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Lekkas Nikolaos.

Abstract

The goal of the thesis was the research of the fuel cell technology as an opposing source of energy to the already existing ones. Apart from that, its application to the transportation domain was also investigated and a feasible suggestion is included as an early application of fuel cell technology to vehicles.

The case study emphasises the replacement of a passenger car battery with a Proton Exchange Membrane (PEM) Fuel Cell.
This type of fuel cell uses hydrogen as fuel. Properties of hydrogen are included in the report while its storage methods on-board the vehicle are analysed and the most suitable for this application is selected.

Comparisons have been made with the existed conventional power supply system regarding economic, performance and environmental issues. Finally, the further developments in the fuel cell industry are stated in order for the fuel cell technology to achieve good commercialisation.

Introduction

It is well known that world faces a huge energy problem due to oil crisis. Fossil fuels are being eliminated rapidly the last few decades while scientists are trying to find other sources of energy to supply our needs. Transportation industry comprises the most important petroleum consumer. Automobiles, trucks and buses are accounted for the main consumption of petroleum worldwide as the number of vehicles on the roads and the total miles driven each year are steadily increasing.

Environment at the same time is affected due to the tailpipe exhausts from the application above. The increased use of petroleum is contributing to air pollution. The poor air quality in many places around the world and the increasing levels of greenhouse gases in the atmosphere are national health concerns.
Alternative energy sources are lately under close investigation to yield a solution to this matter. Renewable sources are of superior interest since they can provide clean, plus efficient energy, for many applications.

Fuel cells have emerged, in the last decade, as a potential replacement for the internal combustion engine (ICE) in vehicles. Fuel cells could revolutionise the way in which electrical power is generated, because they posses the potential for high efficiency, low emissions, fuel flexibility, quite and continuos operation, and modularity. Any hydrogen rich material can theoretically serve as a source of hydrogen for fuel cells.

Leading candidates include fossil derived fuels such as natural gas, methanol, and petroleum distillates, as well as renewable fuels such as methanol, ethanol or hydrogen. Recognising the benefits from this rising technology, many countries around the world have assigned a high priority to developing fuel cell technology for both transportation and stationary applications. Fuel cells are currently being considered as a power system technology for an 80 miles per gallon vehicle under the Partnership for a New Generation of Vehicles (PNGV).

The aim of this thesis is to investigate the use of the fuel cell technology in the transportation industry. But since this new technology is in a very early stage of development it is very difficult to be able and replace the existing car engine with a fuel cell system driving the car at the moment. Further developments have first to be accomplished before the above application to be feasible.

On the other hand, many electrically applications could be powered by this coming technology without 'steeling' power from the car engine as it is being done at the moment. In this way, more power from the engine would be available to the driving wheel of the car since the energy generated from the fuel cell system would be driven to power the electric parts of the car.

Thus, replacing partially the battery of a car with a fuel cell system the author investigates, in this thesis, how this could save energy from the car engine thus improving the efficiency of it. Hence, a better view of the fuel cell technology can be obtained for the use in the transportation industry.

Energy Crisis

Oil crisis

Since the beginning of the Oil Age, the world has burned about 800 billion barrels of petroleum. Somewhere between 1000 billion and 1600 billion barrels of oil are estimated to remain in formations where production would be economically feasible. This may sound as a huge amount of petroleum waiting from humans to be discovered but in reality with the current rate of world oil consumption, 1600 billion barrels would be just enough for the next 60 years. And world consumption is steadily increasing.
Present worldwide petroleum use, already a mind – bending 71 billion barrels a day, is rising by almost 2% a year. This number may also seem to be small but in actuality a 2% annual increase doubles a figure in 34 years. An annually increase by just 2% in oil demand equals the consumption of half of the total amount of petroleum that appears economically and technologically feasible to extract by the year of 2010.
The consumption rate of growth may accelerate, depending upon the development of nation's economy and technology at the same time.

China today consumes 800000 barrels of oil daily. Again, keeping constant the rate of growth at its present value, by the year 2015, China will be importing 8 million barrels a day, which is as much as U.S imports today. In the same manner trying to forecast the future by the year 2025, China may be importing twice as much as the U.S now does. **[2,38]**

If demand continues to rise while petroleum reserves are being eliminated the oil – price equilibrium will rise too and supply will become rare relative to demand.

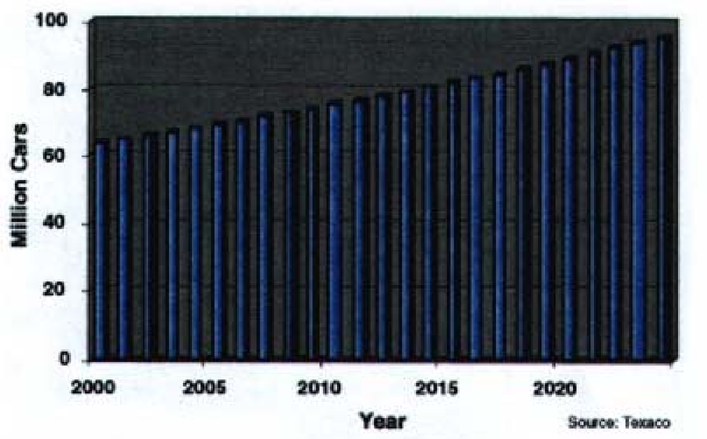
Big companies, like British Petroleum (BP) and Royal Dutch Shell (Shell), are not speaking of the decline of petroleum because they have been infected with the green virus since the latter became the first large oil company to announce support for the Kyoto greenhouse – gas reduction treaty, encouraging more efficient fossil fuel use. They want to remain large profitable fuel companies, and are simply aware that the future of energy will bring changes to the energy production. Other sources of energy are already being investigated. Energy from oil will eventually be replaced.

Alternative sources of energy existing, some producing zero harmful emissions to the environment or even wholly renewable.

Several cities around the world make use of buses and taxis that use compressed natural gas as fuel instead of petroleum, which costs less than oil and produces lower greenhouse gas emissions.

Other possible oil substitutes also exist. Hydrogen made from natural gas or even by using solar energy might power fuel cell vehicles producing no emissions of any kind other than water vapor. An energy economy based on solar power would be totally renewable since its driving source would be the sun.

