Fuel cell vehicles have the potential to become one of the main drivers of platinum or platinum group metal (PGM) demand in the future. Information such as the rate at which fuel cell innovation will diffuse or spread through society should be of value to the platinum mines which, like other mineral suppliers, find it difficult at times to balance mineral production and demand. The diffusion pattern of FCVs should therefore be an important input into the strategic planning process at platinum mining companies. The long lead times in the mining industry require long-term planning and a long-term view of future mineral demand. These long lead times can be ascribed to the long time lags between exploration, mine development and mine production activities, especially for deep-level mines. The long-term nature of mine planning is described by Sloan (1983, pp. 23–24) as follows:

'… the nature of the mining industry limits a company's ability to control the critical variables of demand and the market place. The emphasis must, therefore, shift to an understanding of the market place and the development of an integrated strategy which ensures adequate supplies at competitive costs. The long-run nature of the major commitments made by mining companies makes planning a must. Commitments made today will tie up assets for the next five, ten, twenty more years. It is imperative that the commitments be made in consonance with a long-run strategy.'

Mineral demand and supply forecasting therefore has an important role to play. To produce accurate mineral demand forecasts is not easy, however, even less so when new applications of minerals are emerging. Technological forecasting has been recognized as having the potential to provide the minerals industry with better ways to anticipate and measure the impact of new technologies (Van Rensburg and Bambrick, 1978). This is one of the tools that is explored in this paper. A literature study on FCV forecasts (see Table XV) shows differences among the opinions and forecasts obtained from various sources. The reasons for this are often not clear since forecasting methodologies and assumptions are not always published. The purpose of this document is to provide a framework that can be used to analyse the diffusion of FCVs. The rate of diffusion and diffusion patterns over time is what is important to miners.

The problem that is under investigation can be analysed by answering the following questions:

- Do all types of fuel cells use PGMs?
- Which applications of fuel cells will have the biggest potential impact on future PGM demand?
- What is the potential size of the emerging fuel cell and FCV industries?
- How soon will FCVs be commercialized, if at all?
- Which other alternative fuel vehicles compete with FCVs?
- How big is the need for alternative fuel vehicles?
- How much platinum is used per FCV and what will the impact of an FCV industry be on the future demand for platinum or other PGMs?
- How soon and at what rate will FCVs diffuse (spread) through society?

The above questions are partially addressed in this document. When the above questions are properly addressed, the outcome should preferably be in a quantitative format as illustrated in Table I. The aim is therefore to determine the values of the unknown variables A, B, C, D, … , Q, R, S, T, …, etc.

The values in column II depend on dominant vehicle types and how well FCVs will diffuse over time. Values in column III will depend on dominant vehicle designs and architectures, while values in column IV will depend on fuel cell electrode assembly membrane manufacturing techniques and how they may improve over time.

At this point in time the probability that fuel cells will be adopted in stationary electricity generation applications and as power sources for various portable devices in large numbers seem to be higher than the probability that FCVs will be adopted by customers in very large numbers. One of the reasons for this uncertainty is that the time frames for the introduction of various fuel cell based products are different. The diffusion period of products may also differ. The reasons for this vary from technological maturity to the fitness or competitiveness of the various fuel cell products and various other drivers, such as environmental concerns and energy security. Hydrogen fuel cell cars are most likely to take the longest to diffuse. This is because hydrogen fuel cell cars rely on the co-diffusion of hydrogen generation and distribution networks. The rate of diffusion can, however, be speeded up if the necessary support is provided by governments, the private sector and consumers.

A huge amount of money is currently spent on fuel cell research, development and demonstration (RD&D), as well as the associated hydrogen generation, storage and distribution infrastructure that may be required to fuel these devices. The result is the emergence of a new industry, the fuel cell industry, and a new ubiquitous hydrogen energy carrier that may be a substitute for petrol and diesel in decades to come. The following facts point to the emergence of this industry and the hydrogen economy:

- More than 5 000 patents related to fuel cells have been patented worldwide up to 2003
- More than 4 000 fuel cell systems have been built from 1963 to 2003
- Various improvements and reductions of unit costs have taken place and efforts to meet various goals are continuing
- A number of governments such as those of the USA, Japan, European Union, Canada, Korea, Australia and China are positioning their countries to become important players in this industry. This can be deduced from levels of RD&D spending, investment in infrastructure and fuel cell commercialization strategies
- The private sector, especially a number of automotive original equipment manufacturers (OEMs), have spend billions of dollars on fuel cell RD&D to date
- The inaugural meeting of the International Partnership for the Hydrogen Economy (IPHE) was held on 20 November 2003 and the terms of reference of this partnership were signed by senior representatives of 16 countries (USA, Australia, Brazil, Canada, China, the European Commission, France, Germany, Iceland,

Table I
Fuel cell vehicle forecast and impact on future platinum demand

I	II	III	IV	V
Year	Number of (new) FCVs on the roads globally	Average fuel cell engine capacity (kW/vehicle)	Average platinum loading per kW of vehicle capacity (g/kW)	Total platinum used in FCVs (tons)
2005	A	G	L	Q
2010	B	H	M	R
2015	C	I	N	S
2020	D	J	O	T
...	...	...	...	...
-	15 000 000 (for illustrative purposes only)	75 kW (assumption)	0.15 g/kW (assumption)	168.75 t

India, Italy, Japan, Norway, Korea, the Russian Federation and the UK)
- The variety of fuel cell applications (stationary, mobile and portable) and the variety of possible pathways to fuel cell domination.

There are various possible or partial solutions to the problems of unsustainable transportation, energy security, global warming and pollution and they are the objective of many RD&D programmes. The above facts therefore do not exclude other solutions from playing a major role and even becoming the dominant solution to the said problems. It is therefore also necessary at this stage, the pre-commercialization stage of FCVs, to investigate the various alternatives to FCVs. Some of these alternatives may have serious implications for platinum miners. Various low, medium and high platinum usage scenarios in the automotive industry can be foreseen. One example of a low platinum usage scenario is when simple battery-run vehicles containing no autocatalysts will dominate in the future. This scenario will result in low values in column II of Table I. Another similar future scenario is when most future vehicles will only use small fuel cells, which could be high temperature solid oxide fuel cells (containing no or very few PGMs), for example, and the main energy source will be a battery. As a result, this scenario will have low ,values in columns III and IV in Table I. Initially, before extensive hydrogen distribution networks exist, platinum and other PGMs may be used not only in fuel cells, but also in an onboard reformer. This will result in higher initial values in column IV of Table I.

The methodology of how the missing values of Table I can be obtained is discussed Some background information on fuel cells is provided so that the reader will appreciate the various issues that are involved.The various reasons why fuel cells are so important for the minerals industry are highlighted below.

Miners' interest in fuel cells

There are a number of reasons why miners are interested in fuel cell technology. Some of these are given below:

- Fuel cells can be used to power underground machinery such as locomotives and LHDs (see Table II and Figure 7). Fuel cells provide a solution to the problem of diesel particulates. See Roman (Oct. 2003, p. 141) for more information
- Methane-rich gas fields and pockets of various sizes are often intersected by miners. It has been estimated that millions of cubic metres (Lurie, 1987) of gas have been released (and are still being released) by mining and exploration activities. This and coal-bed methane can be used directly in some types of high temperature fuel cells to generate electricity and heat
- Mines require high quality back-up power. This can be provided by fuel cells
- Fuel cells, distributed generation and mini-grids are options that isolated mines (removed from established electrical infrastructure) should consider
- South African platinum miners may promote their own product by investing in low temperature fuel cell ventures and simultaneously meeting the requirements of the Beneficiation Bill, for example
- Coal miners have a role to play in the emerging hydrogen economy. Coal is one of many sources from which hydrogen can be produced. See Figure 24
- Low temperature fuel cells are most suited to motor vehicles. If FCVs become the dominant alternative vehicle in the future, then this will certainly drive future platinum demand. This can be illustrated as follows: Currently, there are about 700 million vehicles in the world. If the assumption is that all vehicles will in the far future be fuel cell vehicles, then it means that at least 224 million (320 000 oz troy/million x 700 million) ounces of platinum will be required. To put this in perspective, the total global supply of platinum in 2003 was 6.24 million ounces troy (Johnson Matthey, *Platinum* 2004, p. 5). The assumption is that the average vehicle will use about 10 g of platinum in a few years' time (see Table IX for Pt loading). However, vehicle numbers will not remain at the 700 million level. In China alone the number of automobiles may, for example, increase from about 16 million in 2000 to as many as 300 million by 2050 (Feng, 2004, p. 356). Some forecasts show that there may be more than 3.5 billion vehicles in the world by 2050 (Chalk, 24 May, 2004, p. 4). Such high vehicle demand will increase the need for sustainable transportation
- Some coal mines produce hydrogen as a by-product during water purification (Van der Merwe, 14 June 2004). This hydrogen can be utilized in fuel cells. Researchers at Penn State University are developing a microbial fuel cell that runs on organic waste (*New Scientist*, 10 March 2004).

Table II
Advantages and disadvantages of fuel cell driven underground locomotives that use metal hydrides to store hydrogen
(*Capital Equipment News*, Dec. 2003)

Advantages	Disadvantages
Zero emissions, low noise, high volumetric power density, low temperature, low pressure, long life.	High capital cost currently. Project cost: $1.6m. Will economies of scale be reached?
Advanced state of development.	Relatively high capital cost of metal hydride storage.
Metal hydride storage of hydrogen is very safe. Safety and productivity requirements cannot be met by conventional power technologies such as diesels, trailing cables and batteries.	Metal hydride fuel storage has a low gravimetric energy density compared to diesel.
Metal hydride storage is lighter than lead-acid batteries (the Fuelcell Propulsion Institute's locomotive was 30% lighter than the traditional battery version).	
May reduce underground ventilation requirements.	

Introduction to fuel cell technology and systems

In 1839 the principle of the fuel cell was invented by William Grove. It then took about 120 years until NASA used it as a power source during space flight. Since then numerous research organizations and companies have been supporting research and development of fuel cell technology. This has resulted in a vast fuel cell technology 'body of knowledge', of which only some of the basics will be discussed here.

Types of fuel cell

A fuel cell is a galvanic cell (a device in which chemical energy is changed to electrical energy) in which the reactants are continuously supplied (Zumdahl, p. 469). A fuel cell can also be defined as an electrochemical engine with no moving parts (or almost none) that converts chemical energy of a fuel, such as hydrogen, and an oxidant, such as oxygen, directly into electricity. Unlike a battery, it does not need to be charged. There are different types of fuel cells (FCs), e.g. alkaline (AFC), proton exchange membrane (PEMFC), direct methanol (DMFC), phosphoric acid (PAFC), molten carbonate (MCFC) and solid oxide (SOFC) fuel cells. A number of other types of more experimental fuel cells are also emerging, for example biological fuel cells. The PEMFC is also known as the polymer electrolyte membrane fuel cell (PEMFC), the polymer electrolyte fuel cell (PEFC) and solid polymer electrolyte fuel cell (SPEFC). Each type of fuel cell has unique characteristics, advantages and disadvantages.

The various types of fuel cells and the chemical reactions that take place within them are listed in Table III. Note the importance of hydrogen as a fuel and oxygen as an oxidant. Oxygen is usually obtained from an oxygen carrier, i.e. the air. However, very pure hydrogen and oxygen are required for some types of fuel cells. This hydrogen can be obtained from hydrogen carriers such as natural gas, naphta or petrol by means of direct (in some cases) and/or indirect reforming.

In the case of the PEMFC, PEM-DMFC and PAFC, hydrogen ions or protons move from the anode through the electrolyte to the cathode (see Tables III and IV).

The fact that fuel cells run on hydrogen or hydrogen carriers points to the link between fuel cells and the so-called hydrogen economy (see glossary of terms). This is important to note since hydrogen fuel cell technology is a sustainable transportation technology (see glossary of terms) when the hydrogen is produced from renewable energy sources. Hydrogen fuel cell technology may also be one of the best long-term solutions to the energy security problem.

Table V illustrates the different types of electrolytes that are used in the various types of fuel cells. The various types of fuel cells are named after the electrolytes used by them or the fuel that they convert to electrical energy.

The operating temperature of a fuel cell is an important characteristic (see Table VI). A high temperature fuel cell may be very efficient in an application where both its electricity and heat can be used, the so-called CHP applications. Heat, however, is not desired in applications such as laptop power supplies and motor vehicles, and therefore low temperature fuel cells such as the PEMFC stand the best chance currently to be used as main power sources in FCVs. The first motor vehicles that were built in the 1960s and 1970s were driven by AFCs, one of the low temperature fuel cells. Most of the membranes currently used in PEMFCs and DMFCs were not designed to operate at high temperatures. High temperature fuel cells usually have the ability to reform some hydrocarbon fuels directly.

The electrical and total efficiencies of the various types of fuel cells are listed in Table VII. A number of RD&D

Table III
Electrode reactions for various fuel cells (College of the Desert, Dec. 2001, pp. 4–24, 4–29, 4–30, 4–31)

Type of fuel cell	Anode reaction	Cathode reaction
PEMFC	$H_2 \rightarrow 2H^+ + 2e^-$	$^1/_2\ O_2 + 2H^+ + 2e^- \rightarrow H_2O$
(PEM) DMFC	$CH_3OH + H_2O \rightarrow 6H^+ + 6e^- + CO_2$	$1^1/_2\ O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$
AFC	$H^2 + 2K^+ + 2(OH^-) \rightarrow 2K + 2H_2O\ \ 2K \rightarrow 2K^+ + 2e^-$	$^1/_2\ O_2 + H_2O + 2e^- \rightarrow 2(OH^-)$
PAFC	$H_2 \rightarrow 2H^+ + 2e^-$	$^1/_2\ O_2 + 2H^+ + 2e^- \rightarrow H_2O$
MCFC	Occurs regardless of type of fuel: $H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$ When a hydrocarbon fuel is used: $CO + CO_3^{2-} \rightarrow 2CO_2 + 2e^-$ Internal reforming of methane: $CH_4 + H_2O \rightarrow 3H_2 + CO$	$^1/_2\ O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$
SOFC	Occurs regardless of type of fuel: $H_2 + O^{2-} \rightarrow H_2O + 2^{e-}$ When a hydrocarbon fuel is used: $CO + O^{2-} \rightarrow CO_2 + 2e^-$ When methanol is used as fuel: $CH_4 + 2O^{2-} \rightarrow 2H_2O + CO_2 + 8e^-$	_ $O^1/_2 + 2e^- \rightarrow O^{2-}$

Table IV
Mobile ion in the major types of fuel cells (*College of the Desert,* Dec. 2001, pp. 4-23, 4-24, 4-30, 4-31)

Type of fuel cell	Type of ion that moves through electrolyte (mobile ion)
PEMFC	H^+; moves from anode to cathode
DMFC	H^+ in the PEM-DMFC; OH^- in the alkaline DMFC
AFC	OH^-; hydroxyl ions move from the cathode to the anode
PAFC	H^+; moves from the anode to the cathode
MCFC	CO_3^{2-}; moves from the cathode to the anode
SOFC	O^{2-}; moves from the cathode to the anode

Table V
Electrolytes used in different types of fuel cells (College of the Desert, Dec. 2001, pp. 4-22, 4-27; Larminie, 2000, p. 110)

Type of fuel cell	Electrolyte
PEMFC	Sulphonic acid in solid polymer membrane. Nafion is very expensive and cannot operate at very high temperatures (exceeding 100 degrees Celsius) because of its organic nature.
DMFC	Sulphonic acid in a solid polymer membrane/acid solution/inorganic polymers, e.g. zircon phosphate. Nafion causes problems such as 'crossover' in DMFCs. A number of researchers are therefore experimenting with ceramic (inorganic) membranes.
AFC	Alkaline solution e.g. potassium hydroxide (KOH) or sodium hydroxide.
PAFC	Liquid phosphoric acid (100% concentration) within a silicon carbide matrix material.
MCFC	A hot and corrosive mixture of molten lithium, potassium or sodium carbonates. The alkali carbonates are usually retained in a ceramic matrix of lithium aluminate.
SOFC	Solid oxides e.g. zirconium oxide stabilized with rare earth elements such as yttrium. Takes the form of a ceramic.

Table VI
Operating temperature of different types of fuel cells (College of the Desert, Dec. 2001, pp. 4-23, 4-24, 4-28, 4-33)

Type of fuel cell	Operating temperature (degrees Centigrade)
PEMFC	50–125, typically 70 to 90— low temperature
DMFC	130, low temperature
AFC	50–220, low temperature
PAFC	100–220
MCFC	600–700, high temperature
SOFC	500–1 000, high temperature

Table VII
Efficiency of the major types of fuel cells

Type of fuel cell	Total efficiency (when used in combined heat and power systems)	(Electrical) Efficiency
PEMFC		35–45%
DMFC		40–50%
AFC		40–60%
PAFC		37–50%
MCFC	>70%, up to 80%	45–60%
SOFC	>70%, up to 80%	50–65%

programmes have the aim of improving these still further. This characteristic of fuel cells is very important. Fuel cells compete very favourably with other energy conversion devices in terms of efficiency.

Proton exchange membrane fuel cell (PEMFC)

It is not possible to discuss all the different fuel cells here in detail. Since the PEMFC is an important type of fuel cell and currently the dominant or fittest type of fuel cell (see Annexure A) for FCVs, it is discussed briefly. Alkaline fuel cells were used in a few FCVs in the 1950s to 1970s. DaimlerChrysler used a 3 kW DMFC in a go-cart in 2000. SOFCs may be used as auxiliary power units (delivering 5 to 6 kW) in heavy vehicles such as trucks. Some of the reasons why PEMFCs are used to propel fuel cell motor vehicles are given below:

- Low temperature of operation. High temperatures on motor vehicles are undesirable because of cooling requirements.
- Fast start-up. Low temperature fuel cells have faster start-up times than high temperature fuel cells.
- Relatively light. It has good power to mass characteristics – high power density. This is important in smaller vehicles where space is limited.
- PEMFCs respond immediately to varying loads.
- PEMFCs do not require temperature resistant and in some cases anti-corrosive materials as do high temperature fuel cells.

The PEMFC consists of a membrane electrode assembly and flow field plates (see Figure 1). Catalysts are usually incorporated in the membrane electrode assembly to speed up the chemical reaction and thereby increase the power density of the fuel cell. A platinum catalyst assists, for example, in 'stripping' electrons from hydrogen molecules. When hydrated, the membrane allows protons (or hydrogen ions) to pass through it, but not electrons. Electrons must move through the external load that is connected to the fuel cell.

The channels in the bipolar plate or flow plate ensure an adequate supply of hydrogen and air to the whole cell. Hydrogen is brought into contact with the anode, and air is brought into contact with the cathode.

Figures 2 and 3 show how individual fuel cells are connected in series to form a fuel cell stack. Like a (battery) cell, an individual fuel cell produces only a certain electrical potential (0.6 to 0.8 volts), current and output (tens or hundreds of watts, depending on size). Therefore a number of fuel cells have to be connected in series (usually) to provide enough power for a specific application such as an uninterruptible power supply or a vehicle. A combination of fuel cells connected in series and/or parallel is called a fuel cell stack.

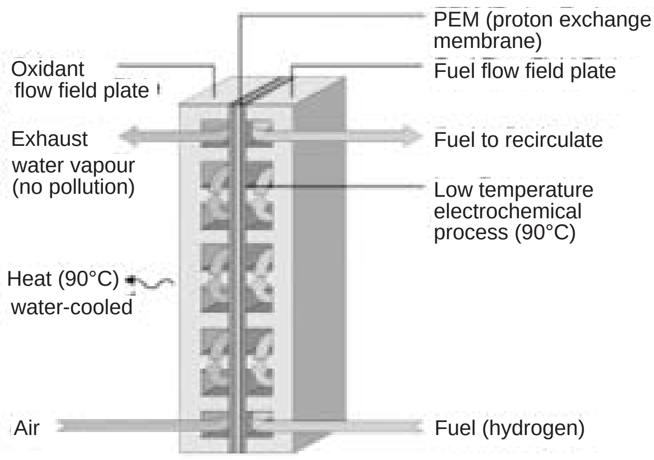


Figure 1. Proton exchange membrane fuel cell (PEMFC)

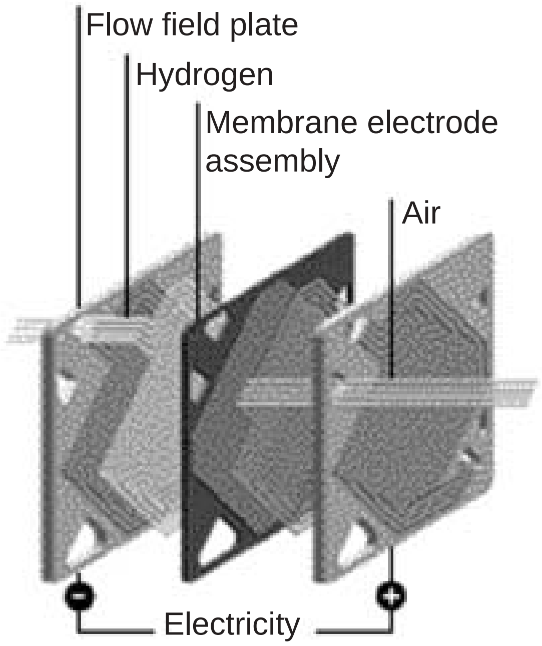


Figure 2. Flow of hydrogen and air through a PEMFC

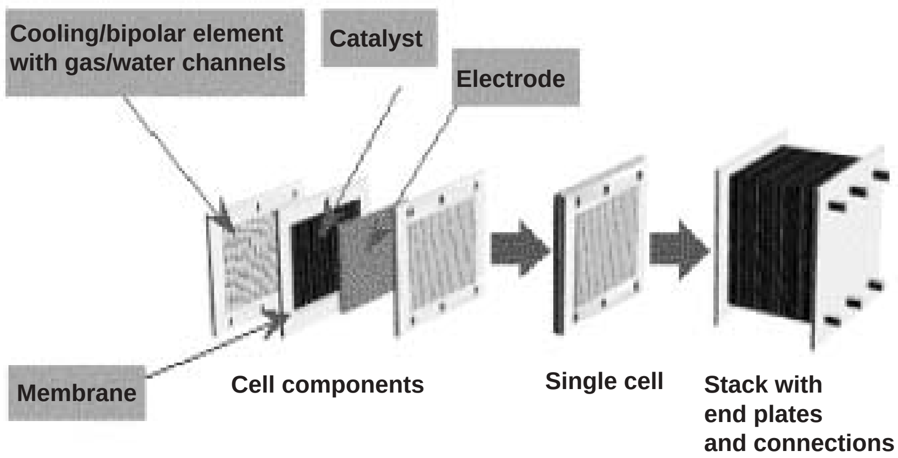


Figure 3. Construction of a fuel cell stack (Source: *Intelligent Energy*)

Fuel cell systems

In the previous section, the various building blocks of a fuel cell and fuel cell stack were discussed briefly. In this section the various systems and applications in which fuel cell stacks are integrated are discussed briefly. Unlike a single fuel cell, fuel cell systems (see Figure 4) may include moving parts. For example, hydrogen and air that enter the fuel cell may have to be compressed. Fuel cell systems therefore do include balance of plant or pheripheral components such as:

- pumps—to circulate fuel
- blowers or compressors—to circulate air
- power conditioning—e.g. 'DC/DC converter/voltage regulator' or 'DC to AC inverter'
- electric motors—to drive pumps, blowers and/or compressors
- fuel storage—hydrogen fuel can be stored, for example, as a liquid, compressed gas or in various types of metallic and chemical hydrides
- control valves, pressure regulators and controller
- cooling system or heat exchanger (CHP)—bigger fuel cell systems.

A fuel cell generates DC, just like a battery. A power converter is therefore required for 'DC to DC' or 'DC to AC' conversion. Low temperature fuel cells use pure hydrogen (see Table III) and a reformer is therefore required to produce hydrogen from various hydrogen carriers such as methanol and petrol if hydrogen is not available. Some of these reformers use PGMs (e.g. Pt and Ru) as catalysts. Another example of peripherals that use PGMs is the use of palladium in hydrogen detectors. Hydrogen detectors will be widely used in the hydrogen economy, not only on board vehicles but also in enclosed vehicle parking areas. It is difficult at present to forecast whether onboard hydrogen will be preferred to methanol or petrol as hydrogen carriers in the future (20–30+ years). Companies such as Toyota are investigating all the options (see Annexure A). Hydrogen carriers will probably be an important fuel for fuel cells until more hydrogen fuelling stations or electrolyzers (for the generation of hydrogen from water with electricity) are in place.

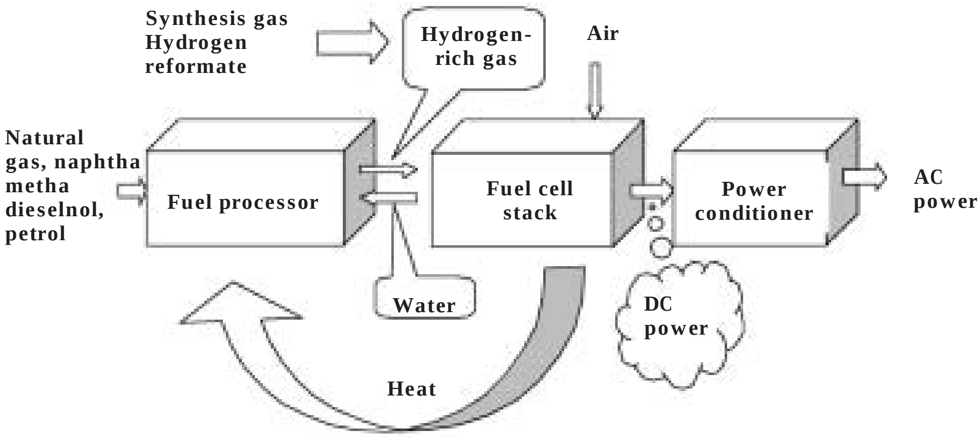


Figure 4. A fuel cell system

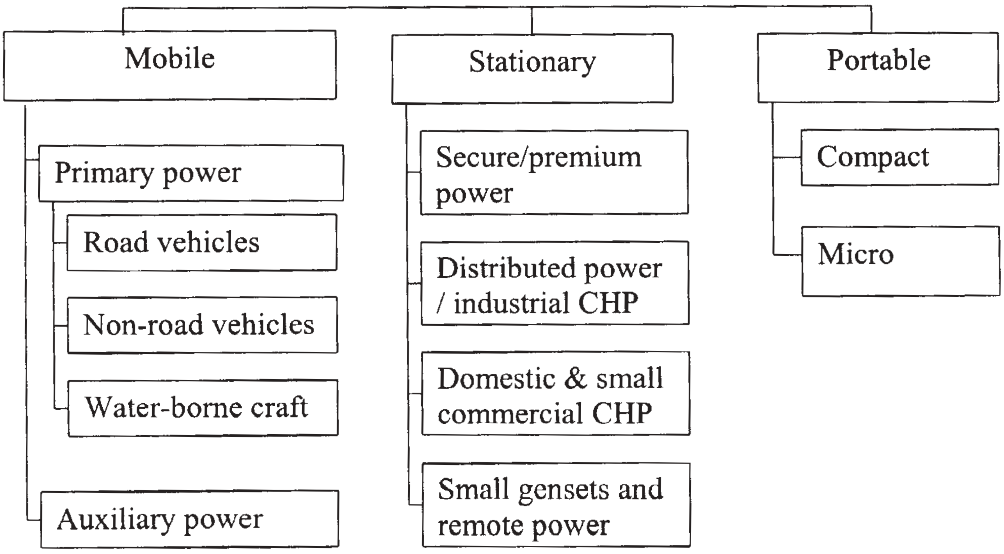


Figure 5. Fuel cell market segmentation

Fuel cell applications

There are a large number of fuel cell applications, as illustrated in Figures 5 to 12. Not all of these applications will have a major impact on future platinum demand. This is because low temperature fuel cells (where PGM catalysts are used) are not preferred for all applications. SOFCs may be preferred as auxiliary power units for vehicles, for example. Low power applications of low temperature fuel cells use much fewer PGMs than high power applications because of the direct relationship between fuel cell power and electrode area (see Table X). This is the reason why this study focuses on fuel cell vehicles since they use PEMFCs of 50 kW (unless battery vehicles with small fuel cells diffuse in large quantities) and more (see Annexure A).

Fuel cell (hybrid) vehicles

The fuel cell stack in a fuel cell car replaces the need for an internal combustion engine (ICE) as the primary power source in a car. The fuel cell stack has to be successfully integrated into a car's design for it to become a viable alternative. This means that control systems and other complementary technologies must be combined with fuel cells to make such a car technically possible. A fuel cell car has many technical advantages over traditional cars. Hydrogen FCVs are, for example, relatively simple (from at least a mechanical perspective) because they do not incorporate a complex ICE and gearbox.

Figure 6. Nissan X-trail

Figure 7. An underground mining fuel cell locomotive

Figure 8. A 109-ton diesel-electric locomotive fitted with a 1.2 MW fuel cell

Figure 9. A fuel cell submarine

Figure 10. A GPS powered by a DMFC

Figure 11. A laptop powered by a DMFC

Figure 12. A fuel cell powered bus

Most fuel cell systems are hybrids. Fuel cell driven laptop computers and uninterruptible power sources usually incorporate batteries. Many FCV prototypes are hybrid vehicles (see Annexure A). A hybrid vehicle has two power sources, both of which are utilized to propel the vehicle. (A vehicle that uses a battery or fuel cell as auxiliary power source to power lights, radio, etc. is therefore not defined as a hybrid vehicle.) The utilization of two power sources instead of one may have a number of advantages, depending on the size and type of power sources used.

Battery/ICE-driven vehicles are fitter (more fuel efficient and more environmentally friendly) than traditional internal combustion engine vehicles (ICEVs). A hybrid vehicle where an ICE or fuel cell is the primary driver can also allow for the optimum operation of the ICE or fuel cell by combining it with an energy storage device such as a battery. The use of slightly smaller ICEs or fuel cells without a drop in performance may be the result. The hybrid vehicle is an example of architectural innovation. Various power source permutations inside a hybrid vehicle are technically possible. A few such power source permutations are as follows:

A—fuel cell and battery
B—fuel cell and ultra capacitors
C—battery and internal combustion engine
D—ICE and ultra capacitors.

Hybrid vehicles with just electric power sources (options A and B) are less complex compared to ICE-hybrid vehicles (options C and D). Regenerative braking is often incorporated as a 'third power source' in hybrid vehicles. A number of vehicle optimizing technologies such as regenerative breaking, brake-by-wire and drive-by-wire (a technology that has been perfected for use in aircraft) can easily be incorporated in all-electric vehicles (options A and B). Electric vehicles can also better support the increasing non-propulsion energy requirements of vehicles (navigation systems, onboard communications, computer-controlled assisted active suspension, side and rear-view bumper cameras, electronic tyre pressure control, etc.) which have already prompted the development of a 42V standard for vehicle auxiliaries. FCVs are well suited to provide remote and back-up electrical power (Lipman, 2003, p. 1322). Fuel cell/battery vehicles (option A) can be divided into two categories. The first category includes vehicles where the fuel cell is the dominant energy source, and the battery is the dominant energy source for the second category of vehicles. Most of the current FCVs fall into the first category. The fuel cells of category 2 vehicles may be too small to recharge the battery over long driving distances and these vehicles may have to be plugged in for the recharging of their batteries. Category 1 vehicles are bigger PGM users due to the size of the fuel cell. Category 2 fuel cell/battery vehicles where small fuel cells are used to extend the range of essentially battery vehicles contain lower platinum loadings per vehicle kW capacity.

Hydrogen FCVs are less complex than FCVs that use fuels such as methanol and petrol. Petrol and methanol FCVs include a reformer, the function of which is to generate hydrogen from the petrol or methanol. Various PGMs are used in such reformers. Reformers complicate and increase the cost of FCVs and are therefore not popular amongst a number of car manufacturers. A huge challenge in commercializing hydrogen fuel cell cars is that of storing hydrogen on board such cars and in providing the necessary fuel supply infrastructure.

The platinum loading of various types of fuel cells and fuel cell applications

In the first section, the research problem is described and the desired outcome is to obtain the values to complete Table I. The values of the last column of Table I 'Total platinum used in FCVs (tons)' can be calculated once the values of columns III and IV ('Average platinum loading per kW of vehicle capacity (g/kW)') are known. The focus in this section is therefore on the platinum and other PGM loading of various fuel cell applications and accessories. The decision to focus on FCVs as the major potential driver of future platinum demand is also explained.

Current fuel cell motor cars use about 70 to 200 g of platinum, depending on whether fuel is reformed on board or not, and will only reach the 15 ± 5 g goal (Bringman, 21 Sept. 2002) after a period of further research and development. See Table VIII. The PGM loading of FCVs is therefore currently significantly higher than that of ICEVs.

Table VIII
The Pt and other PGM loading of a 70 kW PEMFC vehicle where methanol is onboard steam reformed to hydrogen (Bringman, 21 Sept. 2002)

Vehicle component	PGM type	Loading (2002 to future)
PEMFC	Pt	1.5 to < 013 g/kW
Catalytic converter	Pt	0.2 to < 0.07 g/kW
H_2 membrane	Pd	0.6 to < 0.17 g/kW
Total (for 70 kW vehicle with onboard reforming)	PGMs	161 to < 26 g
Total (for 70 kW H_2 FCV)	Pt	105 to < 9.1 g

Table IX
The Pt and other PGM loading of various types of vehicles

Type of vehicle	PGM loading (per vehicle)
Traditional ICEV	< 4 g Pt (Bringman, 21 Sept. 2002)
Hybrid ICE/battery vehicle	Probably less than for traditional ICEV
Hydrogen ICEV	Probably less than for traditional ICEV
Diesel vehicles	3 – 5 grammes of Pt and Pd combined – latest technology by Umicore (Michotte, 16 April 2004) 5 g – 'Stricter environmental rules in Europe have increased the amount of Pt in diesel engines from 3 g to 5 g' (Humble, 11 Mar. 2004, p.1)
Hydrogen FCV (Category 1)	~10 g by, say, 2030 (See Table VIII and Figure 17)
Methanol-driven FCV	~20 g by, say, 2030 (See Table VIII and Figure 17)

A number of factors will impact on the PGM loading of fuel cell vehicles. These factors are as follows:

- 'Fuel cell engine' capacity. The bigger the engine, the bigger the surface area of the fuel cell stack and therefore the amount of PGMs used. An average fuel cell capacity of 70 kW per vehicle is often assumed. From Annexure A an average of about 80 kW was obtained for 2002. However, this may not reflect the average fuel cell size for motor cars or the average for vehicles since a number of heavy vehicles (e.g. sport utility vehicles – SUVs) are included in this Table in Annexure A
- The state of fuel cell technology. The platinum loading of PEMFCs has been reduced significantly over the last number of years. The aim of a number of research programmes is to reduce it further. See Table VIII and Figure 17
- Hydrogen FCVs use fewer PGMs than PEMFC-driven vehicles with onboard reforming of methanol or other fuels. See Table IX.

Various fuel cell applications were briefly discussed earlier. Some fuel cell applications will use no or very few PGMs because high temperature fuel cells are used or because power requirements are low. The PGM requirements of various types of fuel cells are listed in Table X and examples of the power requirements of different fuel cell applications are listed in Table X.

A 12 W fuel cell hybrid laptop computer (powered by both a battery and DMFC fuel cell) will use a fraction of the amount of platinum of that of a 50 kW or 70 kW PEMFC motor car, for example. It is for this reason that the emphasis of this study is restricted to the one fuel cell application that has the potential to really impact dramatically on future platinum demand, the PEMFC vehicle.

In addition to the factors already mentioned, the amount of PGMs (PGM loading) used in autocatalysts, fuel cells and reformers depends on additional factors such as:

- the effectiveness of a specific PGM as a catalyst and its price relative to another catalysts (less Pt is used per autocatalyst compared to Pd)
- the required chemical reaction time or power density.

PGMs may also be used in hydrides that are able to store hydrogen. For example, Mazda has developed a palladium/magnesium alloy hydride (*Refocus*, 2003, p.12). Various hydrides compete with one another and it is difficult to predict which will be used in the future. It is also unlikely that hydrides will be used in mass applications such as to store hydrogen on board motor cars. Hydrides may, however, be used in niche applications such as storing hydrogen for use in underground mine equipment.

This section provided an overview of fuel cell technology and vehicles. This last part addressed a small area of the research problem described earlier – the PGM connection. The rest of the paper addresses the rest of the research problem, the diffusion of FCVs.

The fuel cell innovation life cycle

The fuel cell innovation life cycle puts the different phases of the process of innovation into perspective. Although the innovation life cycle models illustrated in Figure 13 and Table XII are simplistic and seemingly linear in nature, they assist, for example, in the understanding of why FCVs have not yet been commercialized in huge numbers.

Table X
Anode materials and catalysts used in the major fuel cell types + Pt loading

Type of fuel cell	Catalyst loading
PEMFC	Platinum; < 0.2 mg/cm² (Larminie and Dicks, 2003, p.68) Pt (2003): ~1 g per kW (Steel, Sept. 2003) Pt (1993): 2.0 g/kW (Chalk, Sept. 2003, p.1) Pt: 0.2 g/kW – target for FCV performance in 2010 (Black, Sept. 2003, p.4) PGMs (2003): 0.05 mg/cm² – Researchers at the German National Aerospace Research Center – DLR (*Refocus,* p.12) See Figure 17
DMFC	Pt and Ru; 2 mg/cm² or more (Larminie, 2003, p.148)
AFC	Anode catalyst: Ni, Pt, Pd Cathode catalyst: NiO, Au, Pt, Ag (Larminie, 2000, p.118)
PAFC	Pt (mid 1960s): 9 mg/cm² for both the anode and cathode (Larminie, 2003, p.178) Pt (2003): 0.1 mg/cm² for anode and 0.5 mg/cm² for cathode (Larminie, 2003, p.178; http://www.annso.freesurf.fr/PAFC.html)
MCFC	Ni-Cr/Ni-Al alloy (Larminie, 2003, p.193); Nickel – used for internal reforming of light hydrocarbons
SOFC	Nickel and Zirconia (Larminie, 2003, p.210)

Table XI
FC applications and power capacity

FC application (type of fuel cell)	Capacity
Fuel cell hybrid laptop computer – DMFC	12–30 W
Wireless headsets, MP3 music player – DMFC	100 mW
Auxiliary power unit – PEMFC or SOFC	5 to 6 kW
Stationary power units – PAFC	200 kW on average

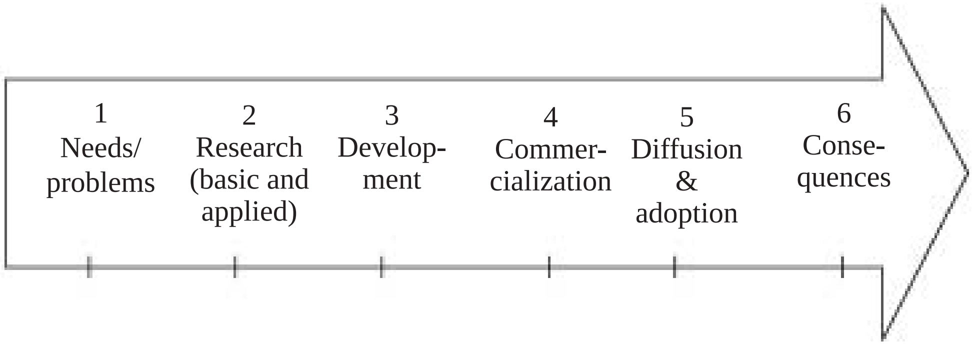


Figure 13. Six main phases in the innovation-development process (Rogers, 1995, p.133)

Table XII
The fuel cell and fuel cell vehicle innovation life cycle

Innovation life cycle phases	Comments on each phase
Basic research	The discovery of the fuel cell principle by William Grove in 1839
Applied research	More than 5 000 patents had been filed globally by 2003. The USA and Japan are the leaders in terms of the number of patents filed worldwide. Germany leads in Europe with more than 400 patents and the UK is far behind Germany with about 80 patents. Research is continuing to address the many obstacles in the path of successful commercialization and diffusion of fuel cell innovation. The development of better and cheaper membranes and fuel cells that use less platinum serve as examples.
Product ideas	Examples of fuel cell applications: • Application of fuel cells in automobiles • Distributed power sources • Replacement of batteries as main power source in laptop computers
Demonstration	A great number of FCV demonstration projects are in place. DaimlerChrysler is in its fifth generation of FCVs (see Annexure A), for example, and has plans to increase its number of demonstration FCVs to 60.
Marketing and promotion	The promotion of products in which fuel cells are embedded. FCVs are not yet produced for commercial purposes.
Diffusion	The (mass) diffusion or adoption of FCVs has yet to start.

A number of activities take place during each of the phases of the innovation life cycle. Certain criteria must be met before an innovation will move from one phase to another. Some of these criteria may differ from one type of innovation to another, while others are generic. Some of the criteria that a radical innovation will have to meet will be different from those that apply to an incremental innovation. Fuel cell technology and FCVs are examples of radical innovations. This is because fuel cells may compete in various applications with other incumbent energy conversion devices such as batteries and diesel generators. FCVs (where the fuel cell is the major power source) compete with battery-powered electric vehicles, spark ignition (SI) and compression ignition (CI) internal combustion engine vehicles as well as a number of hybrid vehicles.