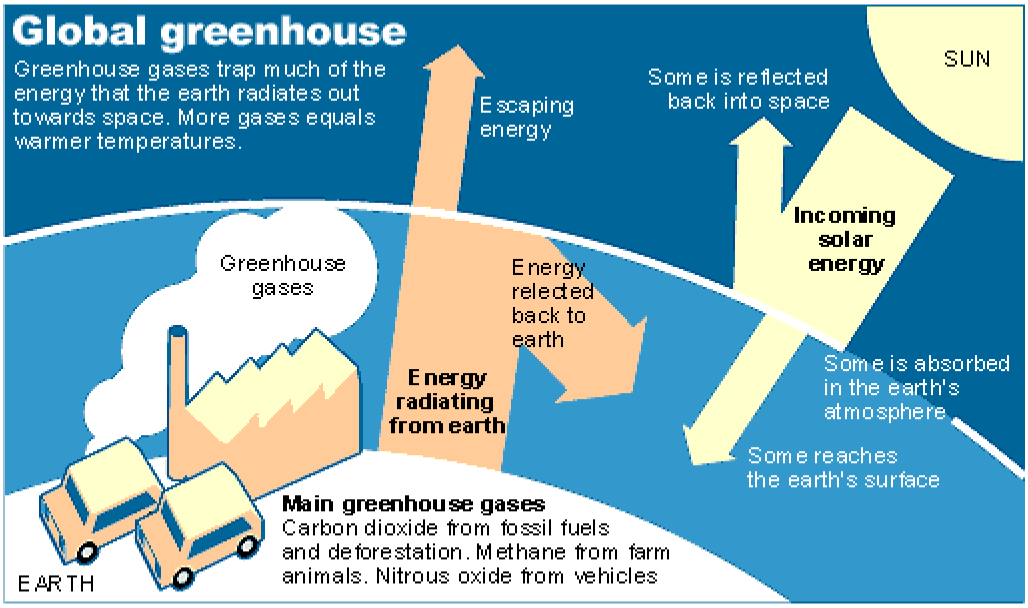
It is estimated that world car production will approach 100 million by 2025, see figure below. At first sight, this increase in car numbers would signify disaster for air quality worldwide. Therefore, in the transportation industry many companies have shown their interest in finding other sources of energy to give power to their products. Their main interest is concentrated on fuel cell technology and they look promising to give real examples in the near future. **[47]**



The greenhouse effect

The 19th century scientist Jean Fourier made up the term greenhouse effect. The greenhouse effect takes place when greenhouse gases allow sunlight to reach the earth's surface but absorb or scatter most of the heat emanating from the earth's surface, thus retaining heat in the atmosphere. Without the natural greenhouse effect, the average temperature would be about –18°C, or –0.4°F. Although the terms greenhouse effect and global warming are used due to their familiarity, the concept at issue here is actually infrared absorptivity of greenhouse gases.

The following figure illustrates what really occurs at earth's surface:



During the past decade, people have become concerned with how human activity may be affecting the world's climate. This concern has focused mainly on anthropogenic greenhouse gases. That is the greenhouse gases generated by human activity such as the combustion of fuel for transportation. These gases magnify the natural greenhouse effect due to the fact that they absorb infrared radiation emitted from the earth's surface, increasing the heat trapped inside the atmosphere.

Greenhouse gases occur naturally in the atmosphere and they are very important to life on earth in its present form. The concern is reinforced when human activities contribute to the increase of the atmospheric greenhouse gases concentration and thus the effect of global warming occurs, having impact to the environment.

The major greenhouse gases are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), fluorocarbons and ozone (O_3). From all these gases carbon dioxide is mostly discussed. Nonetheless, water vapor is the most important greenhouse gas due to its abundance since it represents about three percent of the gases in the earth's atmosphere. Again, water vapor together with carbon dioxide, are the two major products of all hydrocarbon fuel combustion.

Water vapor is the predominant absorber of incoming solar radiation and a major contributor to the natural greenhouse effect. **[43,48]**

The main source of greenhouse gases is the combustion of fossil fuels. Universally, fossil fuel combustion is accounted for over 70% of all human carbon dioxide emissions. Fossil fuels are also a source of nitrous oxide, methane and ozone.

There are four principal strategies available for reducing fossil fuel use and carbon dioxide emissions. Switching from coal and oil to natural gas, improving energy efficiency, expanding the use of nuclear power and developing renewable energy sources.

Using natural gas instead of coal and oil, environment is benefited since the harmful emissions to the environment are reduced. The disadvantage of this kind of energy is that natural gas reserves are limited and hence, its contribution would not last for long enough.

Attempts to increase the energy efficiency have been reported to the past by making use of waste energy but the total cost is then rapidly increased.

In the case of nuclear power many different aspects are employed such as the careful discharge of the radioactive materials, which may cause harm to the environment or the human kind.

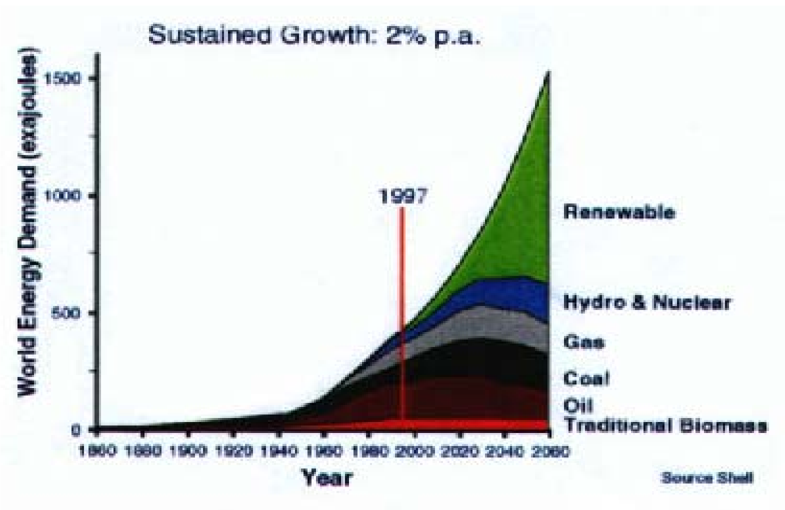
Therefore, renewable sources might yield a solution to this energy matter and also can be friendly to the environment at the same time.