From the ‘diffusion of innovation’ body of knowledge it is known that the diffusion of innovation is related to the attributes of the innovation itself as well as to external (environmental) factors. Technologies that diffuse well have a high level of ‘fitness’. For a new technology to survive, it has to be fitter than incumbent technologies that it attempts to replace or fill a niche that is not yet occupied by an existing technology. New technologies with a lot of potential can, however, also be kept alive by means of government support until such time that they have become fitter and competitive as a result of further R&D. Once a new technology is adopted in the market-place, incremental innovation or evolution continues and it usually becomes even fitter. The continuous improvement of the innovation usually results in the acceleration of the diffusion process. This is one of the reasons why incumbent technologies can cause lock-in. The continuous improvement of a technology is, however, subject to physical, economic and other limitations. Since SI and CI combustion engines were invented, they have undergone considerable refinement and have become technically fitter (competitive) over the years. From a sustainability perspective it can, however, be argued that diesel and petrol engines have become less fit (and will eventually ‘die’) due to, for example, oil resources that are depleted at a very fast rate. Due to increasing concentrations of such vehicles in cities and the increase in global vehicle numbers, the problem of vehicle-related pollution and global warming has not been solved either. FCVs still receive a small part of the total R&D spending in the automotive industry and have the ability to become a lot fitter still.

The characteristics of an innovation that influence fitness and successful diffusion are:

- relative advantage
- compatibility
- complexity
- trialability
- observability.

These characteristics are the prerequisites that an innovation must meet before it is commercialized (phase 4 in Figure 13). Companies usually make sure that these issues are properly addressed before releasing a new product in the market. It is for this reason that the assumption can be made that FCVs will only be mass-produced when they meet these prerequisites. FCVs have a great relative advantage compared to traditional ICE-driven vehicles from an efficiency and environmental point of view. This relative advantage is, however, less when FCVs are compared to hybrid battery and ICEVs. In other words, hybrid battery and ICEVs are fitter than traditional combustion engine vehicles from efficiency and environmentally friendliness perspectives but less fit from a complexity perspective. Battery/ICE hybrid vehicles also have the advantage that they are compatible with existing fuel distribution networks (e.g. petrol/gasoline and diesel refueling stations). Hydrogen FCVs are not. It is therefore necessary to compare the fitness of transportation systems with one another. The fitness of FCVs is discussed in further detail later.

Each type of fuel cell application may have different commercialization time-scales. NEC plans to start selling their notebook with a built-in fuel cell by the end of 2004 (NEC website, 17 Sept. 2003), while the commercialization of FCVs is expected to take off only from about 2010. There are considerably fewer obstacles in commercializing small fuel cells that serve as battery replacers, for example, than in commercializing FCVs. The dynamics of each fuel cell application is unique. Supplying small, low-watt fuel cells with fuel is a much smaller problem compared to implementing a new fuel (e.g. hydrogen) distribution infrastructure for FCVs.

The assumption is made in this study that the diffusion of FCVs will only take off when it can compete with other vehicles. This point in time is the starting point of the fuel cell diffusion process. FCVs are still in the development and demonstration phases of the fuel cell innovation life cycle (see Figure 13 and Table XII). It is therefore not possible to forecast future sales by extrapolating existing market trends–historical sales figures do not exist. Another approach is therefore required. Various technology forecasting and diffusion forecasting techniques are proposed. It is also important to understand the nature of FCV innovation and the variables that need to be forecasted.

DaimlerChrysler divided its FCV commercialization strategy into 4 steps (see Table XIII). This provides a rough time line and an idea of when FCV diffusion may start.

In the next section the focus is on the diffusion phase of the FCV innovation cycle.

Diffusion of (fuel cell vehicle) innovation

Diffusion is one of the most important phenomena in the universe. It is a common denominator amongst a number of subject areas and research problems. ‘Diffuse’ means ‘propagation’, ‘to spread’, ‘to scatter’, ‘to disseminate’ and ‘to disperse’. The word ‘diffuse’ is used in many contexts. It is used in a physical context to describe the diffusion of gas in the air or a dye in a liquid. It is also used to describe the spreading of intangibles such as knowledge, information or culture through society. It is also used to describe the patterns that are observed when new products are first released into the market and adopted over time by consumers. The subject ‘diffusion of innovations’ describes how new technologies spread through a population of potential adopters. The primary objectives of diffusion research are to understand and predict the rate of diffusion of an innovation and the pattern of that diffusion (Hargadon, pp. 3-20 and 3-21). It makes sense to study various characteristics and dynamics of the innovation (in this case fuel cells and FCVs) before developing quantitative models to describe it.

The word ‘diffusion’ is used in the physical and social sciences. Although the movement of matter (e.g. particles) can be described and predicted by the laws of nature, it is sometimes useful to rather study the properties of matter that emerge as a result of the many interactions that take place at micro level. Temperature, pressure and the spatial diffusion of matter are examples of properties that emerge from the characteristics and interaction of matter at micro level. The diffusion of culture, knowledge and information through society falls in the domain of the social sciences where no laws exist that can be used to predict the outcome of the interaction between the various actors and agents that are involved. History has shown, however, that certain diffusion patterns may emerge, as shown in Figure 14.

An innovation could be an object or product such as an FCV, a practice, a new technique or an idea. The diffusion of FCVs is network-dependent in a similar way that the diffusion of cellular phones depends on the diffusion of the cellular network (consisting of base stations, software, etc.). A person in an area with no cellular phone reception is unlikely to buy a cellular phone. The diffusion of the FCV therefore depends on the co-diffusion of hydrogen or hydrogen-carrier (fuel from which hydrogen can be obtained for a low-temperature fuel cell, e.g. PEMFC) generation capacity and distribution infrastructure. This study is therefore not only about the diffusion of a specific type of vehicle, the fuel cell vehicle, but about the diffusion of various transportation systems. A transportation system (for the purpose of this study) consists of vehicle technology, vehicle architecture, fuels and fuel distribution and generation infrastructure. From Annexure A, it is clear that methanol remains a favourite fuel because of its low infrastructure costs. The diffusion of hydrogen networks is discussed. Fuel choice depends on the availability and characteristics of different types of fuels as well as the

Table XIII
Steps in DaimlerChrysler’s fuel cell vehicle commercialization strategy (–ABI, Feb. 2004, p. 30)

Step	Time line	No. of vehicles involved
Step 1 – Market preparation phase	Up to 2003	See Annexure A
Step 2 – Fit for daily use	2004–2007	Plans to place 100 more FCVs on roads in the US, Europe and Asia
Step 3 – Ramp up	2008–2009	-
Step 4 – Full commercialization	~2010 -	? – purpose of this study

fuel's ability to address environmental concerns, the energy security problem and sustainability. The fitness of a transportation system depends not only on the fitness of one component of the system, but all its components as well as the impact of the transportation system on the environment.

A system in which innovation diffuses consists of the following elements (this applies to all systems in which innovation diffuses but includes examples that are relevant to the diffusion of fuel cells and FCVs):

- *Actors* that are responsible for the diffusion of ideas, techniques, products and/or services, but also actors that finance fuel cell RD&D and that are responsible for policies. In addition to the private sector, the governments of countries such as Canada, the US, Japan and Germany are active in supporting the development of the emerging fuel cell industry
- Various *driving forces* that drive the diffusion process. There may be the traditional (economic) drivers of demand, such as price, substitutes and income of households, as well as other driving forces such as sustainable development or, more specifically, sustainable transportation, energy security (strategic driver) and environmental concerns
- *Stumbling blocks* or *constraints* such as lacking or inadequate infrastructure (e.g. hydrogen generation and distribution infrastructure) for hydrogen fuel cells and hydrogen FCVs
- *Status* of the innovation – questions such as 'how ready or fit is the innovation for commercialization or diffusion?' need to be answered.
- *Enablers* and *goals*. Enablers such as regulations and standards need to be put in place. A lot of work is currently being done in this area (Piepereit, Sept. 2003). It is one of the focus areas of the International Partnership for a Hydrogen Economy, for example. Good progress is being made with other enablers such as RD&D spending, national fuel cell and hydrogen strategies and road-maps. For example, the US and Japanese governments invested $220 m and $210 m, respectively, in 2002 (Todd, Sept. 2003, p. 1). See Table XVIII for goals of the US FreedomCAR programme.

Many 'peripheral' and/or 'qualitative' indicators point to fuel cell and FCV diffusion. The number of patents that have been registered to date and the size of fuel cell and fuel cell vehicle R&D points to the effort that is involved to improve the technology so that it can compete better with substitute technologies (e.g. ICE). Most indicators provide a qualitative indication only of how fuel cell technology is improving and how soon FCVs will be mass-produced. (The start of mass production is the start of FCV diffusion for the purpose of this study.)

A number of factors contribute towards the diffusion of technology. Technologies that are superior from one point of view, e.g. quality, do not necessarily become the standard. Good examples of superior technologies that did not become industry standards are:

- video machines: Beta vs. VHS – VHS became the standard
- computer keyboard layouts: Dvorak vs. QWERTY – the QWERTY keyboard layout became the standard due to lock-in.

Many examples from the past show that the 'diffusion of an innovation' is a complex process. It may therefore be difficult to predict which innovations will gain widespread acceptance. Three groups of factors that influence the pattern and rate of product diffusion are:

- characteristics of the innovation/product
- characteristics of the adopters
- characteristics of the social environment.

Hydrogen-powered FCVs have a number of stumbling blocks to overcome. Hydrogen production and distribution networks are extremely small compared to existing petrol (gasoline) and diesel distribution networks. Fuel cell technology is a radical innovation and so is hydrogen as a fuel compared to petrol. This will complicate and even slow the diffusion process unless commitment and political will are very strong. A study by Grübler and others (1999, p. 247) has found that 'technologies that are long-lived and are components of interlocking networks typically require the longest time to diffuse and co-evolve with other technologies in the network; such networks effects yield high barriers to entry even for superior competitors' This is certainly the case for FCVs as well as hydrogen generation and distribution. Figure 14 gives an idea of how long it took in the past for infrastructure to diffuse. (Note the S-shaped pattern.) This could give an indication of how long it may take for a hydrogen infrastructure to get in place.

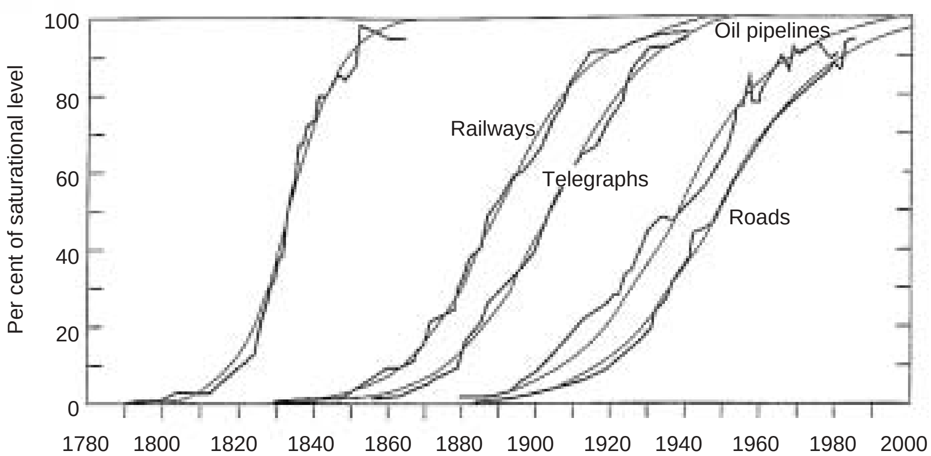


Figure 14. Evolution of infrastructure in the US (Grübler *et al.*, 1999, p. 254)

Revolutionary changes such as fuel cell technology usually take long to diffuse. Grübler (1999, p. 263) describes it as follows: 'A future hydrogen-powered economy will require not only new end use technologies (e.g. fuel cells) but also infrastructures (e.g. hydrogen pipelines) and interdependent technologies (e.g. upstream hydrogen production methods). Individually some of these elements may be able to diffuse rapidly–for example, today there is substantial production of hydrogen for use in refineries–but the system as a whole can emerge only at the pace of the necessary infrastructure, i.e. over a time span of several decades. Indeed, the historical record shows that the largest technological systems diffuse with long time constants (6 to 8 decades).'

The assumption is made in this study that the diffusion of FCVs will only take off when all the stumbling blocks are adequately addressed and when FCVs can compete with other vehicles. It is therefore important to get a feel for how fit fuel cells and their various supporting fuels and fuelling infrastructures are.

The diffusion of FCVs will be influenced by many factors such as:

- its ability to replace the ICE technology – fitness (see section on 'fitness')
- environmental issues, e.g. environmental legislation, global warming, the signing of the Kyoto Protocol
- stumbling blocks such as the establishment of hydrogen distribution networks
- commitment of vehicle manufacturers
- availability of research funds
- the political will of governments to support the change to a hydrogen economy
- energy security concerns
- economics of FCVs and fuels
- limits of traditional fuel stocks and supply scenarios.

The diffusion of FCVs is different from that of most other products or technologies. This is because the diffusion of FCVs depends on the diffusion of an appropriate fuel generation and distribution infrastructure. To establish a widely dispersed hydrogen infrastructure will require huge capital investments and therefore the diffusion of FCVs will probably be much slower than that of cellular phones, whose diffusion also depends on the diffusion of an infrastructure (a network of base stations). Very few studies have been done on the co-diffusion of an innovation and its supporting infrastructure.

Technology and diffusion forecasting techniques

Some of the techniques that can be used to forecast how soon a specific aspect of a technology will be competitive (e.g. fuel cell power density, vehicle range and cost) is described in this section. Bright defines technology forecasting as a 'quantified prediction of the timing and character of the degree of change of technical parameters and attributes associated with the design, production and use of devices, materials and processes, according to a specified system of reasoning' (Van Rensburg and Bambrick, 1978, p. 273). A few technology forecasting techniques are given below (Twiss, 1992, pp. 105, 107):

- Expert judgement
- Delphi technique
- Trend extrapolation
- Normative forecasting
- Forecasting by monitoring
- Dynamic modelling
- Scenarios.

These techniques can be applied to the attributes of a technological device (e.g. fuel cell power density), the process associated with producing the technology (e.g. raw materials, energy consumption, waste materials, environmental effects), the operation of the technology (such as efficiency), and to related requirements such as skill requirements and training needs (Van Rensburg and Bambrick, 1978, p. 273). Before these technology forecasting techniques can be applied, it must be known what aspects or variables of FCVs need to be forecasted. These are usually the critical variables that will affect the performance of the technology and variables that are important to the customer. A brief description of various technology forecasting and cost forecasting techniques follows:

The *Delphi* forecasting technique uses expert opinion. Polling is based on conditions of anonymity, statistical display and feedback of reasoning, which differentiates it from techniques such as brainstorming (Van Rensburg & Bambrick, 1978; Twiss, 1992, p. 107). The opinions of experts on FCV diffusion are listed in Tables XIV and XV. An independent survey is therefore excluded from the scope of this research project.

The *trend extrapolation technique* is based on the premise that technical developments generally advance in a relatively orderly manner over time. It is generally assumed that technical data series produce S-curves (Van Rensburg and Bambrick, 1978, p. 275). This technique can, for example, be used to extrapolate FCV parameters that are important to customers. Some of those parameters may be vehicle range, platinum loading (impact on cost), efficiency, weight, fuel cell lifetime, power density and fuel storage. Parameters such as platinum loading may actually produce an inverted S-curve, depending on arithmetic scale selection. Figures 17, 22 and 23 show a few technology trends.

Normative forecasting is based on the premise that new technology emerges to meet needs or goals. An examination of future needs could therefore reveal major technology that is desirable and that will probably be developed in the future. There is currently, for example, the need for sustainable transportation. This will have to be developed before non-renewable resources such as oil and gas are depleted beyond the point where oil demand surpasses oil supply (Van Rensburg and Bambrick, 1978, p. 275). See Figure 28. Normative techniques can be regarded as both forecasting and planning. Morphological analysis, socio-technological planes, mission flow analysis and relevance trees are examples of normative forecasting techniques. Backcasting is another related technique.

Various types of *models* (e.g. mathematical) can be used in technology forecasting (Van Rensburg and Bambrick, 1978, p. 276). Equation 1 with the assumptions made to apply it is an example of a simple mathematical model.

Learning curve/experience curve–there is a body of knowledge that supports the notion that cost reduction occurs during the production process as volume is scaled up due to economies of scale and learning that takes place. The cost of manufacturer products tends to decline by 10 to 30% with each doubling of cumulative production volume. This logarithmic effect means that cost reductions are achieved rapidly early in a product's history when doublings occur relatively frequently and then slow down as the doublings take longer to achieve (Lipman, 2003, p. 1323). Learning curves can be used to forecast fuel cell and FCV manufacturing costs. Figure 21 shows a cost pattern.

A *scenario* is a narrative description of a consistent set of factors which define in a probabilistic sense alternative sets of future (business) conditions (Huss, 1988, p. 377). The role of scenario analysis is to overcome some of the drawbacks of extrapolative forecasts. Various scenarios about total global oil reserves have to be investigated. Some of the steps in intuitive logic scenario analysis, e.g. the identification of key environmental forces and analysis of such forces, can be utilized. See Huss (1988, p. 382) for more information on these. Other scenario analysis methods include trend-impact analysis and cross-impact analysis. One of the two energy scenarios that Shell has developed for 2050 centres around fuel cell advances (Lipman, 2003, p. 1326; Shell International, 2001).

Forecasting the diffusion of FCVs–quantitative models

An important part of this study is to try to understand the various drivers of FCV diffusion. This information provides the background and can also be used as input in forecasting models. History shows that the cumulative diffusion of innovation has an S-shaped pattern, like function *Q(t)* in Figure 16 (see also Figures 14, 15, 25 and 27.) This S-shaped pattern can be described mathematically by equations such as Equation [1]. Numerous diffusion of innovation cases show similar S-curve patterns. The assumption can therefore be made that the diffusion of fuel cells and FCVs will follow similar patterns. From this follows the next step, that Equation [1] can be used to forecast FCV diffusion. Once this assumption is made, then the challenge shifts to finding a number of possible points on this curve or boundaries within which this curve will have to fit. The rest is then a matter of curve-fitting.

$$N(t) = \frac{\overline{N}}{1 + \frac{\left(\overline{N} - N_o\right)}{N_o} e^\wedge\left[-b\overline{N}\left(t - t_o\right)\right]} \qquad [1]$$

where:

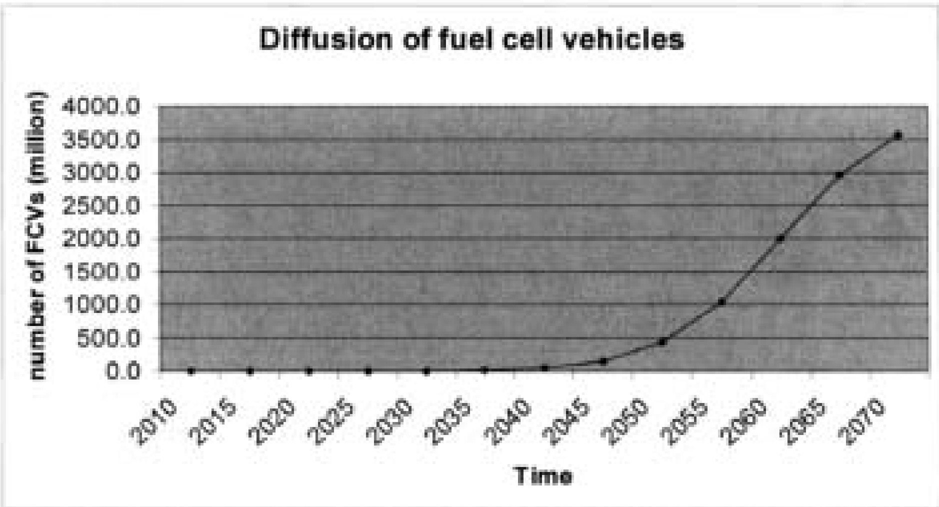
- N = total population (e.g. total number of FCVs or hydrogen fuelling stations of hydrogen pipeline in the world; N could also be expressed as a ratio or percentage)
- $N(t = t_0) = N_0$ = number of units (e.g. FCVs) adopted at the beginning of the process.

If the following assumptions are made (for illustrative purposes):

- that there will be 4 billion vehicles (models may exist or can be developed to forecast this value) in the world by 2110 and that the majority will be FCVs,
- that, from Tables XIV and XV, the diffusion of FCVs will start in 2010, with N_0 = 100 000 FCVs,
- that it will take FCVs 50 years to achieve a market penetration of 50%, which was roughly the case for ICEVs, then.

Equation [1] can be simplified to become: $N(t)$ = 4 000/ (1 + 39 999 $e^{\{-0,211932(t-2010)\}}$, with $N(t)$ measured in millions. Figure 15 was drawn from the values generated from this simplistic mathematical model (Equation [1] + assumptions).

Since FCVs will be substituting petroleum-based ICEVs, there are a number of 'substituting' models that should be considered.



Year	No of FCVs	Year	No of FCVs	Year	No of FCVs	Year	No of FCVs	Year	No of FCVs
2010	0.1	2011	0.1	2012	0.2	2013	0.2	2014	0.2
2015	0.3	2016	0.4	2017	0.4	2018	0.5	2019	0.7
2020	0.8	2021	1.0	2022	1.3	2023	1.6	2024	1.9
2025	2.4	2026	3.0	2027	3.7	2028	4.5	2029	5.6
2030	6.9	2031	8.5	2032	10.6	2033	13.0	2034	16.1
2035	19.9	2036	24.6	2037	30.3	2038	37.4	2039	46.1
2040	56.9	2041	70.1	2042	86.3	2043	106.1	2044	130.3

Figure 15. Illustrative FCV diffusion S-shaped curve (cumulative FCV numbers, measured in millions) and selected values based on Equation [1] and listed assumptions

Various mathematical models can be constructed that will be more sensitive to the various drivers of FCV diffusion. In Figure 16, *P(t)* is for example a function that may limit the diffusion of FCVs due to potential platinum production and resource constraints. Worldwide platinum resources has been estimated by Cawthorn (1999, p. 488) at about 1.5 bn oz troy (about 46 600 ton's) to a mining depth of 2 km. This potential product and recycled platinum currently used in autocatalysts and of which more than 95% can be recovered, could provide enough platinum for hundreds of millions of FCVs. More than 80% of new vehicles sold worldwide are currently fitted with autocatalysts (Cowley, July 2000, p. 38). Marcus Nurdin (2000) from the Fuel Cell Council argued that the availability of platinum for fuel cells should not be a problem due to the relative long period that vehicle fleet substitution may take. Studies into the availability of platinum for fuel cell vehicles have also been done by Borgwardt (2001) and Tonn (2001). *G(t)* is an example of another function that 'translates' the crude oil gap in Figure 28 into the minimum number of alternative fuel vehicles that will have to be produced over time. The hydrogen FCV is a subset of the various alternative fuel vehicles that currently exist.

The diffusion starting point on Figure 16 reflects the readiness and fitness of FCV technology and how well it can compete with incumbent technologies such as ICEs. According to fuel cell innovation cycle theory and the diffusion of innovation body of knowledge, the diffusion starting point will be that point in time when FCVs can compete with ICE-driven vehicles. At the commercialization or diffusion starting point, FCVs will be commercially produced by at least one car manufacturer. At such a manufacturer, FCVs will be taken beyond the 'demonstration phase' of the FCV innovation life cycle. In practical terms it will probably mean that such a manufacturer can produce and sell the vehicles at breakeven cost. Probably 20 000 to 50 000 vehicles will have to be produced of a specific model. Expert opinions and the goals that have been set for various R&D programmes and some technology forecasts can be used to forecast this point.

The technique of backcasting can also be used to determine a 'normative' starting point – the time by which FCVs must appear on the market to ensure sustainable transportation in the future before oil reserves run out or CO_2 concentrations and air pollution reach unacceptable limits. Alternative fuel vehicle diffusion may be synchronized with petroleum depletion under the coordination of regional governments. A number of researchers are forecasting the peaking of global oil supply to take place between 2007 and 2011.

The percentage of future alternative fuel vehicles that will be FCVs will depend on the fitness or competitiveness of FCVs and different fuels or transportation systems. Other lower boundaries may also be determined by developing scenarios that are based on environmental legislation. The California Air Resources Board (CARB) developed a Zero Emission Vehicle (ZEV) diffusion forecast based on the legislative environment in California (see Figure 19).

Path-dependent techno-economic change also plays a major role in the evolution and diffusion of new products.

FCV and hydrogen infrastructure diffusion forecasts—expert opinions

The use of expert opinions in technology forecasting was briefly discussed earlier. A number of such opinions regarding fuel cells, FCVs and the hydrogen economy are listed in Table XIV.

A number of (quantitative) opinions regarding the starting of diffusion are listed in Table XV.

Figure 17 illustrates an FCV forecast by Johnson Matthey. The forecast is based on auto manufacturers' predictions, notably Ford, who stated that by 2025, some 25% of vehicles will be powered by fuel cells (Black, Sept. 2003, p.15). Johnson Matthey assumed in this forecast that the platinum loading per vehicle will fall substantially over the next number of years.

The information shown in Figure 18 is derived from the values shown in Figure 17. An average vehicle power output of 75 kW with a high (0.27 g of Pt per kW by 2025), medium (0.2 g of Pt per kW by 2025) and low (0.13 g Pt per kW by 2025) platinum loading per vehicle is assumed (Black, 2003, p.16). At present, the best platinum loading is about 0.86 g per kW, which equates to 64.5 g per (75 kW) vehicle. The Johnson Matthey scenario assumed hydrogen as fuel. If methanol or another hydrocarbon is used, a reformer will be necessary and this will require more platinum per vehicle. See Table IX.

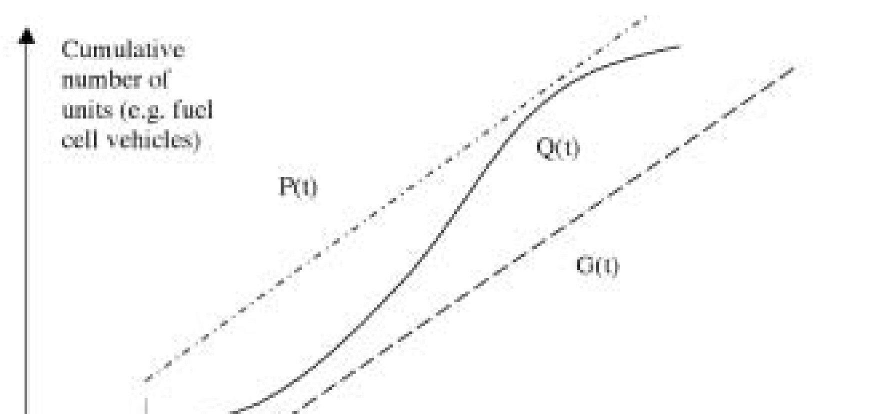


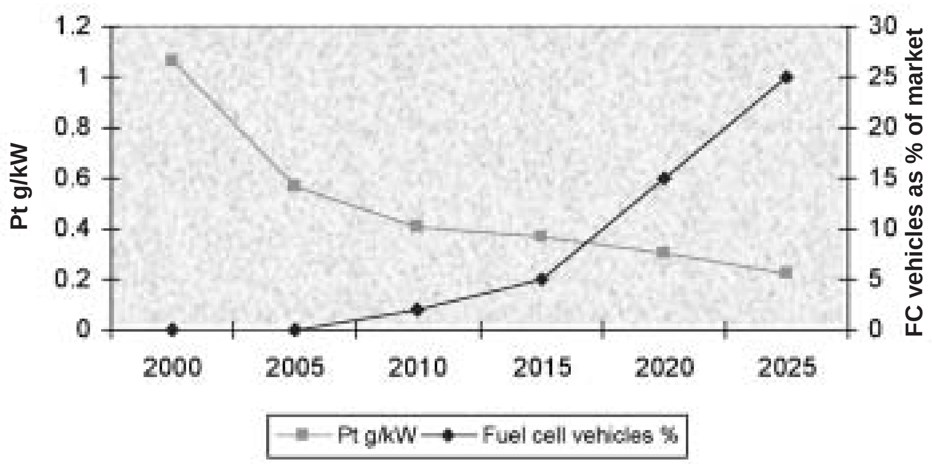
Figure 16. The FCV diffusion S-curve and constraints

Table XIV
A number of opinions on the potential and diffusion of fuel cells, FCVs and the hydrogen economy

Organization and person	Comments
CEA, French Atomic Energy Commission, Alain Bugat (Breakthrough Technologies Institute – BTI, Feb. 2004, p. 41)	'On hydrogen power, we've reached the point of no return. It will happen.'
DaimlerChrysler, Prof. Vöhringer, ex-President, DaimlerChrysler Research and Technology (Panik, 24 Sept. 2003, Slide 6)	'Only a few mega-trends exist that are of special importance to the future: Sustainable Mobility is one of them, and fuel cells are a key technology for it.'
DaimlerChrysler, (Buchholz, Oct. 2003, p. 31)	'Commercialisation stage is unlikely to begin before 2010.'
Ford, William C. Ford, Jr., Chairman of Ford (Panik, 24 Sept. 2003, Slide 6)	'I believe fuel cells could end the 100-year reign of the internal combustion engine.'
Ford, Daniel Kapp at 2003 SAE Conference (*CAR*, May 2003, p. 13)	He said that the petrol engine would continue to dominate for the next 30 years.
Ford (Cropper, 17 Dec. 2003, p. 6)	Ford aims to develop a commercially viable fuel cell car by 2012–15.
Ford (BTI, Feb. 2004, p. 41)	Fuel cell vehicles for mass public consumption are projected to be available by 2010.
General Motors, Byron McCormick (Panik, 24 Sept. 2003, Slide 6)	'Of all the technologies, the fuel cell car seems to be the most promising. It has a good chance of becoming the next mass-market car.'
General Motors (BTI, Feb. 2004, pp. 46, 49)	They think the US government's timetable for commercialization is unnecessarily cautious. They expect significant numbers of FCVs in customers' hands by the end of this decade. They have set the goal to sell the first one million FCVs at a profit. They are planning to establish high-volume FC production before 2010. They want to sell hundreds of thousands of FCs and FCVs by 2020.
General Motors, Larry Burns, Vice-President, Research, Development and Planning (Birch, April 2003, p. 105)	'We could get Hy-wire into production in four to five years if it went down the cost curve.' Burns did not indicate the likely time it would take to tackle that cost curve, but it is probably at least two to three years. Development time would then be added to that, taking the time frame to about 2010.
Honda, Hiroyuki Yoshina, Honda's President and CEO (Panik, 24 Sept. 2003, Slide 6)	'It's the most promising technology for future cars' power trains. Performance-wise, even today, they are better than conventional cars. The starting torque is very high and smoother.'
Honda, Ben Knight, Vice-President R&D America (*Automania*, 1 Sept 2003) Hydrogen Energy System Society of Japan, Prof. K. Ota, Chairperson (*Fuel Cell Today*, 19 June 2004)	'We believe that any societal gains from the technology [fuel cell vehicles] are more than a decade away. … Hydrogen power represents the greatest potential for the removal of the automobile from the environmental equation.' He says that Japan's target of introducing 50 000 FCVs by 2010 looks very difficult to achieve at present.
Mazda (BTI, Feb. 2004, p. 66)	Wants to be the world's leader in commercially produced fuel cell-powered components for vehicles.
PSA Peugot Citroën (BTI, Feb. 2004, pp. 74, 75)	PSA expects FCVs to be mass-marketed by 2015 and to be cost-competitive with conventional systems by that time. Peugot believes the first commercial FCVs will be electric hybrids with small fuel cells used as range extenders. Commercialization of this could take place between 2005 and 2010. After 2010, Peugot expects that 'fuel cells will be the main source of energy for vehicles' configuring using onboard reformers and syngas or ethanol.
Renault (ABI, Feb. 2004, p. 78)	Renault plans to have an FCV in production by 2010.
Roland Berger Strategy Consultants, Thomas Sedran, partner (Buchholz, Oct. 2003, p. 31)	'In a fuel-cell study we conducted two years ago, our estimated market volume for 2010 was around 100 000 vehicles in a best-case scenario.'
Romm, J.J. (Ziff, May 2004)	Romm argues that hydrogen would not make sense as a fuel source until at least 2035 because it will take several decades before technology allows for a way to generate hydrogen cheaply and cleanly.
Texaco, Peter Bijur, Chairman and CEO Texaco Inc. (Panik, 24 Sept. 2003, Slide 6)	'The days of the traditional oil company are numbered, in part because of emerging technologies such as fuel cells and countries with emerging economies that will exert more control of their natural resources.'
Toyota, (ABI, Feb. 2004, p. 84)	Senior officials of Toyota were very optimistic about fuel cells during the 1990s and at one point projected commercialization by 2003. Toyota is now saying that FCVs will not be commercial before 2010.
Toyota, Hiroyuki Watanabe, Senior Managing Director of Toyota (ABI, Feb. 2004, p. 18) (Yamaguchi, Aug. 2002, p. 42)	At a fuel cell seminar in Miami he said that no single technology would achieve the long-term energy efficiency and emission goals that must be achieved in the face of market expansion to remove vehicles from the pollution equation and open an era of truly sustainable mobility. Watanabe said that fuel cells hold the key, since they would allow fundamental redesign of vehicles, including the use of small, highly efficient wheel motors. '… it will be well into the 2010s when real production FC vehicles will appear.'
U.S. DOE (Chalk, Sept. 2003, p. 2) Mr Abraham, Secretary (Chalk, 24 May 2004, p. 12)	'The results of the R&D conducted by the two partnerships [FreedomCar and Hydrogen Fuel Initiatives] will enable an industry commercialization decision by 2015, and initial market penetration of fuel cell vehicles and hydrogen fueling stations by 2020.' IPHE Vision: '… consumers will have the practical option of purchasing a competitively priced hydrogen power vehicle, and be able to refuel it near their homes and places of work, by 2020.'
VW (ABI, Feb. 2004, p. 90)	'VW has openly promoted advanced diesel and gasoline engines as the appropriate response to energy security and environmental concerns … VW is unlikely to be a leader in commercializing fuel cell vehicles.'

Table XV
FCV diffusion forecasts by various organizations

Year	Total no. of new motor cars produced p.a.	Number of FCVs	Area, source, etc.
2003		43	California (BTI, Feb. 2004, p. 15)
		300	Light-duty FCVs worldwide (BTI, Feb. 2004, p. 17)
2005		1 000–5 000 200 000	JM (Stephenson, 2003, Slide 4) Annual, global, Frost & Sullivan (US Dept of Commerce – USDOC, 2002, p. 43)
2007		31 680	Cumulative – Global, PriceWaterhouseCoopers (PWC) (Black, Sept. 2003, p. 17)
2008		500	Fuel cell buses in China – assumption that 10% of buses in Beijing will be FC-driven (Feng, 2004, p.360)
2009		275 520 30 000–100 000	Cumulative – Global, PWC (Black, Sept. 2003, p. 17) Cumulative – Allied Business Intelligence
2010	73 m	10 000	Korea only; Hyundai (BTI, Feb. 2004, p. 63)
		100 000	ZEVs in California (CARB, 2001)
		140 000–240 000	Cumulative – Allied Business Intelligence
		10 000	UTC, (Black, Sept. 2003, p. 17)
		50 000	Cumulative – Japan only; Gov. of Japan (Fuel Cell Today, 19 June 2004)
		100 000	Cumulative global?, Roland Berger Strategy Consultants (Buchholz, Oct. 2003, p. 31)
		1–2 million	Cumulative, global (USDOC, Sept. 2002, p. 42)
		8 million	Annual, global? Arthur D. Little (USDOC, Sept. 2002, p. 42)
		608 000–1.2 m	Cumulative, USA, ABI (USDOC, Sept. 2002, p. 42)
2011		1 600 000	Cumulative – Global, PWC (Black, Sept. 2003, p. 17)
		1.5–2.4 m	Cumulative – Global, ABI (USDOC, Sept. 2002, p. 42)
		200 000-500 000	Cumulative – JM, (Stephenson, Sept. 2003, Slide 4)
2012		150 000	Cumulative, ZEVs in California, CARB, (Lipman, 2004, p. 104)
2015		250 000	Cumulative, ZEVs in California, CARB, (Lipman, 2004, p. 104)
2018		380 000	Cumulative – ZEVs in California, CARB, (Lipman, 2004, p. 104)
2020		1 000 000	E. Lovery, GM’s vice-president for energy and environment (Nauman, 24 Sept. 2003)
		5 000 000	Cumulative – Japan only; Gov. of Japan (*Fuel Cell Today*, 19 June 2004)
		10–30 million	Annual, global? Arthur D. Little (USDOC, Sept. 2002, p. 42)
2025			Shell’s scenario that half of all vehicle sales in OECD countries and one-quarter of all vehicle sales worldwide will be FCVs (Shell International, 2001)
2030		15 000 000	Cumulative – Japan only, 20% of 75 m, the 2004 automobile count (*Fuel Cell Today*, 12 May 2004)
		10–30 million	Cumulative, global (USDOC, Sept. 2002, p. 42)
2040	384.5 m	384.5 m	Annual, global, Frost & Sullivan (USDOC, 2002, p. 43)
2050			> 3.5 bn vehicles (cumulative) in the world (Chalk, 24 May 2004, p. 4)



Figur 17. Fuel cell Pt loading and FCV market penetration (Steel, Sept. 2003, Slide 15)

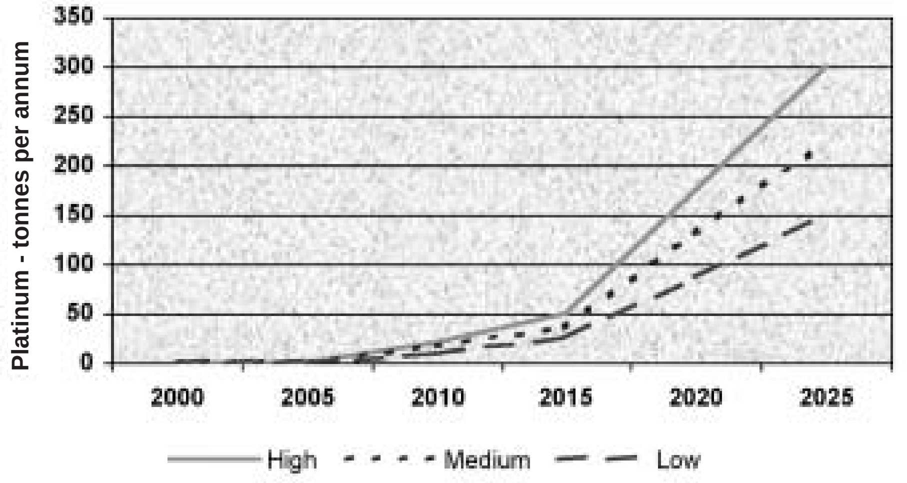


Figure 18. Forecasted platinum demand for FCVs (Steel, Sept. 2003, Slide 16)

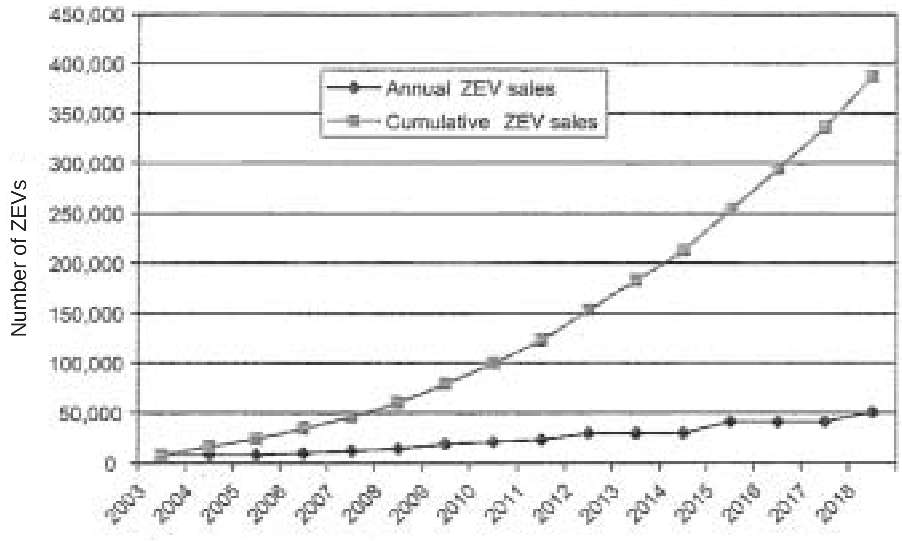


Figure 19. Annual and cumulative California ZEV sales forecast (example scenario) (California Air Resources Board, 2001; Lipman, *et al*. 2004, p. 104)

Fitness of various transportation systems: engines, vehicles and fuel

FCVs are competing against a variety of other types of vehicles such as electric (battery) vehicles, SI and CI internal combustion driven vehicles. Due to space restrictions it is not possible to evaluate all vehicle and fuel permutations here. It is quite possible that the ICE will show further fitness improvement in the future. Franz Pischinger, head of FEV Motorentechnik in Germany, said at the 2003 SAE Conference that measures such as direct injection, roller bearing crankshafts, reduced capacity with turbocharging, variable valve timing and cylinder deactivation could raise petrol engine efficiency to almost 40% (*CAR*, May 2003, p. 13). The development of successful camless ICEs will probably require much further R&D investment, may result in more complex engines and produce small increases in efficiency. In Table XVI a number of advantages of fuel cells in general are listed before the fitness of FCVs is described.