Renewable sources

The following briefing is based on the construction paper 1) 'New and Renewable Energy: Prospects for the 21-Century'. **[46]**

Since predominantly based on fossil fuel energy resources, today's societies have to face two basic issues regarding their future energy supply. First, fossil energy is becoming increasingly scarce, and second, the combustion of fossil fuels contributes significantly to environmental deterioration. The need for sustainability requires a search for new and renewable energies based on non fossil fuels which are continuously and sustainable available in our environment. These sources produce significantly lower levels of environmental pollutants than conventional sources of energy, in particular, they generally emit no greenhouse gases or are neutral over their life cycle in greenhouse gas terms. The transfer of new and renewable energies into a competitive product on the domestic market poses a challenge for future activities in the construction sector regarding new energy plants and associated projects, and it may also turn into an opportunity to enter a new global market.

As clearly shown on the following diagram, renewable sources are likely to make up more than 50% of the total energy supply after 2050. While, the use of oil will start to decline after the year 2020. The message someone can get from the diagram is quite simple. The power plant for the car industry will need to use a fuel that can be derived from a variety of sources. This means that major structural changes are needed in the infrastructure of fuel supply and the car industry itself.



Various technologies underlying new and renewable energy sources are summarized below:

Solar energy: Solar technologies use the sun's energy and light to provide heat, light, hot water, electricity, and even cooling, for homes, businesses, and industry.
According to the various technologies in use three categories of solar energy are distinguished:

Passive Solar Design uses the form and fabric of a building to capture solar radiation and so reduce the building's energy needs for artificial light.

Active Solar Heating employees collectors to capture and store the sun's heat primarily for space and water heating.

Photovoltaics involve the direct conversion of light energy from the sun into electricity by means of specially prepared semiconductors.

Wind power: Wind energy uses the energy in the wind for practical purposes like generating electricity, charging batteries, pumping water, or grinding grain.
Wind energy is very widespread, with wind mean speeds in excess of 5m/s being quite common. It is not in general a predictable or dependable energy source, although there are exceptions: thermally driven winds around the edges of desert regions will exhibit a daily cycle. Wind is a diffuse source of energy, and outputs from turbines are unlikely to reach 100 Watts per square meter of rotor area, on average throughout a year. So if substantial amounts of power are required, very large of areas of wind must be intercepted.

Tidal power: Tidal power traditionally involves erecting a dam across the opening to a tidal basin. The dam includes a sluice that is opened to allow the tide to flow into the basin, the sluice is then closed, and as the sea level drops, traditional hydropower technologies can be used to generate electricity from the elevated water in the basin.
The energy potential of tidal basins is large — the largest facility, the La Rance station in France, generates 240 megawatts of power.

Hydropower: Flowing water creates energy that can be captured and turned into electricity. This is called hydropower. Hydropower is currently the largest source of renewable power.

The most common type of hydropower plant uses a dam on a river to store water in a reservoir. Water released from the reservoir flows through a turbine, spinning it, which, in turn, activates a generator to produce electricity. But hydropower doesn't necessarily require a large dam. Some hydropower plants just use a small canal to channel the river water through a turbine.

Wave energy: Wave power devices are designed to absorb the energy present in the motion of the waves and convert it into electricity. Developing and commercialising the related technology would induce a major contribution on the supply of energy to islands.

Geothermal: Geothermal energy is the energy that earth generates in the form of heat. Geothermal is the world's largest energy resource. It contributes to our world's energy needs today and the potential for greater use tomorrow as energy generation becomes a very important subject nowadays. By the use of geothermal activity, electricity can be produced for heating purposes or even cooling. The main advantage by using this method of electricity production is that geothermal energy is clean and the environment is not affected.

Biomass: All the earth's leaving matter, its biomass, exists in the thin surface layer called the biosphere. It represents only a tiny fraction of the total mass of the earth, but in human terms it is an enormous store of energy. More significantly, it is a store which is being replenished continually. The source which supplies the energy is the sun. although just a small fraction of the solar energy is reaching the earth each year is fixed by organic matter on land, it is nevertheless equivalent to some eight times our total primary energy consumption. This energy stored in plants is recycled naturally through a series of conversions involving chemical and physical processes in the plant, the soil, the surrounding atmosphere and other living matter, until it is eventually radiated away from the earth as low – temperature heat – except from a small fraction which may remain in a tiny proportion which may slowly become fossil fuel energy.

The importance of this cyclic process for humans is to be able and capture some of the biomass at the stage where it is acting as a store of chemical energy, thus collecting valuable energy.

Biofuels: biofuels are any solid, liquid or gaseous fuels produced from organic matter, either directly from plants or indirectly from industrial, commercial, domestic or agricultural waste.

Fuel Cells: fuel cells convert the chemical energy of the reaction between a fuel and an oxidant directly into electricity. This energy source is considered to be a non-polluting power source, efficient that produces no noise or any harmful emissions to the environment. Such cells are used to provide electricity on spacecraft since 1960s. In more down to earth applications, they could be used as electricity generating plants or as a power source for nearly exhaust free automobiles. The main disadvantage of fuel cell is their high cost of manufacture but now falling prices and new technologies suggest that that the fuel cell's day may finally have arrived.

Renewable energy sources tend to have relatively high capital costs, because normally they use dispersed source with low energy concentrations compared to fossil fuels, e.g. wind, water.
Since they depend generally on natural processes involving weather conditions, the security is not always the same as with fossil fuels and the range of sources available internationally will vary significantly from country to country.

Renewable energy sources are estimated to meet between 15 and 20 percent of current final world energy consumption, while meeting around 6 percent of European energy demand. They are seen by many institutions projecting future energy needs as making an increasing contribution in the medium term and playing a very significant role in the long term.

The current emphasis on sustainability and CO2 reductions has led most countries to institute policies and programs to assist renewable sources to become competitive on a widespread basis and to promote their deployment.

Estimates based on World Energy Council projections indicate cumulative investment in renewable energy sources ranging from £150 billion to £400 billion between 2000 and 2010. **[4,37,43]**

Summarising all of the above it can be said that renewable energy sources seem to be promising a new way of producing energy, better and cleaner from the energy produced from the burnt of oil.

With the passage of time, and as the fossil fuel reserves are getting smaller, renewable source of energy will eventually bring changes worldwide in the energy sector as they may offer a solution to the matter above.

Fuel Cells – Transportation

What is a Fuel Cell

Fuel cells are devices that can generate electricity by converting chemical energy into electrical power without any moving parts. Power generation via fuel cells is a rapidly emerging technology that provides electricity with high efficiency and low noise. Fuel cells provide the opportunity to transition from fossil fuels, such as natural gas, methane, and liquid hydrocarbons, to what many consider to be the fuel of the future: hydrogen. The oxygen used in the fuel cell is atmospheric oxygen and the hydrogen is either elemental hydrogen or hydrogen extracted from hydrocarbon fuels using a device called a reformer. Fuel cell power plants that produce up to 11,000 kW have been built from multiple 200 kW units.