In Figure 20 relative efficiency of a PEMFC is measured on the vertical axis and 'per cent of peak power' is measured on the horizontal axis. It is clear from this graph that PEMFCs are very efficient at partial loads. This is a huge advantage in a number of applications such as when an FCV is used in city traffic. The fact that the PEMFC is more efficient at lower percentages of peak power means that it can also be successfully used in hybrid applications.

A number of techno-economic indicators can be used to determine how ready FCVs are for the next phase, the commercialization phase. These are price, life cycle cost, range and so on. A brief discussion of a number of such indicators follows:

Cost and price

The current high cost of concept FCVs (say about \$1 to \$5 million) can be attributed to a number of factors such as the current high price of fuel cell membranes (e.g. Nafion), the amount of platinum used as a catalyst (about 100 g currently) and the fact that they are not mass produced – there are no economies of scale. The lease charges of Toyota's FCHV SUV is about \$10 000 per month, while that of Honda's FCX is about \$6 700 per month including maintenance, service and support charges (Yamaguchi, March 2003, p. 55). The lease price of the Nissan X-TRAIL

Table XVI
Advantages of fuel cells in general

Characteristic	Description
Efficiency	Fuel cells are more efficient than ICEs. Fuel cells are very efficient because they produce power electrochemically rather than by means of a thermal cycle. Thermal machines are subject to the Carnot cycle limitation. The optimum ('Carnot') thermodynamic efficiency of a heat engine is given by the equation: $1 - T_2/T_1$ where T_1 = absolute temperature of inlet and T_2 = absolute temperature of the outlet. Furthermore, fuel cells are efficient in small and large sizes and at partial power output. See Figure 20.
High energy density	Weight for weight, fuel cells contain around 1 000 times the energy of a lead-acid battery and 200 times that of the latest lithium ion technology. Weizsäcker says that fuel 'is a better way to carry stored energy than electric batteries, which have less than 1 per cent as much useful energy per pound'. This is one of the important reasons why pure battery cars cannot compete against traditional vehicles or most alternative fuel vehicles.
Simplicity	Fuel cells have a small number of moving parts. Maintenance cost is therefore low.
Low emissions/ environmental friendliness	Fuel cells only emit water if pure hydrogen is used as a fuel. This is evident from Table III which shows the electrochemical reactions.
Very quiet	Fuel cells are very quiet—less than 60 dB at 30 m away.
Scalability/ modularity	Fuel cells are scalable. Manufacturing efficiencies can be achieved by replicating a small number of core fuel cell stack designs to meet a range of power demands.
Power quality	Modular fuel cell design mitigates against operations failure. The failure of a single cell or stack could only result in some loss of power rather than a complete shutdown. Fuel cells also exhibit good load-following characteristics.
Recoverability of waste heat	Waste heat can be used in the so-called CHP applications. This does not apply to applications of fuel cells in motor cars.
Fuel flexibility	Fuel flexibility can be obtained in low temperature fuel cell systems when a fuel reformer is incorporated. Direct internal reforming is a characteristic of high temperature fuel cells (e.g. MCFC).

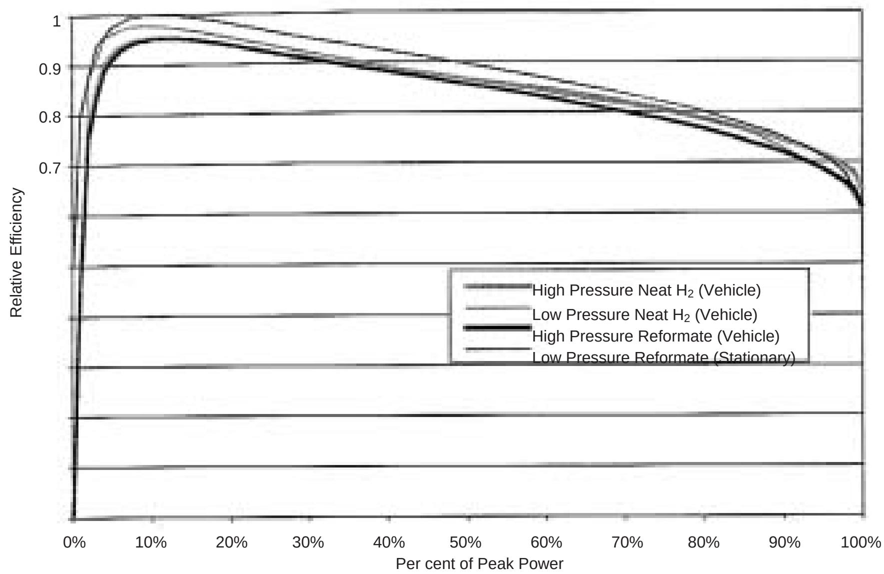


Figure 20. PEMFC system relative efficiency (Lipman *et al*., 2004, p.109)

FCV is 1 000 000 yen (~$10 000) per month. Dieter Seipler, President and Chief Executive Officer of Mann+Hummel GmbH, thinks that FCV production levels will have to reach three to four million units a year before profits will be generated (Buchholz, 2003, p. 30). Figure 21 illustrates, for example, how the cost of bipolar plates can be reduced as production volumes are increased.

Larry Burns, Vice-President of Research, Development and Planning at General Motors (GM), thinks that fuel cell technology may actually empower the auto industry to rethink the current business model which is heading for a profit squeeze. Excess capacity is pushing down prices while stricter regulations are resulting in higher costs. FCVs are simple from a mechanical perspective and offer many cost-saving possibilities in terms of transmission, drivetrain, radiator, and exhaust system. GM are within a factor of 10 of where they need to be on fuel cell costs. The use of onboard reformers for methanol or petrol has been rejected by GM partly because of costs (Birch, April 2003, pp.107, 108).

FCVs and other low-emission vehicles or zero-emission vehicles are subsidized in some parts of the world e.g. California. FCVs will, however, have to be able to compete with traditional ICE-driven vehicles and ICE/battery hybrid vehicles in terms of price before they will be adopted in large numbers. Various cost reduction strategies can be

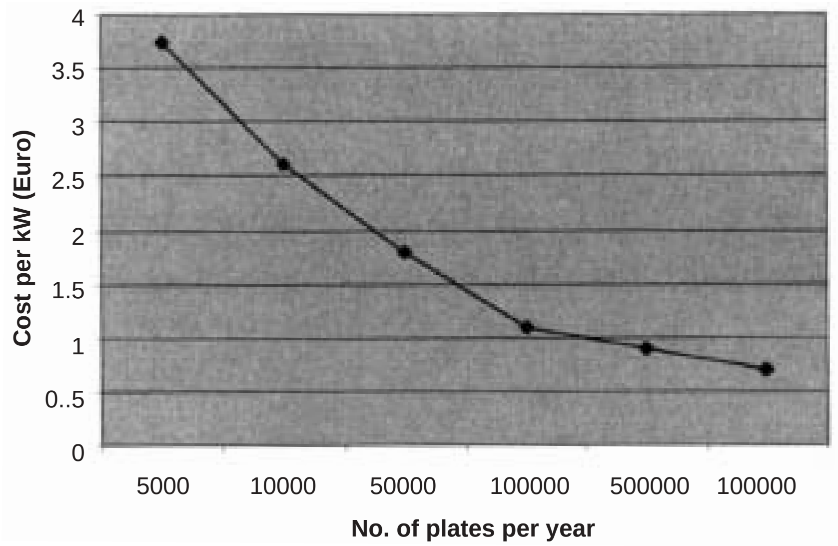


Figure 21. Cost vs. production rate for moulded bipolar plates for plate thickness of 2.5 mm, density of 1.6 g/cm², conductivity of 150 S/cm² and output of 1.4 kW/m2 (Heinzel, Sept. 2003, Slide 18)

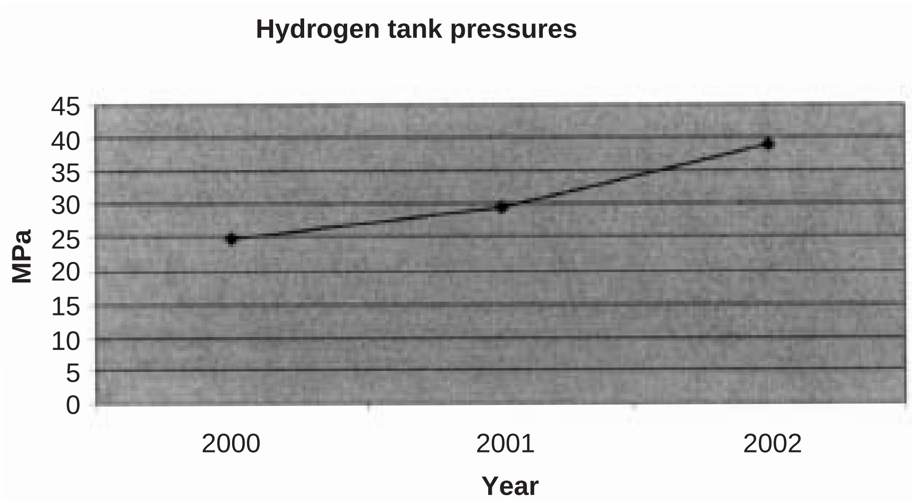


Figure 22. Average hydrogen tank pressures of FCVs listed in Annexure A

used to reduce the price of fuel cells. A few of these are mentioned below:

- Cheaper thermoplastics such as poly ether-ether ketone or ethylene styrene can, for example, be sulphonate (Black, Sept. 2003, p. 3)
- Reduce the amount of Pt per kW or cm² of fuel cell
- Recycle Pt and membranes
- Reduce processing costs
- Use thinner membranes
- Increased power density will result in less membrane, less gas diffusion media and less bipolar plate area per unit of energy (Grot, Sept. 2003, p. 1).

The cost of FCVs is reduced by focusing not only on the fuel cell but also on the fuel-storage system, traction system and electrical components (Birch, April 2003, p. 108).

Life cycle cost of vehicles

Not only the purchasing price but also the operating costs of a vehicle determine how well it can compete with substitutes. Hydrogen, which is one of the preferred fuels for FCVs, is more expensive than petrol or diesel (for the same energy content). The price of petrol and diesel will, however, increase in the future as more oil shocks such as those in 1973 and 1978 occur and definitely after world oil production has peaked. Oil security (e.g. US military spending to secure oil) and environmental costs are not currently truly reflected in the price of petrol and diesel. With the signing of the Kyoto Treaty (or from 2005 in Europe) the environmental cost of carbon-rich fuels will be reflected more strongly in market prices. The maintenance of FCVs may be lower than that of traditional vehicles. A number of issues therefore have to be considered before the life cycle costs of the two types of vehicles can be compared. It was found in a study by Ogden (2004, p. 7) and others that hydrogen fuel cell cars, at mass-produced numbers, have the lowest projected life cycle cost.

Range (km per tank of fuel)

The range of fuel cell cars that store hydrogen in a compressed form (see Annexure A) is less than conventional (ICE-driven) cars due to the bulkiness of hydrogen. This has to be improved. Considerable progress is being made at storing hydrogen at higher pressures. The next phase is for OEMs to utilize 70 MPa (700 bar/10 000 psi) storage tanks on board vehicles. General Motors is planning to increase the typical vehicle range to 480 km with the introduction of 700 bar compressed hydrogen tanks (Birch, April 2003, p. 105).

Storage space is less of a problem for buses. Hydrogen is usually stored in cylinders on the roof. Range is not as critical for vehicles such as taxis, public transportation and company vehicles (e.g. off-road mine vehicles) that operate within relatively short distances from refuelling stations. The best range that Honda can currently obtain in its latest fuel cell stack car is 395 km per tank (PowerPulse.Net, 21 Oct. 2003).

Low temperature operation

FCVs cannot operate at very low temperatures. The latest improvement by Honda is to get a vehicle fuel cell to operate at -20°C (PowerPulse.Net, 21 Oct. 2003). The target low temperature of -40°C may take several years still to achieve (Birch, April 2003, p. 108).

Acceleration

The acceleration of FCVs does not seem to be a problem. The torque of electric motors used in FCVs delivers satisfactory performance. Acceleration of the VW HyPower: 0–100 km/h in 12 s (Holt, July 2002, p. 29).

Refuelling time

It takes only 4 minutes to fill the compressed hydrogen tanks of the Honda FCX (*Automania*, 2003).

Start-up time

The Honda FCX takes about 10 seconds while a system check takes place (*Automania*, 2003). The start-up time of GM's Hy-wire is negligible in warm conditions but increases to 30 seconds at -20°C (Birch, April 2003, p. 108).

Power density

A fuel cell stack or system's power density is important for motor car applications since space is limited. PEMFC's power density has improved significantly over the last number of years as demonstrated in Table XVII and Figure 23. It can compete with the power density of the ICE.

Safety concerns

There may be perceptions that hydrogen on board vehicles may be more hazardous than petrol. Such perceptions will have to be addressed.

Overall performance of FCVs

'If no one mentioned that a hydrogen-operated fuel cell rather than gasoline was powering the FCX, most drivers would probably never imagine it was anything uncommon' (*Automania*, 2003).

One of the aims of the FreedomCAR programme that was announced by President Bush is to increase the fitness of FCVs. A number of the objectives of this programme are listed in Table XVIII.

The fitness of the ICEV and FCV is compared in Table XIX.

Table XVII
PEMFC power density over time

Year	Power density (watt per litre)	Remarks
1989	100 W/*l*	Ballard PEMFC stack (Lipman, 2003, p. 1320)
1996	1 100 W/*l*	Ballard PEMFC stack (Lipman, 2003, p. 1320)
2001	2 200 W/*l*	Ballard Mark 902 PEMFC stack (Lipman, 2003, p. 1320)
2001	1 600 W/*l*	GM's Stack 2000 used in its HydroGen1 and Chevy S-10 FCVs (Lipman, 2003, p. 1320)
2001	1 750 W/*l*	GM's 640 cell stack (Lipman, 2003, p. 1320)

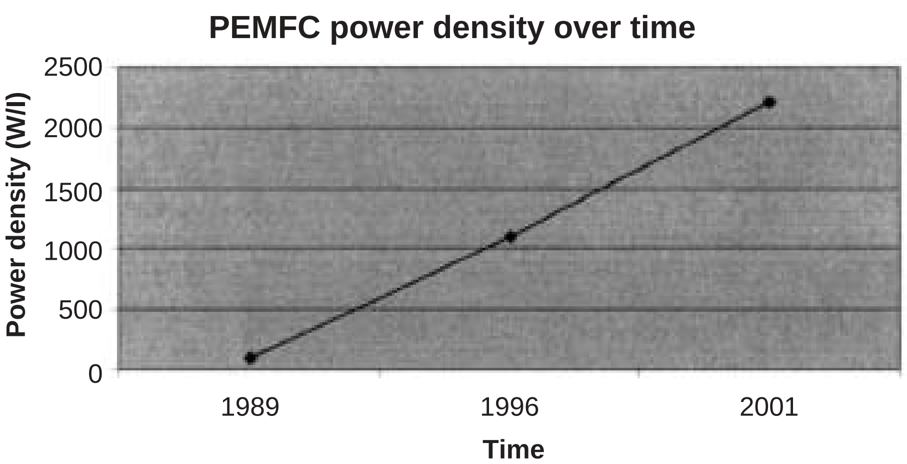


Figure 23. Ballard PEMFC power density pattern

Table XVIII
Some of the objectives of the FreedomCAR programme (Chalk, Sept. 2003, Slide 8), (Panik, Sept. 2003, Slide 25)

Vehicle, fuel and programme characteristics	Objectives
Range of vehicle	Minimum of 480 km (300 miles)
Cost of hydrogen	To be competitive with petrol ($1.50 untaxed/gallon of petrol equivalent without carbon sequestration)
Fuel cell cost	$45/kW by 2010, $30/kW by 2015
Operation time	5 000 hours for a vehicle (> 100 000 miles)
Fuel cell power conversion efficiency	60%
Commercialization decision	By 2015

Table XIX
Comparison of ICE, ICE/battery hybrid and FCVs

Feature	FCV	ICEV
Price of vehicle	GM's Hy-wire >$5 m (Birch, April 2003, p. 106)	ICE/battery hybrid vehicles Prius (2004)—$25 000 when 10 000 units are produced per month. More than 10% higher than comparable non-hybrid ICEVs (Inoue, 3 June 2004, p. 8).
Price premium	Most London taxi drivers are willing to pay a 5% price premium for fuel cell-driven taxis compared to diesel-driven taxis (Mourato, 2004, p. 693).	$3 000 for hybrid ICE/battery vehicles. This equates to a decade's worth in fuel efficiency (Gartner, 5 Jan 2004, *Wired*). A study by Roland Berger Associates has shown that a maximum markup of 10% on ICE/battery hybrid vehicles is acceptable before customer interest significantly tapers off (Roland Berger, 7 Sept. 2001).
Price of engine or FC power system	General Motors: $50/kW is achievable (BTI, Feb. 2004, p. 46) A.D. Little study (Davis, 31 Oct. 2000): 2000: fuel cell cost = $177/kW 2000: fuel cell system (incl. fuel processor) = $294/kW 2000: fuel processor = $4 310 See Table XVIII – FreedomCAR target	$10 to $50 per kW for ICE
(Tank to wheels) efficiency	50%—Toyota FCHV-4; only 38% without hybrid technology (Yamaguchi, Aug. 2002, p. 43) 60% target—Toyota and US FreedomCAR (Yamaguchi, Aug. 2002, p. 43)	ICE average: 15% H_2 ICEV: 35% (USDOC, 2002, p. 37)
(Well to wheel) efficiency	29%—Toyota FCHV-4; 42%—Toyota's target (Yamaguchi, Aug. 2002, p. 43)	14% for traditional ICEV (Yamaguchi, 2002, p. 43) 26%—Petrol ICE/electric hybrid (Yamaguchi, 2002, p. 43)
Fuel efficiency	The mpg-equivalent efficiencies of most hydrogen FCVs (no reforming required) is between 50 to 60	Traditional ICEVs – average (O'Dell, 27 June 2004): Toyota: 27 mpg (cars and trucks) Honda: 28.6 mpg Volkswagen: 27.8 GM: 24.1 mpg Nissan Motor: 24.1 mpg DaimlerChrysler: 23.9 mpg Ford: 22 mpg Diesel ICEVs: 30 to 40 mpg
Part load efficiency	Higher efficiency at part load than at full load. See Figure 20.	Heat engines operate with highest efficiency when run at their design speed. Rapid decrease in efficiency at part load.
Environmental impact	Low Meets Tier 2 Bin 0 (ZEV)	Contributes to smog and pollution. Limited potential of end-of-pipe technologies (e.g. catalytic convertors) to reduce emissions—meets Tier 2 Bin 5 (Hoogers, 2001, p.3; Cole, 1 Oct. 2003) H_2 ICEVs produce significant nitrous oxides
Power density (See also Table XVII)	600 W/l (including reformer?)—2010 target for 50 kW PEMFC operating on direct H_2 (Chalk, Sept. 2003, Slide 13) Hy-wire's FC stack: 1.6 kW/l (Birch, April 2003, p.106)	~ 1 kW/litre
Life	5 000 hours (target)/100 000 miles	4 000 hours

Most of the major OEMs in the auto industry are investing in fuel cell technology as powertrain technology (see Annexure A). One exception is BMW. They believe that hydrogen is the fuel of the future but are currently only interested in fuel cells as auxiliary power units. BMW prefer hydrogen ICEs to fuel cells because ICEs are proven and cheaper to maintain in their view (Chinworth, Sept. 2002, p. 94). Some analysts feel that hydrogen ICEs could be as efficient as fuel cells if a hydrogen ICE is designed from the ground up to burn hydrogen (USDOC, Sept. 2002, p. 37). Like BMW, Ford has also done extensive work with hydrogen ICEs but also pursues fuel cell technology as powertrain technology.

From the information provided in this section it should be clear that work is underway to get the FCV to compete successfully with other vehicles. Technology forecasting as well as R&D goals can give an indication of when that will be. Competition is not, however, between energy conversion and storage devices (e.g. ICEs, fuel cells and batteries) or different types of vehicles (e.g. FCVs, ICEVs) only, but also between transportation systems which consist of fuel and fuel distribution infrastructure as well. In Table XX the advantages and disadvantages of different types of fuels are listed.

Hydrogen is the preferred fuel for fuel cells but the lack of a hydrogen infrastructure is a stumbling block that needs to be solved. The diffusion of hydrogen infrastructure is briefly described in the next section.

The various pathways to produce hydrogen are illustrated in Figure 24. This is one of the reasons why hydrogen is such a competitive or fit fuel. Hydrogen can be produced from a number of renewable sources, which is why it may be an important component of a sustainable transportation system. The many ways in which hydrogen can be produced is one of the reasons why it could become the next fuel standard.

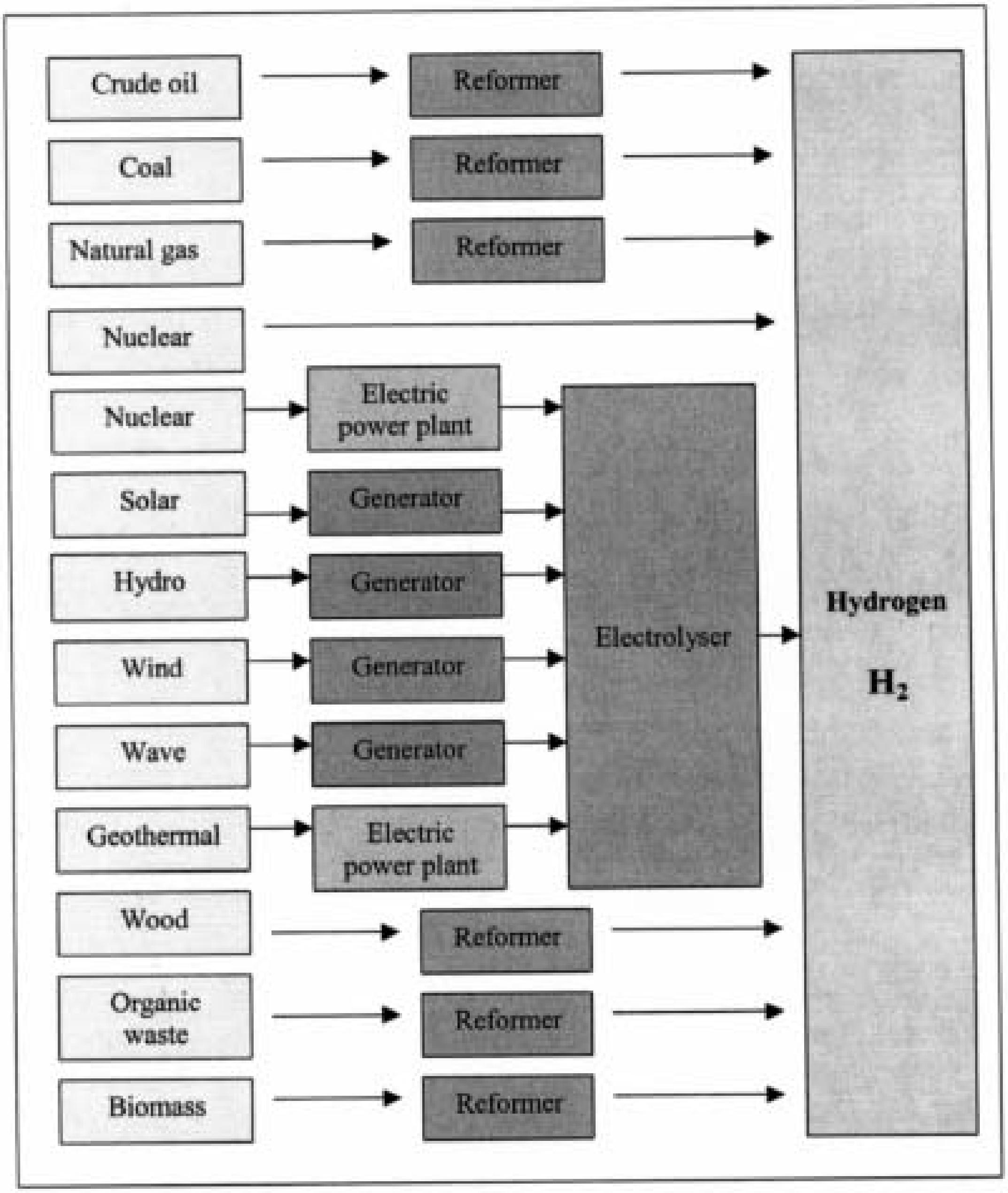


Figure 24. Hydrogen pathways (Cole, 1 Oct. 2003)

Table XX
Advantages and disadvantages (fitness) of a few transportation fuels (not comprehensive)

Fuel (method of production)	Advantages	Disadvantages
Biodiesel (produced from oil seeds or used cooking oil)	• No or lower levels of sulphur, therefore more environmentally friendly. •Renewable/sustainable fuel. •Existing fuel distribution and retailing agricultural land. (fuel station) networks can be used.	• Cannot be produced in large quantities by annuals. Probably limited to supply 5 to 10% of total global fuel demand due to limited agricultural land.Biodiesel could, however, make a bigger contribution in the future if genetically modified perennials can be developed that do not require existing agricultural land for production. • Cannot be used directly in low temperature fuel cells. Additional cost and lower efficiencies of onboard reforming.
Biogas	• Renewable energy source.	• Quantities?
Diesel (from crude oil)	• Fuel distribution networks are in place. • There is a lot of support for diesel engines in the auto industry. The use of diesel as a fuel has grown significantly in Europe (Gehm, May 2002, p. 40; Birch, May 2002, p. 69; Broge, Jan. 2004, p. 33) Many European countries maintain lower taxes on automotive diesel.	• Not environmentally friendly. End-of-pipe (autocatalysts and particle trap) clean-up is required. • Not renewable/sustainable. • Energy security problem • Cannot be used directly in low temperature fuel cells. Additional cost and lower efficiencies of onboard reforming.
Ethanol	• Renewable energy source. • Substitute or additive (Gasohol) for petrol—use existing distribution infrastructure. • Good combustion properties.	• Energy density (24 GJ/m³) is less than for petroleum (39 GJ/m³) (Twidell, 1986, p. 301). • Quantities?
Hydrogen (in general)	• Can be used directly in fuel cells. • It can be produced from a number of renewable energy sources. • Can be produced from numerous energy sources including nuclear fission and possibly nuclear fusion in the future. • General Motors prefer hydrogen as a fuel cell fuel. They do not think that the economics of hydrogen will be a problem (Birch, April 2003, p. 108). • Has the highest energy content per unit of weight ofany known fuel (120.7 kJ/g). • 'BMW has researched and tested various fuels as possibilities to supplant gasoline, including methanol, ethanol, propane, and butane,'and we feel hydrogen is the fuel of the future,' said Cristoph Huss, BMW's Senior Vice President of Science and Traffic Policy, …'(Chinworth, Sept. 2002, p. 94).	• Distribution network is not sufficient for transportation applications by far—problem is similar to that of natural gas and other alternative fuel distribution. • Chicken and egg problem. Energy companies do not want to build a costly infrastructure until there are many vehicles to use it. Consumers do not want to buy vehicles for which there is no easily accessible refuelling infrastructure. • At source of generation the untaxed price of hydrogen (produced from natural gas) is the same as petrol. Transportation and distribution costs increase this five- to tenfold. Very clever design of various generation and distribution options will have to be implemented. • Some automakers in the US think that hydrogen will have to be available in at least 30% of the nations fuelling stations for a viable hydrogen-based transportation sector to emerge (USDOC, Sept. 2002, p. 31).
Hydrogen (electrolysis)	• Can be produced in small, decentralized volumes anywhere where the electrical grid (or distributed generation) is available.	• Currently only a viable option if a cheap source of electricity is available (e.g. geothermally generated electricity in Iceland).
Hydrogen (from natural as/methane)	• Efficient—can be as high as 70%; 58% at Toyota with a well to tank efficiency goal of 70% (Yamaguchi, Aug. 2002, p. 43). • Can be produced wherever gas infrastructure is available. • More environmentally friendly than petrol and diesel. • Natural gas, which consists mostly of methane (CH_4), has the highest hydrogen-to-carbon ratio of any hydrocarbon (4 to 1).	• Cost of producing hydrogen from natural gas is about 4 times as much as petrol with similar energy content. • Does it make sense to first convert natural gas to hydrogen and then to use it in a vehicle? Every conversion results in efficiency reduction. Why not use it directly in an ICE? (Dicks, Sept. 2003, p. 4). • It may be better to use natural gas in electricity generation (instead of coal) rather than to produce hydrogen from it (Wald, May 2004, p.69).
Compressed hydrogen	• The refuelling of a compressed hydrogen tank is about 4 minutes (Automania, Sept. 2003). For hydrogen that is stored in a metallic or chemical hydride it is longer. • No onboard reforming is required—the result is cheaper, lighter and less complex vehicles. • DaimlerChrysler believes that the most technologically advanced method of storing hydrogen is in pure compressed or liquid form (Jost, Sept. 2002, p. 27).	• High pressure hydrogen (350 to 700 bar) could be dangerous when vehicles are involved in accidents. • Energy and equipment are required for compression. • Expensive tanks.
Liquified hydrogen	• Use less volume and weight than compressed hydrogen.	• Loss (boil-off) of hydrogen when vehicle is not used. Target is under 1% per day when resting for more than 15 days (Chinworth, Sept. 2002, p. 95) • High energy consumption in liquefaction of hydrogen to -253°C.
Hydrogen stored in chemical or metallic hydrides	• Safer than compressed hydrogen (usually stored at much lower pressures). • Safe for use in underground applications (Coutts, 28 Sept. 1998, p. 18). • More volume-efficient than compressed H_2 (Jost, Sept. 2002, p. 27).	• Currently the percentage of hydrogen stored as weight compared to that of metallic containment medium is low. • Weight is double that of compressed hydrogen for a 480 km range in a mini-van (Jost, Sept. 2002, p. 27). • Significant infrastructure requirements if used on a massive scale. • Most expensive method of storing hydrogen (Jost, Sept. 2002, p. 27).
Hydrogen from onboard reformed petrol	• Use of existing petrol infrastructure	• Cannot be used directly in low temperature fuel cells. Additional cost and lower efficiencies of complex, sophisticated onboard reforming (Davis, 31 Oct. 2000). • BMW are not interested in reforming hydrogen. They think it is too difficult and costly (Chinworth, Sept. 2002, p. 94). • Purer (e.g. sulphur-free) petrol may be required. • No logical continuation towards hydrogen produced from renewable energy. • Reformation requires temperatures as high as 600°C compared to methanol, which requires about 240°C.
Hydrogen from onboard reformed methanol	• Good 'compromise' fuel. • Can be handled in a similar way to petrol and diesel. • Possible to use existing petrol and diesel storage tanks if a new 'lining' is provided—lower cost. Easier to implement than hydrogen distribution network. • Can be easily processed into hydrogen using steam reforming (SR), partial oxidation (PO) a lower temperature process than steam reforming, or autothermal reforming which is a combination of SR and PO. • PO of methanol provides more hydrogen than in the case of PO of petrol. • Reforming of MeOH produces fewer emissions than reforming of petrol (AEI, Jul. 2002, p. 67). • A high percentage of the world's gas fields are too far from the markets to ensure economical exploitation by gas pipeline. The conversion of such gas to methanol may, however, improve the transportation economics. • Hyundai thinks that the path to FCV commercialization lies with a liquid fuel such as methanol (BTI, Feb. 2004, p. 63)	• Distribution network has to be developed although at lower cost than a hydrogen distribution network. • Cannot be used directly in low temperature fuel cells. Additional cost and lower efficiencies of onboard reforming. • Fuel reforming weight needs to be reduced by at least an order of magnitude (Automotive Engineering International Jul. 2002, p. 72). Toxic; groundwater contamination concerns. • Enough methanol? • Fuel processing system must be heated before processing can begin (AEI, Jul. 2002, p. 72).
Natural gas	• More environmentally friendly than petrol.	• Distribution network is not sufficient for transporation applications by far—problem is similar to that of hydrogen distribution. • Chicken and egg problem related to distribution network and natural gas vehicle sales.
Petrol/gasoline (from oil)	• Fuel distribution networks are in place.	• Not environmentally friendly. End-of-pipe (autocatalysts) clean-up is required. • Not renewable/sustainable. • Energy security problem.
Synthetic fuels (gas to liquids technology)	• Does not contain sulphur.	• Cannot be used directly in low temperature fuel cells. Additional cost and lower efficiencies of onboard reforming. • Economics still largely unknown due to absence of big plants.

The diffusion of hydrogen infrastructure

Today, the petrol distribution infrastructure in the developed world is extensive. However, onboard reforming of petrol increases the cost of FCVs, adds to their complexity and does not solve the problems of fossil oil security and depletion. Hydrogen infrastructure may therefore play an important role in the establishment of a sustainable transportation system. Inadequate distribution networks have been partially blamed for the disappointing rate of diffusion of alternative fuel vehicles such as ethanol, methanol and natural gas-driven cars. Adequate refuelling infrastructure is an essential component of a fit transportation ecosystem. However, current hydrogen distribution networks are very limited. Addressing this problem will require significant capital investment and political will. The cost of hydrogen pipelines varies from $300 000 to $1 400 000 per mile, depending on various parameters such as size. Argonne National Laboratory estimates that as much as $500 billion may be necessary to put in place the infrastructure (hydrogen at about 40% of current fuelling stations) required to support the widespread use of hydrogen-fuelled vehicles on a significant scale in the USA (Chinworth, Sept. 2002, p. 96). To deliver hydrogen from large plants to dispersed small hydrogen users is now about five times more expensive than producing the hydrogen (Sperling, Spring 2004, p. 85). Designing more cost-effective hydrogen distribution networks is a huge challenge.

A number of initiatives has already been taken to put hydrogen distribution and refuelling networks in place. For example, BP and Ford are partners in the US Department of Energy's 'Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project' (BP, 27 April 2004). One of the boldest hydrogen infrastructure decisions has been taken by California to establish more than 200 hydrogen refuelling stations along its major highways by 2010 (Hydrogen Highway, 2004). The US state of Illinois also plans to build a hydrogen highway (*Fuel Cell Today*, 23 June 2004).

Mike Jones from BP thinks that 30 to 50% of current refuelling stations will have to stock hydrogen (Black, Sept. 2003, p. 7) to support the diffusion of hydrogen-driven vehicles.

From the information provided in this section it is clear that current hydrogen infrastructure is inadequate to support the mass diffusion of hydrogen FCVs. Plans are, however, in the pipeline to put such infrastructure in place. This will require large investments and the challenge is therefore to have a smooth transition from today's petrol and diesel-ICE-transportation system to a sustainable transportation system. Ways the current transportation system can evolve into a future sustainable one are briefly described in the next section.

Table XXI
The diffusion of hydrogen generation and distribution infrastructure

Year	Region	Targets/comments
2003 2010	California	The California Fuel Cell Partnership (CaFCP) has about 7 hydrogen fuel stations (BTI, Feb. 2004, p. 15). 200 H_2 refuelling stations are planned for 2010 (Ziff, May 2004).
2003 2030	Japan	'Japan does not have a hydrogen-supplying infrastructure as of yet. The first of six hydrogen fueling stations, all in the Tokyo area, is to open in August 2003 under a program sponsored by the Ministry of Economy, Industry, and Trade' (Yamaguchi, March 2003, p. 55). Japan is planning to have about 8 500 hydrogen stations in place by 2030 (*Fuel Cell Today*, 12 May 2004)
2020	Europe	Suggestion by the Alternative Motor Fuel Communication: 20% of motor fuel should be from non-petroleum sources; 5% of motor fuel should be hydrogen (BTI, Feb. 2004, p. 9).
-	Germany	'In the long term we are expecting a nationwide network of 10 000 hydrogen filling stations in Germany' Christopher Huss, head of Science and Traffic Policy at BMW (Broge, May 2003, p. 40).
2010	Canada	Canada's prime minister announced a plan to build a 'hydrogen highway' from Whistler, B.C. to Vancouver in time for the 2010 Winter Olympics (Suzuki, 12 May 2004).
2040	USA	"If we develop hydrogen power to its full potential, we can reduce our demand for oil by over 11 million barrels per day by the year 2040,' said Bush" (Ponticel, March 2003, p. 96).

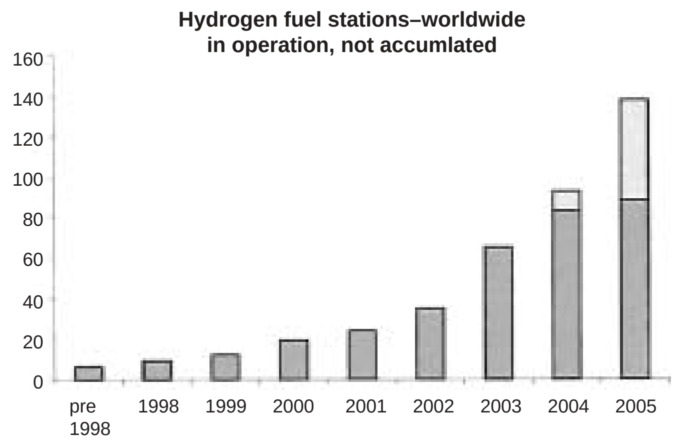


Figure 25. Global diffusion of hydrogen refuelling stations (Source: www.fuelcelltoday.com)

Table XXII
Current and future hydrogen production/consumption

Year	Amount	Remarks
1999	15.864 trillion cubic feet (tcf) or 449 billion m^3	Total global H_2 consumption (Chinworth, Sept. 2002, p. 90)
1999	3.2 trillion cubic feet (tcf) or 91 billion m^3	Total US H_2 consumption (Chinworth, Sept. 2002, p. 90)
2004	BP produce 5 000 tons of H_2 per day (enough for about 1.7m vehicles?)	(BP, 27 April 2004)
2019	South Korea plans to produce 30 000 tons of H_2 per annum by 2019	(*Fuel Cell Today*, 15 April 2004)

Pathways to FCV domination and the hydrogen economy

A sustainable transportation system with FCVs and a hydrogen infrastructure will only be possible if it is feasible and if logical pathways exist or can be found to take us from our current unsustainable transportation system to the sustainable one. A number of such paths are very briefly discussed in this section. Every country, state, province or geographical area will have to decide on those pathways that may suit its specific needs and energy resource mix.

Toyota Motor Corporation (TMC) must be confident that ICE/battery hybrid vehicles will be the next step in the evolution of vehicles. TMC sold almost 120 000 of its Prius ICE/battery hybrid during the period of its introduction in 1997 and January 2003. In June 2004, Toyota increased production of the Prius to 10 000 units per month (Inoue, 3 June 2004, p. 8). Toyota plans to have all its vehicles operating on petrol/battery hybrid engines by 2012. Toyota's aim is to sell 300 000 ICE/battery hybrids a year by 2005 (Hybrids Gain Popularity, http://www.japanauto.com). Takehisa Yaegashi, Senior Manager for powertrain management, said at the 2003 SAE Conference that petrol-electric hybrids are the best option for fuel economy over the next 30 years before the advent of viable FCVs (*CAR*, May 2003, p. 13).

Should ICE/battery hybrid vehicles therefore be considered as the bridge between traditional vehicles and FCVs? This scenario is illustrated in Figure 26. Will FCVs only diffuse significantly after ICE/battery hybrid vehicles have been established as the next motor industry standard? These are important questions since the specific evolutionary path or trajectory that vehicle technology and architecture will follow will impact on how soon FCVs may take off and the rate at which they will diffuse.

ICE/battery hybrid technology will impact on the viability of (hybrid) FCVs since they use a number of common components. Most FCVs are also hybrids (either fuel cell/ultra capacitor or fuel cell/battery–see Annexure A) and therefore share some architectural similarities with petrol/battery hybrids. Doanh Tran from DaimlerChrysler confirms this: 'At Chrysler, we believe that the fuel cell will be hybridized. This way you can optimize the cost of the fuel-cell system, capture the regenerative braking, and provide more functionality' (Holt, 2002, p. 28). The impact of petrol hybrid on the viability of fuel cell hybrids is further explained by Ben Knight, Vice-President, Automotive Engineering, Honda R&D Americas Inc. as follows: 'I think as industry moves into gasoline [petrol] hybrids, hybrid technology will help make a pathway to reduce the costs both for the high voltage controllers, the dc/dc converters, and the motor architecture manufacturing … Whether the hybrid is transitional depends on the viability of the fuel-cell vehicle. Hybrids [will] probably have a good term and really provide a benchmark for performance that the fuel cell needs to surpass' (Holt, 2002, p. 28). Compared to traditional ICE-driven vehicles, FCVs will find it harder to compete with hybrid ICE/battery vehicles from an environmental and efficiency point of view (see Table XIX). The petrol consumption of hybrid ICE/battery vehicles is significantly lower than that of traditional ICE-driven vehicles. Hybrids can also use ICEs with smaller capacity without reduction in acceleration and performance in general. Based on these factors alone (excluding stricter environmental legislation in the future, for example) the scenario sketched in Figure 26 may therefore result in reduced or constant vehicle platinum

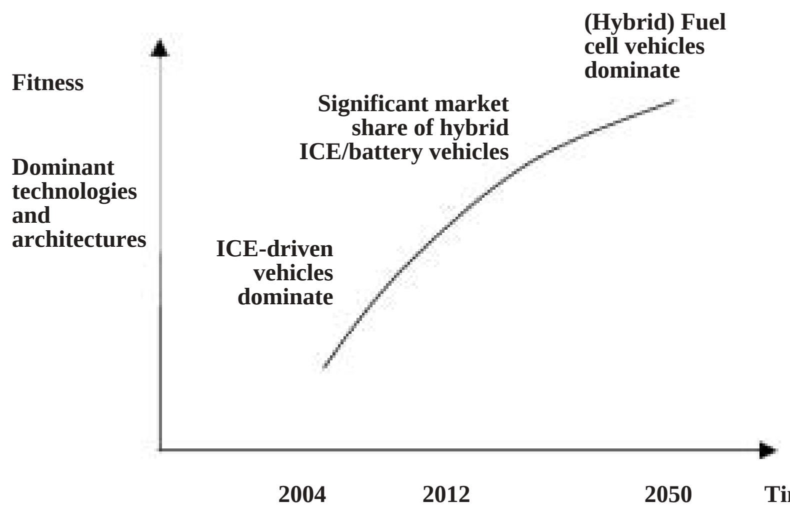


Figure 26. Evolution of vehicle technology scenario—vehicle technology and architecture trajectory and impact on vehicle platinum loading

loading should ICE/battery hybrid vehicles dominate for a while. This could, however, be offset by higher platinum requirements of the initial FCVs that use onboard reformers. The platinum loading of later FCVs will probably be lower due to better established hydrogen infrastructure.