History of fuel cells

It was not earlier than the year 1839 that Sir William Grove made his personal contribution in the invention of a new technology concerning the production of electric energy.
Sir William Grove managed to show that the water electrolysis in dilute sulphuric acid was reversible. And that was the first step to the fuel cell discovery. He found that water could be split into oxygen and hydrogen by making use of a cell with two platinum electrodes in an aqueous solution of an acid. Not even that, a cell voltage was also measurable when the current was interrupted. After supplying hydrogen and oxygen to the electrodes a current flew into the cell and then it was possible to gain electricity from the system.

With the passage of years, another man, called Bacon, was to continue Sir William Grove's experiments.

Bacon had the idea to use nonoble catalysts. Fuel cell technology gained another step forward when the same man managed to control the electrode's porosity. That was something that caused the available reaction rate to increase rapidly.
In the following years Allis Chalmers succeeded to demonstrate a fuel cell powered tractor.

Next to contribute in this technology was the National Aeronautics and Space Administration (NASA) agency in the late 1950s.
NASA agency was keen on a small power generator that could provide power to spacecraft while on space missions. As nuclear power termed "risky", from the same agency, and batteries where to heavy and short lived for such applications, fuel cell technology was next to be analysed to yield a possible solution.
Hence, fuel cell industry benefited since NASA funded more than 200 research contracts into all aspects of that technology.
Today, fuel cells have proven their valuable role in space since they constitute a very significant source of power for many spacecraft applications.

Small size, high efficiency, low emissions, minimal water use or net water productions all these characteristics of a fuel cell make possible its application to stationary power producers too.
It has finally become clear that fuel cells represent an alternative source of energy that may yield a solution to the worldwide energy crisis. **[3]**

Fuel cell operation

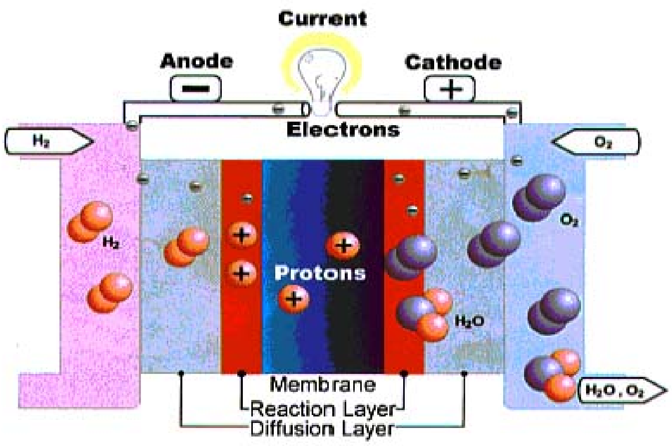
The operation of a fuel cell is very simple. Its basic principle of operation is similar to that of a normal battery. Unlike the latter, a fuel cell always operates at certain value of efficiency without running down or requires recharging. Fuel cells will continuously producing energy in the form of electricity and heat as long as fuel is supplied.

A fuel cell consists of two electrodes placed around an electrolyte. In the case of a hydrogen oxygen fuel cell, oxygen passes over one electrode and hydrogen over the other, generating electricity, water and heat. Hydrogen fuel is fed into the anode of the fuel cell. On the other hand oxygen, or air passes through the cathode to enter the fuel cell. The hydrogen atom splits into a proton and an electron, which take different paths to the cathode, with this reaction being encountered by a catalyst, and the proton passes through the electrolyte.

The electrons create a separate current that can be utilised before they return to the cathode, to be reunited with the hydrogen and oxygen in a molecule of water.

A fuel cell system that includes a fuel reformer can utilise the hydrogen from any hydrocarbon fuel, from natural gas to methanol, and even gasoline.

For a better understanding of how a fuel cell works, let as consider the **Proton Exchange Membrane (PEM)** fuel cell case shown on the figure below.



The **PEM** lies at the center of the fuel cell. As shown above, it is surrounded by two layers, a diffusion and a reaction layer. Hydrogen and oxygen are constantly supplying the fuel cell. The hydrogen diffuses through the anode and the diffusion layer up to the platinum catalyst, which is the reaction layer. The reaction between hydrogen and oxygen results in the current diffusion.

There are two electrochemical reactions taking place during the fuel cell operation. One occurs at the anode while the other one occurs at the cathode.

The reaction, which takes place at the anode, releases hydrogen ions and electrons whose transport is very important to the energy production.
More specifically the reaction at the anode is:

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

The hydrogen ion on its way to the cathode passes through the polymer membrane while the only possible way for the electrons is through an outer circuit. Then, the hydrogen ions together with the electrons of the outer electric circuit and the oxygen that has diffused through the porous cathode reacts and forms water.
This reaction is given to be:

$$2H^+ + {}^1/_2O_2 + 2e^- \rightarrow H_2O$$

As someone may notice from the above reaction, water is being produced. This water is extracted from the system by the excess air flow.
The reaction is:

$$H + {}^1/_2O_2 \rightarrow H_2O$$

This process occurs in <u>all</u> types of fuel cells. **[49]**

Fuel Cell types

Fuel cells are currently under research and development. There are different types of fuel cells each type with different characteristics. In this part of the thesis report these types of fuel cells are summarised as follows:

The Solid Oxide Fuel Cell (SOFC)
The Molten Carbonate Fuel Cell (MCFC)
The Phosphoric Acid Fuel Cell (FAFC)

The Alkaline Fuel Cell
Direct Methanol Fuel Cell (DMFC)
Solid Polymer Fuel Cell (SPFC)

The Solid Oxide Fuel Cell (SOFC)

This type of fuel cell operates at temperatures around 1000 °C. The SOFC is not the most reactive fuel cell due to the low conductivity of its yttria – stabilised zirconia electrolyte. This type of fuel cell has reached 50% efficiency on converting chemical energy to electrical. Moreover, the heat produced from its operation may be used in co-generation of steam turbine for additional power. In this way the overall efficiency of the SOFC is increased to a greater value than 50%. This application has been applied to large power plants.

Due to its simplicity, SOFC is considered to be the most desirable fuel cell for generating electricity from hydrocarbon fuels. Nevertheless, using other fuel than hydrogen will have an effect on the nature of emissions and, hence, to the environment.