It is not clear whether all automobile manufacturers agree that hybrid technology is core to their business. Toyota, the current market leader, sells its hybrid technology currently to Nissan and Ford (Inoue, 3 June 2004, p. 8). Ford plans to build 20 000 ICE/battery hydrid vehicles per year (O'Dell, 27 June 2004).

The ICE/battery hybrid vehicle may be an important technological step in the evolution to a more sustainable vehicle. The question of how current fuels and fuel infrastructure should be transformed to a more sustainable situation is discussed next.

Another obstacle to the diffusion of FCVs is the lack of a hydrogen or methanol distribution network. Current hydrogen and methanol distribution networks are very small compared to the size of the current petrol (gasoline) and diesel distribution networks. In the US the total hydrogen network is limited to about 1 130 km compared to about 290 000 km of natural gas pipelines (Chinworth, Sept. 2002, p. 95) or 1.3 million miles of transmission and distribution lines according to another source (Natural Gas Vehicle Coalition). There are a number of methods to overcome the small hydrogen infrastructure problems

- Hydrogen can be produced from natural gas at relatively low cost wherever natural gas is available. Natural gas distribution networks can therefore be seen as a substitute for hydrogen distribution networks. A new natural gas infrastructure should be hydrogen compliant to ensure that it can be used in the future for the distribution of hydrogen
- The lack of pipelines can be overcome by transporting hydrogen in liquid form by tankers to distribution points
- Hydrogen can be produced from petrol, diesel, methanol, ethanol and other hydrogen carriers by means of chemical processes such as steam reforming and partial oxidation. An onboard reformer solves the hydrogen infrastructure problem but adds to the cost of an FCV and has the other disadvantage that it lowers the efficiency of the combined fuel and fuel cell life cycle. The continued use of petrol in FCVs does not provide a solution to the oil depletion problem, however, and is considered a short-term transitional solution. Neither does it provide a solution to the energy security and energy independence problem that countries such as South Africa, the USA, Europe and others have. A number of automobile manufacturers are investigating the onboard hydrogen-carrier reforming option (see Annexure A). This option has the potential to accelerate FCV diffusion while hydrogen distribution networks are put in place.

Table XXIII
ICE/battery hybrid vehicle diffusion (sales per year)–see also Figure 27

Year	ICE/battery hybrid vehicle sales (per annum)
2003	40 000 {J.D. Power and Associates forecast (Gartner, 5 Jan 2004, *Wired*)}
2004	100 000 {Forecast by Butto from Toyota (Gartner, 5 Jan 2004, *Wired*)}
2005	177 000 {J.D. Power and Associates forecast (Gartner, 5 Jan 2004, *Wired*)} 300 000 to be produced by Toyota (USDOC, Sept. 2002, pp. 44)
2008	344 000, {J.D. Power and Associates forecast (Gartner, 5 Jan 2004, *Wired*)} 440 000, {J.D. Power & Associates forecast (O'Dell, 27 June 2004)}
2010	Hyundai Motor plans to produce 10 000 petrol/battery hybrid cars per year from 2010 (*Fuel Cell Today*, 27 June 2004)

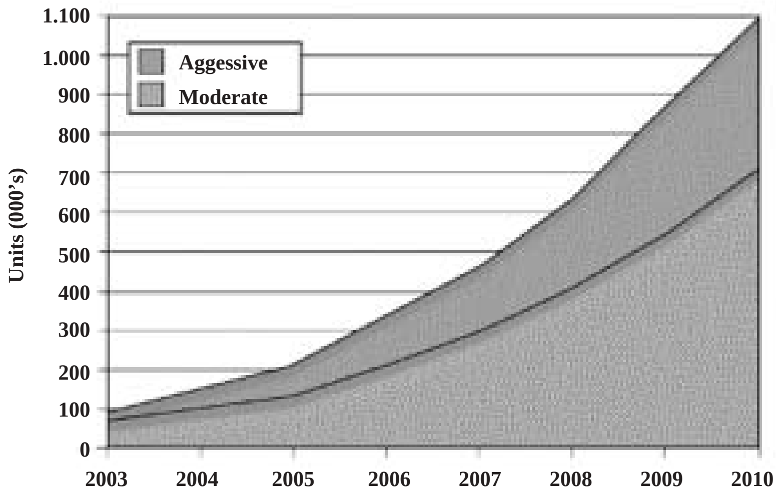


Figure 27. Annual global hybrid vehicle production forecast (ABI, 20 April 2004)

Companies such as BMW and Mazda want to commercialize hydrogen ICEVs. Mazda has announced ambitious plans for the commercialization of its hydrogen rotary engine-driven vehicles. A target date of 2007 has been set by Mazda, while BMW is planning to offer a production version of the 745h during the period 2007–2009 in Europe (BTI, Feb. 2004, p. 66; Chinworth, Sept. 2002, p. 95). Hydrogen demand from not only fuel cells and FCVs but also ICEVs could stimulate the demand for a hydrogen infrastructure better than just fuel cells alone. The larger resulting economies of scale could therefore expedite investment in additional hydrogen generation and distribution infrastructure.

General Motors think that the diffusion of stationary fuel cell applications will start sooner than automotive applications and are therefore involved in that fuel cell market segment as well. Early commercialization of other (non-automotive) applications of fuel cells will result in increased fuel cell production volumes, decreased unit costs and improved returns on R&D investment. This will expedite the cost competitiveness and overall fitness of fuel cells. Toyota also sees merit in selling small fuel cell electricity generators in an effort to bring down fuel cell development costs (ABI, Feb. 2004, p. 84).

The lock-in by existing technology is not a factor in geographical areas where such a technology has not yet significantly diffused through society. The introduction of newer, fitter technologies in such areas may therefore experience less resistance than elsewhere. A petrol infrastructure does not yet exist in a number of countries to the same extent as in most western countries. For example, General Motors discussed the idea of leapfrogging a petrol infrastructure in favour of a hydrogen one with the Chinese government (ABI, Feb. 2004, p. 50).

Another strategy is to introduce those FCV applications first where there are fewer stumbling blocks. For example, taxis, buses and vehicles used within a plant, mine or factory do not need a regional or national hydrogen refuelling infrastructure. Storage space for compressed hydrogen is not a problem on buses and other large vehicles either. If a number of big cities start such projects, then a regional (or even national) refuelling network will eventually emerge.

The standardization of hydrogen infrastructure, for example refuelling coupling units, will play an important role in the successful diffusion of hydrogen as a fuel.

Drivers of FCV diffusion

A number of drivers of FCV diffusion, alternative fuel vehicles, alternative fuels and hydrogen as fuel are briefly described in this section.

(Transport) Energy security

The energy security problem basically exists because of the mismatch between the quantities of energy used (especially for transportation) and produced from mostly non-renewable sources in different parts of the world. Renewable sources of energy such as wind, solar and biomass are more evenly distributed around the world compared to petroleum. The gap between petroleum supply and demand in certain countries has increased due to growing energy needs, slow diversification of energy sources towards renewable energy sources, and high depletion levels of local petroleum reserves. The result is that fewer countries in the world are producing more petroleum than is locally consumed. This trend will continue due to finite petroleum resources. Long pipelines and other crude oil distribution infrastructure are vulnerable to sabotage.

The production of crude oil in the US peaked in 1971 and since then it has become more reliant on oil imports. Today the US imports 54% of its petroleum. Some 40% of US energy is produced from petroleum. The transportation sector consumes 67% of the petroleum use in the United States and is 95% dependent on petroleum (Chalk, Sept. 2003, p. 1). Countries such as Japan, India and South Africa rely very heavily on petroleum imports. Energy security also concerns the European Union, which is becoming more reliant on external sources of energy (European Commission, 2001). All countries that rely on imported oil are affected by OPEC's decisions and the unstable Middle-East.

All vehicles that run at higher efficiencies and/or on alternative fuels than traditional petrol and diesel ICEVs (e.g. hydrogen FCVs) offer a potential partial solution to the transport energy security problem.

Oil depletion as a fuel cell diffusion driver

Petroleum depletion is an example of a constraint that could impact on future alternative fuel vehicle diffusion. The normative approach could, for example, be applied in this situation to determine the amount of alternative fuels that will have to be used in the future due to the gap between oil supply and demand illustrated in Figure 28.

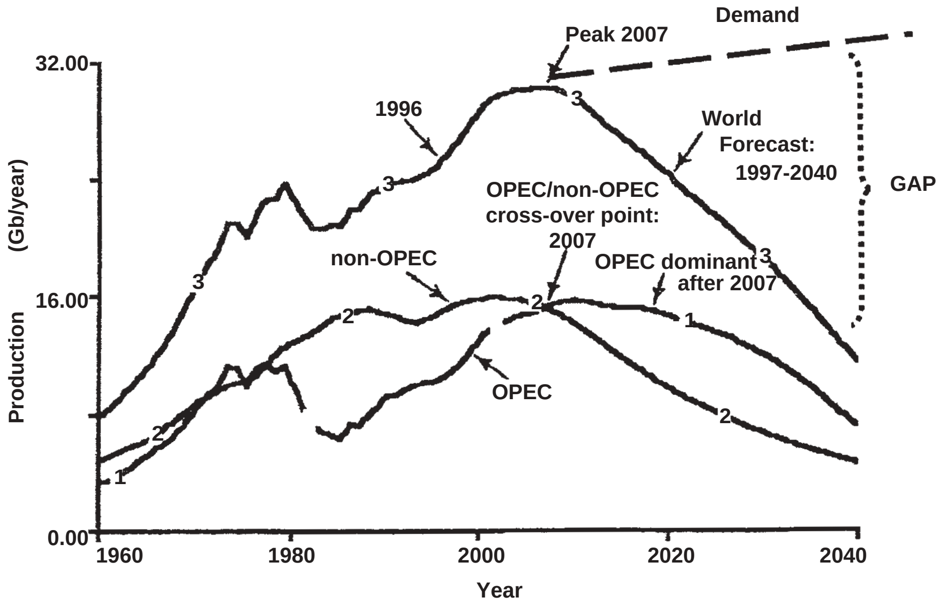
The demand for oil can be reduced by using more 'oil-efficient' cars such as ICE/battery hybrids or FCVs that use reformed petroleum products. Since oil is used not only in the transportation sector but also in electricity generation and the petrochemical industry, it may also be possible to replace oil with other means of generating electricity, for example.

Environmental concerns

More environmentally friendly transportation options are required to solve the problem of high pollution levels in cities and global warming. ICEVs are becoming more expensive due to stricter vehicle emissions standards. The environmental philosophy that is followed by ICEVs is to first pollute and then to clean by end-of-pipe technologies (e.g. autocatalysts). The philosophy that is followed in a sustainable transportation system is to use renewable energy sources to generate energy carriers such as hydrogen and to use a clean energy conversion device such as a fuel cell. Considerable progress has been made since the early 1970s to reduce vehicle emissions—99% reduction in the USA and 92% reduction in Europe (Birch, April 2003, p. 107). However, this is not sufficient due to the growth in vehicle numbers and kilometres travelled by vehicle owners. Vehicle miles travelled have increased by 150% over the last 30 years. According to Larry Burns from General Motors, a 45% improvement in fuel consumption (which is about the case for ICE hybrid vehicles) will only buy the auto industry five years in terms of miles travelled (Birch, April 2003).

Job creation

Fuel cells will create new job opportunities (BTI, p. 4) but will also destroy some. This is because some applications of fuel cells will compete with incumbent technologies. The fuel cell industry in Canada supports over 1 800 jobs (Todd, 24 Sept. 2003, p. 1). Some fuel cell investments are made from a job creation point of view.



World, OPEC, and non-OPEC oil production life cycles. Years 1960–2040 curves and peaks of the world (curve 3, peak 2007), non-OPEC (curve 2, peak 2001), and OPEC (curve 3, peak 2010). Cross-over point when OPEC production exceeds non-OPEC production (year 2007). In 2007, almost all OPEC production will be in the Persian Gulf region. OPEC nations outside the Gulf will have minor production, except for Venezuela. Some countries may have dropped out of OPEC because domestic demand exceeded production, with no surplus to export

Figure 28. The Duncan and Youngquist oil supply scenario (adapted from Duncan and Youngquist, 1999)

Fuel cell industry enablers: policy, finance and RD&D

Policies, regulations, standards, adequate finance and enough RD&D spending are all enablers for the emerging FCV industry. DaimlerChrysler alone invested about $900 million in the year 2000 in hybrid and fuel cell R&D (USDOC, Sept. 2002). This shows the level of commitment from automotive OEMs.

Due to space constraints fuel cell industry enablers will not be analysed in any further detail here.

Conclusion and the way forward

The question of future platinum demand will be a recurring one. It will be asked every time an existing platinum mine wants to expand its existing operations (brown field project) or a decision has to be made about the approval of a new platinum venture (green field project). In this paper a few unlikely scenarios are sketched in which platinum demand by the automotive industry may reduce in the future. The more likely scenario, however, is that it may increase significantly from about 2015 and that FCVs may become one of the most important drivers of future platinum demand. The purpose of this study is to quantify future platinum demand generated from the successful diffusion of FCVs since this may offer production expansion opportunities for platinum miners.

This paper provides a framework that can be used to obtain the values that are required to complete Table I. Expert opinions, S-curves and other techniques can be used to forecast the missing values of column II ('Number of (new) FCVs on the roads globally') in Table I. Information provided in this paper points to the fact that category I fuel cell hybrid vehicles (those with big fuel cells and relatively small batteries) may dominate in future. Fuel cell capacity can be expected to be more or less in line with that of vehicles used today. Technological trends can be used to forecast values for column IV—'Average platinum loading per kW of vehicle capacity (g/kW)'. Whether onboard reformers are used or not will impact significantly on the PGM loading per kW of fuel cell system (stack + reformer) capacity. Studies such as those by Youngquist show that diversification to alternative fuels such as hydrogen may be more urgent than what is generally perceived to be the case. (This definitely requires further investigation.) Petrol-reforming is therefore not a strong option (at least not for petroleum-importing countries) under such a scenario. Methanol-reforming may, however, still be an option. Over the long term sustainable transportation will become the major driver, resulting in a new transportation ecosystem with hydrogen as the fuel standard.

Various indicators point to the scenario that FCVs will become an important technology within a number of decades in spite of all the stumbling blocks. This is because certain constraints or limits are in place such as limited further improvement in ICE efficiency and oil depletion that will make obsolete the lock-in that petroleum enjoyed as a fuel for the majority of vehicles on the roads today.

Ongoing research is required to analyse various issues that were merely mentioned in this paper.

Glossary of terminology

(See also *Wilhelm's Science, Engineering and Technology* website at http://www.etscience.co.za).

Architecture—A product's architecture determines how components fit and work together.

Auxiliary power—Power from an independent source (e.g. 5 kW SOFC in a diesel truck) that augments the prime power source (e.g. CI ICE).

Catalyst—A substance that increases the rate of approach to equilibrium of a chemical reaction without being substantially consumed by the reaction. The following happens during the catalytic process:

- Reactants adsorb onto the catalyst surface
- Reaction occurs
- Products desorb from the catalyst surface

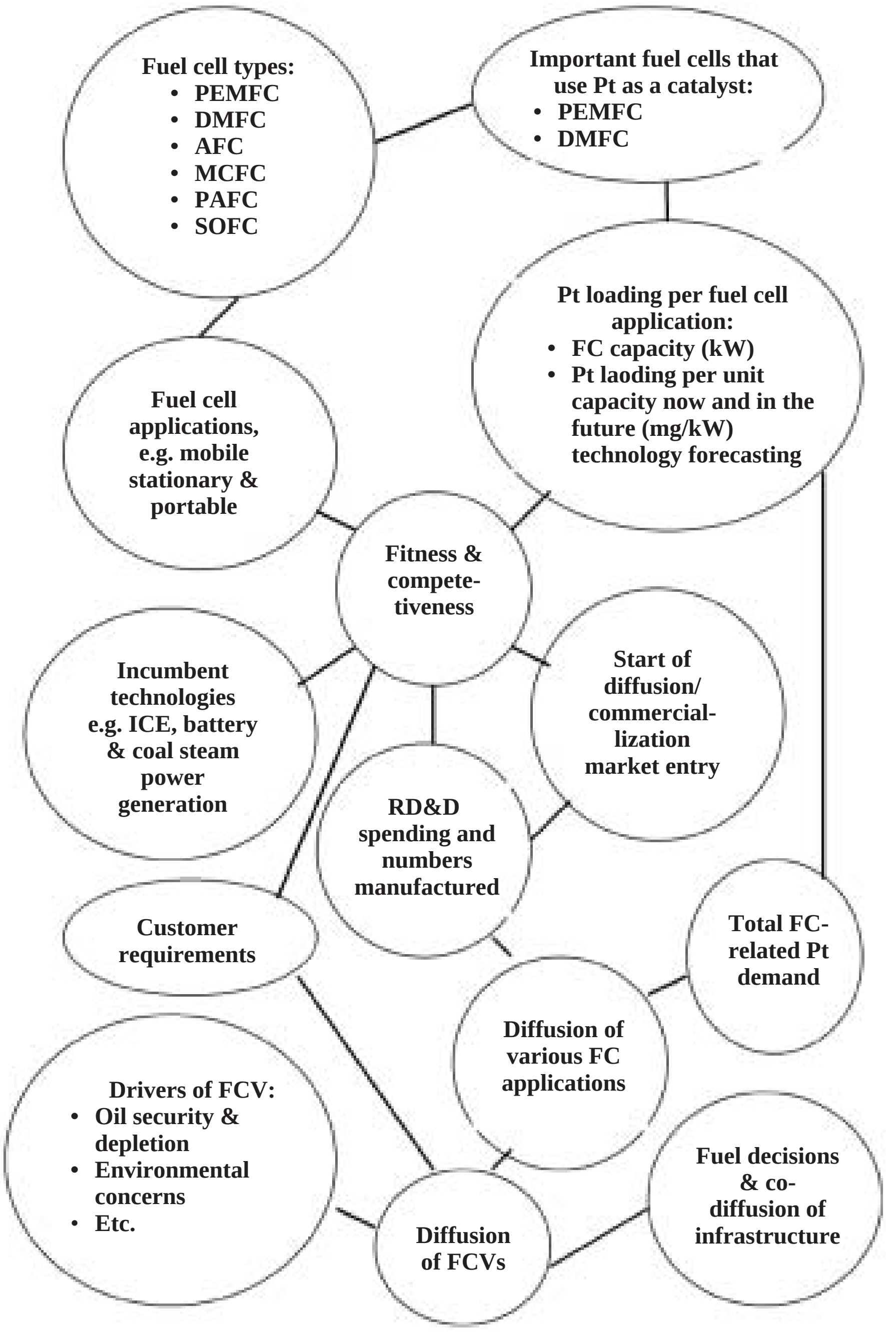


Figure 29. Mind map illustrating the impact of fuel cell technology on platinum demand

The catalyst lowers the activation energy required, allowing the reaction to proceed more quickly or at a lower temperature. Maximum catalytic activity is expected for those metals having the smallest, non-zero number of vacant d orbitals.

Catalyst loading—The amount of catalyst incorporated in the fuel cell per unit area (usually measured in mg/cm^2 in the case of fuel cells).

Diffusion—In the context of this paper it means 'spreading through society' or 'adoption by society'.

Direct methanol fuel cell (DMFC)—A type of fuel cell that uses methanol, which is a readily available fuel. Methanol is used directly in the fuel cell without having to be reformed.

Distributed generation—Small modular power systems that are sited at or near to their point of use.

Electrolysis—A chemical change in substance that results from the passage of an electric current through an electrolyte. The production of commercial hydrogen by separating the elements of water, hydrogen and oxygen by charging the water with an electrical current.

Electrolyte—A non-metalic liquid or solid conductor that carries current by the movement of ions (instead of electrons) with the liberation of matter at the electrodes of an electrochemical cell.

Energy security—Policy that considers the risk of dependence on fuel sources located in remote and unstable regions of the world and the benefits of domestic and diverse fuel sources.

Fuel cell vehicle (FCV)—A vehicle that incorporates a fuel cell engine. It is envisaged that most fuel cell vehicles will be hybrid vehicles in the future. A vehicle that uses a fuel cell for auxiliary power only (e.g. to power an air-conditioner) is not classified as a fuel cell vehicle.

Heat engine—A device that produces mechanical energy directly from two heat reservoirs of different temperatures. A machine that converts thermal energy to mechanical energy, such as a steam engine or turbine.

Hubbert's Peak—'Precisely, as forecasted by Hubbert in 1956 (either ignored, or regarded in gross error by most people at the time), US oil production peaked in 1970. The United States actually had to begin to import oil about 15 years before the peak was reached, as demand already had outstripped production capacity by peak production time. The fact that US production had peaked in 1970, and then began to decline further assured the success of the Arab oil embargo against the United States in 1973, and altered US-Middle East foreign policy ... When the world oil production peaks, there will be nowhere else for the world to go for more oil' (Duncan, 1999, p. 220). 'Hubbert observed that in any large region, unrestrained extraction of a finite resource rises along a bell-shaped curve that peaks when about half the resource is gone.' (Campbell, 1998, p. 81).

Hybrid vehicle—Usually hybrid engine vehicles, for example a vehicle that employs a combustion engine system together with an electric propulsion system. Hybrid technologies expand the usable range of engine vehicles beyond what an all-electric vehicle can achieve with batteries only. An example is a vehicle that uses batteries and an internal combustion engine (e.g. petrol or diesel engine). A vehicle that uses both batteries and a fuel cell stack to power it is another example of a hybrid vehicle. Hybrid cars increase fuel efficiency by turning the internal combustion engine off at low speeds and by utilizing regenerative breaking.

Hydride—Many metals form metal hydrides. An effective hydride must both absorb and release the same quantity of hydrogen many times without deterioration. Hy-Stor 208 (nickel alloy) can be charged and discharged more than 100 000 times. Some hydrides can store twice the amount of hydrogen that can be stored in the same volume of liquid hydrogen (*Fuel Cell Today*, 15 April 2003).

Advantage of hydrides:

- Hydrogen is safely locked up—inherently safer than compressed hydrogen or liquid hydrogen

Disadvantages of hydrides

- Additional mass
- Energy is required to store hydrogen and extract it from the hydrides

Hydrogen carrier—A fuel (e.g. methanol, petrol and methane) that contains hydrogen and that can be released by means of reforming. Methane is hydrogen rich (CH_4) and therefore a 'good' hydrogen carrier.

Hydrogen economy—An economy whose energy infrastructure uses hydrogen as the primary energy carrier.

Hydrogen storage—Hydrogen can be stored as a high pressure gas, as a crygenic liquid, in certain alloys known as hydrides, or in certain nanomaterials. Hydrogen can also be stored in conventional fuels such as methanol, gasoline (petrol) or ethanol, the so-called hydrogen carriers.

Load following—A mode of operation where the fuel cell power plant generates variable power depending on the AC load demand.

Membrane electrode assembly—Membrane electrode assembly is at the heart of a PEMFC. It consists of the following three main components—two electrodes and a solid electrolyte in the form of a polymer membrane. Each electrode consists of a carbon-based substrate coated with a platinum catalyst.

Nafion—A perfluorosulfonic acid membrane that was invented by employees of DuPont in the early 1970s. It is the membrane that was traditionally used in the manufacturing of PEM-type fuel cells.

Ounce troy—1 oz troy = 31.10347 grams, therefore 1 gram = 0.03215 ounces troy.

Partial oxidation—Fuel-reforming reaction in which the fuel is partially oxidized to carbon monoxide and hydrogen rather than fully oxidized to carbon dioxide and water. This is accomplished by injecting air with the fuel stream prior to the reformer. The advantage of partial oxidation over steam reforming of the fuel is that it is an exothermic reaction rather than an endothermic reaction and therefore generates its own heat.

Preferential oxidation (or selective oxidation)—A reaction that oxidizes one chemical rather than the other. In fuel cell systems, the reaction is used to preferentially oxidize carbon monoxide from the reformate stream after the water-gas shift reactor (see shift conversion) and before the fuel cell.

Phosphoric acid fuel cell (PAFC)—A fuel cell that operates at 190 to 210 degrees Celsius. It uses phosphoric acid as an electrolyte. The potential applications of PAFCs are CHP and distributed power generation. The electrodes are made of carbon. This is covered with platinum.

Reformer—A vessel within which fuel gas and other gaseous recycle streams are reacted with water vapour and heat, usually in the presence of a catalyst, to produce hydrogen-rich gas for use within the fuel cell power plant.

Renewable energy—Biomass, solar, wind, wave, geothermal and hydropower are examples of renewable energy sources. In 1998 renewable energy resources supplied about 14% of the world primary energy consumption. The potential of renewable energy is enormous since it can meet many times the current world energy demand. Most renewable energy technologies are however, still at an early stage of development and often not commercially available (UNDP, 2000, p. 220). Hydrogen may play an important role in the future as energy carrier and storage medium during times (e.g. night) when renewable energy forms such as wind and solar are not available.

Shift conversion—The reaction of CO and water to form hydrogen and carbon dioxide. This process is performed immediately after the reformer and before the preferential oxidizer and reduces CO from approximately 10% down to 0.5% to 0.1% usually through a water-gas shift reaction.

Steam reforming—A process for separating hydrogen from a hydrocarbon fuel, typically natural gas, in the presence of steam. This is the commonly preferred method for bulk hydrogen generation.

Sustainable technology—Weaver (2000, p. 66) defines sustainable technology as technology that is designed from the outset to be intrinsically compatible with eco-capacity constraints.

Technology trajectory—'the activity of technological process along the economic and technological trade-offs defined by paradigm' (Dosi, 1988, p. 16).

Note: See http://www.etscience.co.za for more terms.

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Year	Vehicle type/model (manufacturer/OEM)	Fuel cell type; FC capacity; architecture	Fuel & {P if CH_2 psi}; Reformer?	Max. speed (km/h)	Range (km)
1994	NECAR 1 – 180 Van (DaimlerChrysler)	PEMFC; 50 kW	CH2 {4 300 psi}	90	130
1995					
1996	NECAR 2, V-Class (DaimlerChrysler)	PEMFC; 50 kW	CH2 {3 600 psi}	110	250
	RAV 4 FCEV, SUV (Toyota)	PEMFC – 20 kW; FC/battery hybrid	MHH2	100	250
	Averages/dominant FC - 1996	**PEMFC; 35 kW**		**105**	**250**
1997	NECAR 3, A-Class (DaimlerChrysler)	PEMFC; 50 kW	MeOH; methanol-reforming	120	400
	EV1 FCEV (General Motors/Opel)	FC/battery hybrid	MeOH	-	-
	Sintra, mini-van (General Motors/Opel)	PEMFC - 50 kW	-	-	-
	Demio (Mazda)	PEMFC – 20 kW; FC/ultra capacitor hybrid	MHH2	90	170
	Leguna wagon (Renault)	PEMFC – 30 kW; FC/battery hybrid	LH2	120	400
	RAV 4 FECEV, SUV (Toyota)	PEMFC – 25 kW; FC/battery hybrid	MeOH; methanol-reforming	125	500
	Averages/dominant FC – 1997	**PEMFC; 35 kW**		**114**	**368**
1998	Zafira mini-van (General Motors/Opel)	PEMFC – 50 kW; FC only	MeOH; methanol-reforming Mpg equivalent: 80 mpg	120	483
1999	MOVE EV-FC, micro-van (Daihatsu)	PEMFC; 16 kW; FC/battery hybrid	MeOH; methanol-reforming	-	-
·	NECAR 4, A-Class (DaimlerChrysler)	PEMFC; 70 kW; FC only	LH2	145	450
	P2000 HFC, sedan (Ford)	PEMFC – 75 kW; FC only	CH2; P? Mpg equivalent: 67 mpg	-	160
	FCX-V1 (Honda)	PEMFC – 60 kW; FC/battery hybrid	MHH2	130	177
	FCX-V2 (Honda)	PEMFC – 60 kW; FC only	MeOH; methanol-reforming	130	-
	MFCV (Mitsubishi)	PEMFC; FC only	MeOH; methanol-reforming	-	-
	R'nessa, SUV (Nissan)	PEMFC – 10 kW; FC/battery hybrid	MeOH; methanol-reforming	70	-
	VW Estate, EU Capri Project (VW)	PEMFC – 15 kW; FC/battery	MeOH; methanol-reforming	-	250
	Averages; dominant FC and fuel	**PEMFC; 44 kW**	**MeOH**	**119**	**262**

Annexure A. Fuel cell vehicles (continues)

Year	Vehicle type/model (manufacturer/OEM)	Fuel cell type; FC capacity; architecture	Fuel & {P if CH_2 psi}; Reformer? Fuel consumption/economy	Max. speed (km/h)	Range (km)
2000	Jeep Commander 2, SUV (DaimlerChrysler)	PEMFC – 50 kW FC; FC/battery (90 kW NiMH) hybrid Acceleration: 0 to 100 km/h in 13 seconds	MeOH; steam-reforming Fuel efficiency: 10l/100 km or 23,5 mpg Refuelling time similar to petrol vehicles (AEI, Jul. 2002, p.70)	-	190?
	NECAR 4 Advanced (DaimlerChrysler)	PEMFC; 85 kW; FC only	CH2 (1,8 kg) Mpg equivalent: 53,46 mpg	145	200
	NECAR 5, A-class (DaimlerChrysler)	PEMFC; 85 kW; FC only	MeOH; methanol-reforming	150	450
	Focus FCV (Ford)	PEMFC - 85 kW; FC only	CH2 {3 600 psi}	128	160
	TH!NK FC5 (Ford)	PEMFC – 85 kW; FC only	MeOH; methanol-reforming	128	-
	Precept FCEV (General Motors/Opel)	PEMFC – 100 kW; FC/battery hybrid	MHH2 Mpg equivalent: 108 mpg (estimated)	193	800
	HydroGen 1, Zafira van (General Motors/Opel)	PEMFC – 80 kW; FC/battery hybrid	LH2	140	400
	FCX-V3 (Honda)	PEMFC – 62 kW; FC/ultra capacitor hybrid	CH2 {3 600 psi} 26 gal.	130	173
	Santa Fe SUV (Hyundai)	PEMFC – 75 kW; FC only	CH2 Mpg equivalent: 50-60 mpg	124	160
	Xterra, SUV (Nissan)	PEMFC – 85 kW; FC/battery hybrid	CH2	120	161
	Hymotion (VW)	PEMFC – 75 kW; FC only	LH2	140	350
	Averages; dominant fuel and FC	**PEMFC; 82 kW**	**CH2 {3 600 psi / 24,8MPa}**	**140**	**304**
			Average for CH2:		**171**

Legend
CH2 – Compressed hydrogen (H_2)
CHH2 – Chemical hydride hydrogen
FC – fuel cell
MeOH – methanol (CH_3-OH)
MHH2 – hydrogen stored in a metal hydride
OEM – Original equipment manufacturer
psi – pounds per square inch

Annexure A. Fuel cell vehicles (continues)

Year	Vehicle type/model (manufacturer/OEM)	Fuel cell type; FC capacity; architecture	Fuel & {P if CH_2 psi}; Reformer?	Max. speed (km/h)	Range (km)
2001	MOVE FCV, KII, mini-vehicle (Daihatsu)	PEMFC; 30 kW; FC/battery hybrid	CH2 {3 600 psi}	105	120
	NECAR 5.2, A-class (DaimlerChrysler)	PEMFC; 85 kW; FC/battery hybrid	MeOH; methanol-reforming	150	482
	Sprinter Van (DaimlerChrysler)	PEMFC; 85 kW; FC only	CH2 {5 000 psi}	120	150
	Natrium mini-van (DaimlerChrysler)	PEMFC; 54 kW; FC/battery hybrid	CHH2 - Sodium Borohydride Mpg equivalent: 30 mpg	129	483
	Hycar (ESORO)	PEMFC; 6,4 kW; FC/battery hybrid	CH2 {-}	120	360
	Seicento Elettra (Fiat)	PEMFC – 75 kW; FC/battery hybrid	CH2 {-}	100	140
	HydroGen 3, Zafira van (General Motors)	PEMFC – 94 kW; FC only	LH2	160	400
	Chevy S-10 (General Motors/Opel)	PEMFC – 25 kW; FC/battery hybrid	Low sulfur clean petrol/CHF; reforming Mpg equivalent: 40 mpg	113	386
	Phoenix mini-van (General Motors/PATAC)	PEMFC – 25 kW; FC/battery hybrid	CH2 {-}	113	200
	FCX-V4 (Honda)	PEMFC – 85 kW; FC/ultra capacitors hybrid	CH2 {5 000 psi} 3,75 kg / 130l Mpg equivalent: ~50 mpg	140	300
	Santa Fe SUV (Hyundai)	PEMFC – 75 kW; FC only	CH2 {-}	-	402
	Premacy FC-EV (Mazda)	PEMFC – 85 kW; FC only	MeOH, methanol-reforming	124	-
	SpaceLiner (Mitsubishi)	PEMFC – 40 kW; FC/battery hybrid	MeOH, methanol-reformating	-	-
	Hydro-Gen (PSA Peugeot Citron)	PEMFC – 30 kW; FC/battery hybrid	CH2 {-}	95	300
	Taxi PAC (PSA Peugeot Citron)	PEMFC – 55 kW; FC/battery hybrid	CH2 {4 300 psi} 80l	95	300
	Covie (Suzuki)	Fuel cell only	-	-	-
	FCHV-3, KlugerV/Highlander SUV (Toyota)	PEMFC – 90 kW; FC/battery hybrid	MHH2	150	300
	FCHV-4, Kluger V/Highlander SUV (Toyota)	PEMFC – 90 kW; FC/battery hybrid (Nickel/metal hydride battery)	CH2 {3 600 psi / 25 MPa}	152	250
	FCHV-5, Kluger V/Highlander SUV (Toyota)	PEMFC – 90 kW; FC/battery hybrid	Low sulfur clean petrol/clean hydrocarbon fuel (CHF); reforming	-	
	Averages; dominant fuel and FC	**PEMFC; 62 kW; FC/battery hybrid**	**CH2 {4 300 psi / 29,6 MPa}**	**124**	**289**
			Average for CH2:		**255**

Annexure A. Fuel cell vehicles (continues)

Year	Vehicle type/model (manufacturer/OEM)	Fuel cell type; FC capacity; architecture	Fuel & {P if CH_2 psi}; Reformer?	Max. speed (km/h)	Range (km)
2002	F-Cell, A-class (DaimlerChrysler)	PEMFC; 85 kW; FC/battery hybrid	CH2 {5 000 psi} 1,8 kg Mpg equivalent: 56 mpg	140	145
	Advanced Focus FCV (Ford)	PEMFC – 85 kW; FC/battery (NiMH) hybrid FC peak power: 68 kW Acceleration (0-60 mph): 10-14 s	CH2 {5 000 psi} 4 kg Car mass: 180 kg heavier than normal car Mpg equivalent: ~50 mpg	128	290 to 320
	AUTOnomy (General Motors/Opel)	-	Mpg equivalent: 100 mpg (projected)	-	-
	Hy-Wire (General Motors/Opel)	PEMFC – 94 kW continuously and a peak of 129 kW; FC only	CH2 {5 000 psi} 2 kg Mpg equivalent: ~41 mpg	160	129
	Adv. HydroGen 3, Zafira van (General Motors/Opel)	PEMFC – 94 kW; FC only	CH2 {10 000 psi} 3,1 kg Mpg equivalent: ~55 mpg	160	270
	FCX (Honda)	PEMFC – 85 kW; FC/ultra capacitors Mass: 1 684 kg	CH2 {5 000 psi} 156,6l Mpg equivalent: ~50 mpg	150	274/ 355?
	X-TRAIL SUV (Nissan)	PEMFC – 63 kW; FC/battery (Li-ion) hybrid Maximum power: 85 kW	CH2 {5 000 psi}	145	> 350
	FCHV, Kluger V/Highlander SUV (Toyota)	PEMFC – 90 kW; FC/battery hybrid	CH2 {5 000 psi / 34,5 MPa}	155	290
	HyPower (VW)	PEMFC – 40 kW (125 cells); FC/super capacitors (360 W.h; 350V; peak 60 kW – 15 s @ 50 kW) hybrid; Electric engine – 75 kW Max. torque: 255N.m	CH2 {5075 psi / 35 MPa} Acceleration: 0-100 km/h in 12 s	-	150
	Averages; dominant fuel and FC	**PEMFC; 79,5 kW; FC/battery hybrid**	**CH2 {5 634 psi / 38,8 MPa}**	**148**	**257**

Annexure A. Fuel cell vehicles (continues)

Year	Vehicle type/model (manufacturer/OEM)	Fuel cell type; FC capacity; architecture	Fuel & {P if CH_2 psi}; Reformer?	Max. speed (km/h)	Range (km)
2003	Jeep Treo (DaimlerChrysler)	-	-	-	-
	Seicento Elettra (Fiat)	40 kW PEMFC, FC/battery hybrid	CH2 {-}	130	220
	GloCar (Ford)		-	-	-
	Kiwami (Honda)	-	-	-	-
	Grandis FCV mini-van (Mitsubishi)	PEMFC – 68 kW; FC/battery hybrid	CH2	140	150
	Effis (Nissan)	FC/battery hybrid	-	-	-
	Mobile Terrace (Suzuki)	Fuel cell only	-	-	-
	Mr Wagon (Suzuki)	Fuel cell only			
	FINE-S (Toyota)	-	-	-	-

Year	Vehicle type/model (manufacturer/OEM)	Fuel cell type; FC capacity; architecture	Fuel & {P if CH_2 psi}; Reformer?	Max. speed (km/h)	Range (km)
2004	Hyundai Tuscon FCEV, SUV	PEMFC; 80 kW; FC/battery (Li-Ion polymer) hybrid Power-to-weight ratio is similar to a conventional SUV	CH2 {35 MPa} Tank capacity: 1521 Cold weather starting capability	150	300

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Annexure B. Hydrogen internal combustion engine vehicles (ICEVs)

Year	Vehicle type/model (manufacturer/OEM)	Engine capacity; architecture	Fuel & {P if CH_2 psi}; Reformer?	Max. speed (km/h)	Range (km)
2000	Series 7, 745h sedan (BMW)	5 kW PEMFC as auxiliary power unit	Petrol/liquid hydrogen	140 mph	300
2003	Panda Hydrogen (Fiat)	-	CH2	-	-
	H2RV/Focus wagon Hydrogen research vehicle (Ford)	2,3l supercharged, intercooled H_2 ICE, Modular Hybrid Transmission System (MHTS), 288V, 3,6 Ah Advanced Li-Ion battery, 288V/14V dc to dc converter Mass: 1 551 kg Engine power: 110 hp/82 kW @ 4 500 rpm MHTS assist: 33 hp Total power: 143 hp/107 kW	CH2 {5 000 psi / 34,5 MPa} 2,8 kg of H_2 Acceleration: 0-60 mph/97 km/h = 11 s Fuel economy: 45 mile/72 km per kg of H_2 (MH cycle)		201 km 125 mi
	RX-8 Hydrogen RE (Mazda)	Rotary ICE, Hydrogen-petrol hybrid	Hydrogen and petrol	-	-

Sources and vehicles

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- Fuel Cells 2000, http://www.fuelcells.org/fct/carchart.pdf - tables with different vehicles

Annexure C. ICE/battery hybrid vehicles

Year	Vehicle type/model (manufacturer/OEM)	Engine capacity; architecture	Fuel & {P if CH_2 psi}; Reformer?	Max. speed (km/h)	Range (km)
	Prius (Toyota)	4 cylinder SI + battery 70 hp @ 4 500 rpm	Fuel consumption: 48 mpg Acceleration: 0-60 mph – 12s	100 mph	
	Insight (Honda)	3 cylinder SI + battery 67 hp @ 5 700 rpm	Fuel consumption: 57 mpg Acceleration: 0-60 mph – 12s	110 mph	

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