The SOFC has three designs. Tabular, planar and monolithic types.

The Molten Carbonate Fuel Cell (MCFC)

This fuel cell is named Molten Carbonate after its electrolyte, which uses molten alkali carbonate mixture, retained in a matrix. The operating temperature for this type of fuel cell is about 650 °C. The MCFC may use carbon monoxide as a fuel input on the cathode side but needs hydrogen on the anode.

A disadvantage of MCFC is that small quantities of sulphur may damage the cell. Carbonate ions produced at the cathode and flow across the membrane to react with hydrogen and form two electrons, water and carbon dioxide. It has the ability to reform inside the stack. The efficiency of such fuel cell may reach up to 60% when operating on natural gas.

The Phosphoric Acid Fuel Cell

The Phosphoric Acid Fuel Cell (PAFC) has been under development for the last 15 years as an electric power plant. This type of fuel cell is the oldest one using phosphoric acid as its electrolyte. Different acids have been tested for the improvement of the fuel cell efficiency. PAFC has the ability to reform methane to a hydrogen rich gas for use as fuel together with the waste heat from the fuel cell stack.
PAFC is ideal for use in small power plants due to its lower temperature which may be around 200°C. The efficiency of the PAFC is low, compared to other fuel cells, around 40%. Again, the overall efficiency may be increased if the heat generated from its operation is used for heating purposes. Therefore, making use of energy that considered to be wasted. Methanol or ethanol can be used as fuels for this type of fuel cell but caution has to be paid to avoid poisoning the anode by carbon monoxide and hydrogen sulphide.
The PAFCs are currently available at the price of about $2875.00 per kilowatt by International Fuel Cells.

The Alkaline Fuel Cell

This type of fuel cells employees a solution of potassium hydroxide in water as the electrolyte. Carbon dioxide may harm the electrolyte. Hence, this type of fuel cell is limited to applications where pure hydrogen and oxygen are available.
The Alkaline fuel cell operates in temperatures between 50°C and 250°C and has been successfully been used in space missions where its application was extended to drinking water production for the crew of the space shuttle.

Direct Methanol Fuel Cell (DMFC)

As the name of this fuel cell type indicates, direct methanol is used as fuel without being reformed to hydrogen. The Direct Methanol Fuel Cell is better applied to very small plants since its operating temperature is very small (50°C – 100°C). DMFC uses a thin polymer as an electrolyte. The further development of this fuel cell has been abandoned in the past due its low efficiency, about 25%, but after huge improvements in the last few years DMFC is again under research and development since it is nowadays believed that its efficiency can reach 40% in the near future. It is also believed that if the efficiency of the fuel cell above reach even greater values then it can satisfactorily be used in transportation.

Solid Polymer Fuel Cell (SPFC)

The Solid Polymer fuel cell is also known as the Proton Exchange Membrane Fuel Cell or Polymer Electrolyte Fuel Cell (PEFC). The operating temperature in the case of SPFC is about 90°C a perfluorinated sulphuric membrane is used as an electrolyte between the two platinum catalysed porous electrodes. Pure hydrogen and oxygen are used as inputs to the fuel cell. There are many companies producing SPFCs, the best known is Ballard Power Systems Inc.

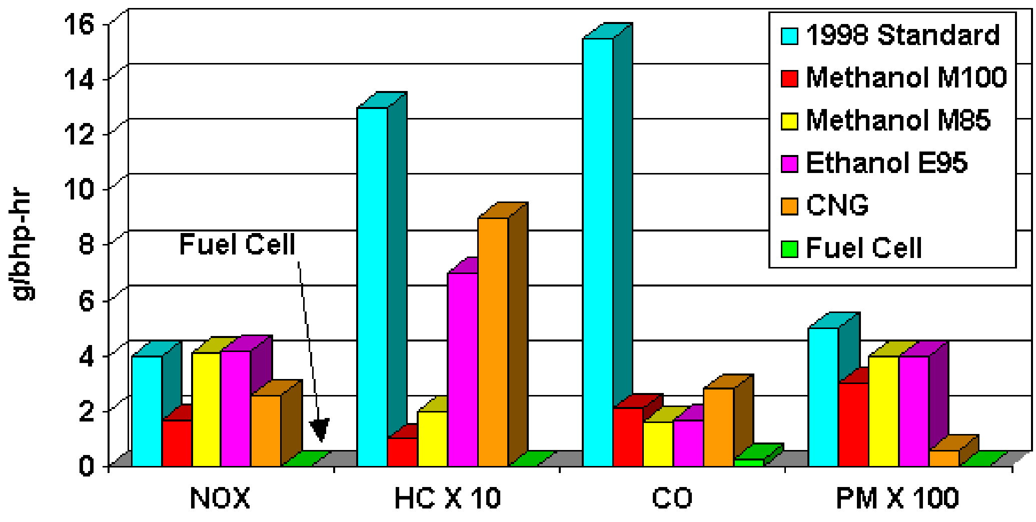
SPFC is better applied to transportation since it uses a solid electrolyte and therefore it is considered to be safer than other type of fuel cells.

The main characteristics of the fuel cell types are summarised below:

Type of fuel cell and of fuel	Fuel efficiency (%)		Power density (mW cm^{-2})		Rated power level projected (kW)	Lifetime projected (h)	Capital costs projected ($/ kW)	Applications, time frame
	Present	Projected	Present	Projected				
Alkaline H_2	40	50	100-200	>300	10-100	>10000	>200	Space 1960- Transportation 1996- Standby power 1996-
Phosphoric Acid;CH_4,CH_3OH	40	45	200	250	100-5000	>40000	$1000-	Onsite integrated energy systems peak sharing 1992-
Molten carbonate; CH_4 ;coal	45	50-60	100	200	1000-100000	>40000	$1000	Base load and intermediate load power generation, cogeneration 1996-
Solid oxide fuel cell CH_4 ; coal	45	50-60	240	300	100-100000	>40000	$1500	Base load and intermediate load power generation, cogeneration 2000- Regenerative 2010- Space and terrestrial Space
Solid polymer H_2 ; CH_3OH	45	50	350	>600	1-1000	>40000	>200	Space 1960- Transportation 1996- Standby power 1992- Underwater 1996-
Direct methanol $CH_3O + 1$	30	40	40	>100	1-100	>10000	>200	Transportation 2010- Remote power 2000-

Environmental impacts

Each fuel cell type has different impact on the environment according to the fuel used. In the case where only hydrogen is used, the emissions to the environment are zero since heat and water are the only by-products from the fuel cell operation. Hydrogen though, it is not often used due to problems related to hydrogen storage and transportation. In the future many people have predicted the growth of a 'solar hydrogen economy' known as water electrolysis. In this case fuel cell powered vehicles or even fuel cell power plants would have minimal pollution to the environment.



Comparison of Pollutant Emissions of Vehicle Power Systems as compared to the 1998 Standards

When methanol produced from biomass, is used as fuel, fuel cells emit no carbon dioxide. Its high temperature combustion, similar to the ones that take place in an internal combustion engine fuelled by methanol, produces NO_x gases, which contribute to acid rain. Fuel Cells, on the other hand, eliminate NO_x emissions due to their lower temperature of their chemical reactions.

Fuel cells, when using processed fossil fuels, still have CO_2 and sulphur emissions but these are significantly lower than those from traditional thermal power plants or internal combustion engines due to their higher efficiency of fuel cell technology. **[43]**

Other engineering benefits associated with Fuel Cell technology

As it has already been discussed above, Fuel cell technology offers a great alternative source of energy. Apart from that, environment plus humans are being benefited from its operation since it can produce clean energy at low noise levels compared to other conventional energy systems.
As far as the 'engineering benefits' are employed these can be summarised as follows: **[42]**

Efficiency benefits:
Electrical efficiency can theoretically reach 85% in the case of a fuel cell plant. In practice though, it can nowadays achieve an efficiency value of about 55% at atmospheric pressure and about 60% with pressurised systems. Even higher efficiencies may be achieved but the total fuel cell cost would increases rapidly.

The above high efficiencies can be achieved over a wide range, linearly from 30% until full load. Diesel engines only come close to these efficiencies and only at a full load. Due to the fact that most of the electric generators are over sized for loading considerations, fuel cells have even greater efficiencies compared to conventional technologies with respect to generation load equivalency. Apart from that, when fuel cells producing zero energy their fuel consumption is also zero. On the other hand, motor driven generators use 5 –15 % of full power under the same conditions.

Also, in the case of energy transmission, a great amount of money can be saved in the case of fuel cell system since such power station can easily be located very close to loads and therefore transmission lines plus losses, may be decreased.

Fuel Flexibility:
The optimum fuel for the operation of a fuel cell system is considered to be hydrogen. Hydrogen cannot be found 'free' on nature but it may be produced by various methods.
These methods include Steam Reforming, Water Electrolysis, Photoconvertion, Photoelectrochemical electroproduction, Pyrolysis of Biomass.

Fuel Cells, may even be operated by using alcohol (methanol, ethanol) as a fuel apart from hydrogen.
Ethanol is ideal fuel for portable fuel cell system. Ethanol and methanol can be produced from either natural gas or biomass.

<u>Size of Fuel Cells:</u>
Each fuel cell, individually, can produce an output voltage of 0.6V up to 1.23V. Therefore, for the needs of higher values of electricity these fuel cells can be put together to yield the required energy output. They can form a fuel cell stack, producing the voltage levels required. Fuel cells may be connected together either in series or in parallel according to the output requirement.
The current produced from a fuel cell is proportional to the area of the electrode. Therefore taking into consideration all these parameters, a fuel cell can be constructed in virtually any size, voltage or frequency desired.

<u>Reliability and Lifetime:</u>
Due to the fact that fuel cells are very simple in their design and operation, they are considered to be very reliable. Even prototype fuel cell versions have reported very reliable showing no crucial problems during their operation.
Fuel cells have a projected life of 40000 hours of operation at full load and even more when operating at lower power levels. Fuel cell operation is required to pause only once or twice a year for routine inspection.

Problems related to Fuel Cell Technology

The main disadvantage of the fuel cell technology is the manufacturing cost of such cell. More specifically, while the manufacturing cost of an automotive internal combustion engine power plant lies on the range of $25 – 35 /kW, a fuel cell system costs something less than $50/kW for the technology to be competitive. A basic reason that affects the cost of the construction of a fuel cell power plant system is that the number of such systems that currently being produced is very small and thus makes it expensive. And those that are being produced are constrained to small power

output compared to conventional power systems, thus resulting in insufficient economy of scale. Another thing is that fuel cell technology is still under research and development while manufacturing has been accomplished in laboratories and not at any plants of mass production, meaning that optimised techniques are still to be refined. Also another parameter that affects the manufacturing cost of a fuel cell is its own materials whose price is very expensive. High priced materials, especially the use of precious metals to catalyse internal fuel cell reactions, are prohibitively expensive.
Finally, the absence of a history of widespread use and lack of general public acceptance of fuel cells represent another development barrier.

In the transportation domain, fuel handling and fuel processing of a fuel cell is of high importance and manufacturing companies are currently trying to make another step forward to this topic. For example, Proton Exchange Membrane (PEM) fuel cell, which is considered as the most suitable fuel cell for transportation applications, runs on clean hydrogen fuel. Consequently, restrictive requirements must be placed on the processing of transportation fuels such as gasoline and methanol to eliminate compounds that could poison the cells. So the development of an efficient reformer technology is of major concerns. Another key element that is also under research and development is the storage and the direct use of hydrogen as a fuel.

Fuel Cell Technology applying to Transportation

Nowadays, government and industry around the world are currently facing the challenge of a growing demand for transportation services while minimizing the adverse energy and environmental impacts. Fuel cells, on the other hand, are lately under development phase in order to provide us with an efficient alternative source of energy to replace the existing internal combustion engines in all areas of transportation. Accordingly, both the United States and the European Community, have shown their interest on fuel cell technology and have assigned high priority to the research and the development of this technology in order to accelerate their use in the transportation sector. **[39]**

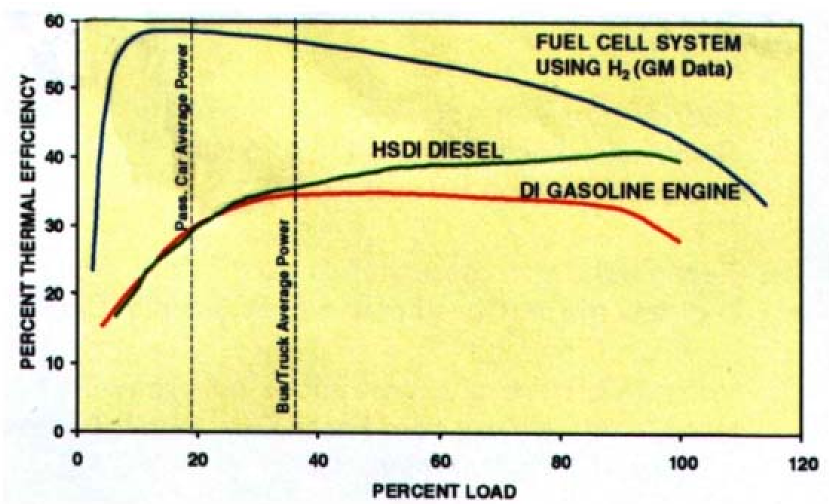
Fuel cell characteristics (high efficiency, low emissions, fuel flexibility, low noise and vibration etc.) make feasible the fuel cell application in transport.

In the European Community, more or less 20% of the primary energy is being used mostly for road transportation. The emissions to the environment and basically about the 60% of the NO_x emissions and a great portion of the hydrocarbon (HC) and CO emissions are being emitted from transportation. The adverse energy and environmental impacts of transportation are forecast to worsen on the following years due to the fact that the number of vehicles, together with the number of miles driven by each car, increases.

Therefore, the current energy and environmental concerns have led the governments to implement regulations requiring greater fuel efficiency for new models.

Proton Exchange Membrane (PEM) fuel cells fulfill the above requirement since their fuel efficiency lies between 35 – 40 % while the fuel efficiency of internal combustion engines lies on the range of 10 – 20 %.

The figure below demonstrates the efficiency curves for a High Speed Direct Injection Diesel (HSDI), which is considered to be the most efficient car engine available, a direct injection gasoline engine, the latest more efficient gasoline engine, and finally the theoretical curve for a fuel cell engine fuelled by hydrogen.



As someone may observe from the figure above, in the case of the fuel cell engine, the maximum efficiency is reached at about 20% load and this is the average load for a passenger car engine.

Daimler – Chrysler, back in September 1997, revealed its fuel cell powered NECar3 in Germany, the one shown on the picture below, and later on in March 1999, the same company announced the first zero-emission fuel cell car in the US (NECar4).
Daimler – Chrysler plans to be producing between 40000 and 100000 fuel cell powered cars per year by 2004 or 2005.

A Mercedes test vehicle that runs on fuel cell technology

The cost of the NECar4 was $30000 which is considered to be extremely high price compared to the price of a conventional internal combustion engine powered car.

Other automobile makers have also shown their personal interest on this technology and have assigned first priority the construction of such vehicles powered by fuel cell energy. Among these automobile makers are Ford Motor Corporation, General Motors, BMW, Peugeot, Citroen, Renault, Volkswagen, Volvo, Toyota, Mazda, Nissan, Honda, Daewoo Motor, Hyundai and Mitsubishi.
Most of these companies are willing to be able and produce fuel cell vehicles by the year 2004 – 2005.

Fuel Cell Vehicle Fuel

A very important factor for the operation of a fuel cell vehicle is its own fuel that is used to power the vehicle itself. There are basically two categories that concentrate most of the interest.

- The use of hydrogen as a fuel in Fuel Cell Vehicles
- The use of methanol or natural gas as a fuel in Fuel Cell Vehicles

The first category is the most important one. By using hydrogen as a fuel high efficiencies can be achieved (50 – 60 %). Not even that, when hydrogen is produced by electrolysis using renewable or nuclear electricity, none of any hazardous substances, such CO_2 or any other pollutant to the environment, is formed. Even when hydrogen is produced by natural gas, by the use of stationary reformers, overall pollutant emissions are between 100 and 1000 times less than for internal combustion engine driven vehicles.

When falling into the second category, a fuel reformer is established. When alcohol (methanol or ethanol) is used then an on-board reformer is used to convert the alcohol into hydrogen to power the fuel cells. Thus, the fuel cell system structure is now more complex due to the fact that primary fuel has to be converted into hydrogen for the operation of the fuel cell engine.

Again, emissions are much lower than those from the internal combustion engine driven vehicles. Another advantage is that refuelling in this case requires an infrastructure very similar to the existing liquid fuel distribution systems, consequently no further research has to be carried out for the construction of such an infrastructure.

Concluding, it has to be pointed out, that the first option is more favourable over the second one, because when an on-board reformer is established, for the conversion of natural gas or methanol into hydrogen, start up time gets longer, CO emissions have to be cleaned up, transient response gets slower and there is always the need for additional components such as batteries. So, further researches and developments have still to be carried out to yield improvements to the fuel cell performance characteristics.

Hydrogen as a transportation fuel:

Hydrogen is considered by many to be the optimum fuel for the fuel cell operation. The storage of hydrogen on board a fuel cell vehicle simplifies the power generation system design since it does not require an on board fuel processing. It also results in a more energy efficient system.

Since hydrogen is a gas, a relatively large volume is required to contain enough energy to provide the same driving range as today's automobiles. Therefore the most discussed methods of storing hydrogen on board the fuel cell vehicles are the following two:

- Compressed gas in storage tank at high pressure.
- Liquid hydrogen in insulated storage tank at low temperature and pressure.

Other methods include the use of metal hybrids, solid adsorbents and glass micro spheres but are not very well developed yet and their use is not yet feasible.

The fact that hydrogen is highly flammable gas, its use as fuel is not discouraging if the right engineering attention is paid. In other words, hydrogen can be as safe as the current fuel systems in automobiles.

Safety tests performed by Ford Motor Company have found that the technologies being tested for the hydrogen storage on board a fuel cell vehicle are actually safer than storage gasoline due to four factors stated below:

- Carbon fibre wrapped composite storage tanks are able to withstand greater impacts than the vehicle itself without any failure, thereby minimising the risks of a hydrogen release as a result of a collision.
- Hydrogen, if released, disperses much faster than gasoline due to much greater buoyancy, reducing the risks of a post collision fire.
- The fuel cell vehicle would carry 60% less total energy than a gasoline or natural gas vehicle, resulting in less potential hazard should it ignite.
- The fuel cell vehicle design includes an inertial activated switch that may simultaneously shut off the flow of hydrogen in the case of a collision and also cut the electrical power from the battery to prevent any possible hydrogen explosion.

Therefore, if all the required precaution is taken, hydrogen is no longer considered as dangerous fuel for on board vehicle storage. On the other hand it can be intrinsically clean if it is produced by the electrolysis of water with renewable electricity.
The following three conclusions where made from a European Community workshop on 'Hydrogen for Transportation'

- The use of hydrogen in ground transportation can reduce pollution.
- Internal combustion engines fuelled by hydrogen could come close to offering zero emissions and they can be made available soon.
- Fuel cell vehicles using hydrogen as fuel are true zero emission vehicles and offer a much higher efficiency than combustion engines.

Apart from storing hydrogen on board a vehicle, another issue has also to be concerned and this is the hydrogen refuelling stations.
As vehicles, powered by conventional internal combustion engines, have to make a stop at any petrol station for refuelling purposes, fuel cell vehicles also need to make their 'refuelling stop' at similar stations that may supply the vehicles with hydrogen instead of gasoline or natural gas. Thereby, a hydrogen infrastructure has also to be taken under consideration and development at the same time.

In spite of the fact that this kind of technology seems to be very expensive to be applied on transportation, in the long run it could be proved to be cheaper to operate due to fuel savings. **[42]**

Commercialisation Issues – Comparisons and Conclusions

As already discussed, the Fuel Cell Vehicle under successful development and commercialisation can provide worldwide benefits. Improved air quality, reduced emissions of greenhouse gases, energy and economic savings, reduced petroleum dependence and increased use of alternative fuels and renewable sources are the basic ones.

Even though internal combustion engines, that are being used for over hundred years, have made huge technological improvements they still need to be developed further in order to be highly comparable to new technologies such as the fuel cells may provide. Fuel cells, even at this early stage of development may reach very high efficiency values (up to 50 or even 60 percent) even double from those values obtained from the internal combustion engines. Apart from that, fuel cells may reach high levels of efficiency even at low loads. As already been discussed, fuel cell powered vehicles are friendly to the environment. Because of that, by fitting fuel cell engines to both light and heavy duty vehicles, pollutant emissions to the environment may theoretically be eliminated.

Right commercialisation is a key factor for fuel cell technology application in the transport domain.

Fuel cell prospects are very encouraging in the long term. But even at the short term Fuel Cell Vehicles are highly comparable to other advanced alternatives. They can compete with conventional internal combustion engine driven vehicles in many areas (see above). Likewise, Fuel Cell Vehicles may compared with the battery powered electrically vehicles, since they do not have long recharging time or have any strict mileage range to be covered before they need to be refuelled as battery powered electric vehicles may have.

Fuel cell technology can be applied to all areas of transportation, ranging from passenger cars to heavy lorries, trains or even submarines. All these applications tend to increase the market for Fuel Cell Vehicles and reinforce their potential for global benefits.

However, the cost for such application of a fuel cell is a drawback due to the fact that this technology is in early stage of development and its use can be proved costly especially in the short term application. Recent studies though, have shown that people is willing to try this new technology and purchase themselves 'clean' vehicles.
Automobile makers believe that Fuel Cell Vehicles would be highly competitive with the existing Internal Combustion Engine cars if they could be priced lower. Only then Fuel Cell Vehicles could attain a very good position in the marketplace. If the levels of Fuel Cell Vehicles production increase, economies of scale should help to reduce the total purchase cost.

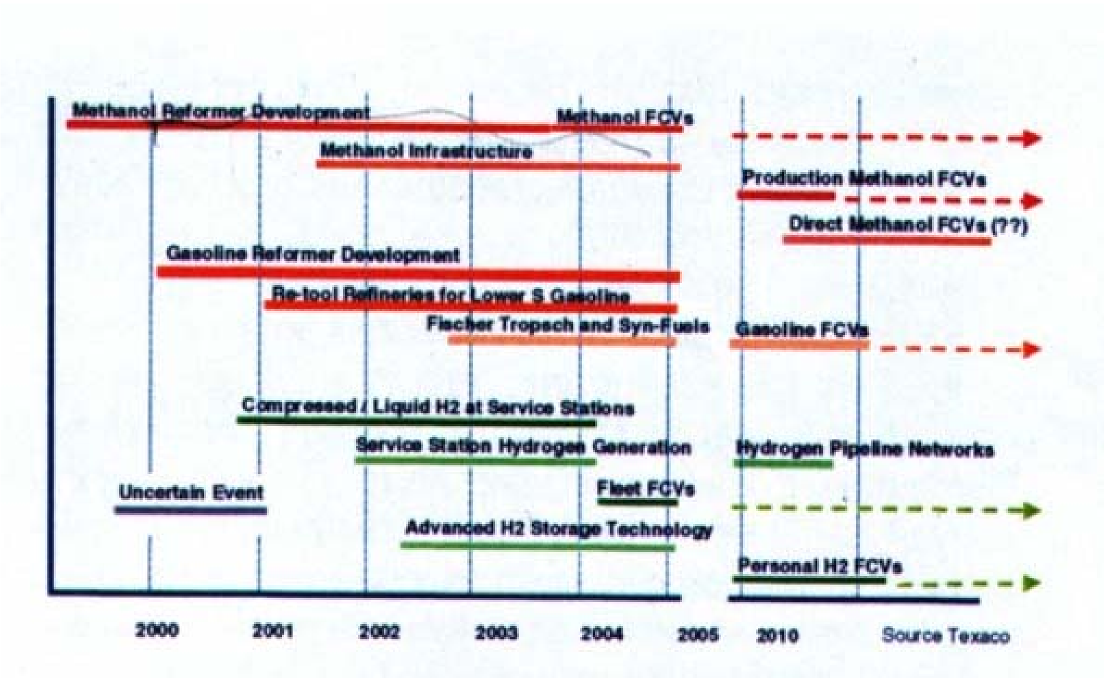
Another key parameter that benefits Fuel Cell Technology is that Internal Combustion Engines are not capable of meeting any stricter environmental regulations. Its development cannot offer much more in this domain. Even then, if they do further be developed to meet new requirements their cost would be rapidly increased having bad influence to their marketplace.

Fuel cell vehicles, together with all the advantages that they can offer worldwide they will be much more preferable than Internal Combustion Engine powered vehicles in the near future. But even at the near term, fuel cell technology can be highly competitive when applied to urban buses and thus be compared with the current Diesel systems on a life cycle cost basis. The much lower operating and maintenance costs for fuel cell buses compensate to their initially higher cost.
The commercial transportation market for fuel cell is expected to be in heavy duty vehicles for the reason above.

In conclusion, it can be said that there is an intense competition around the world in fuel cells. Companies in Europe, Asia and US are already testing fuel cell vehicle prototypes. It is believed that this country that would develop commercial fuel cell technology would have the key to the next generation of power production.

The Future (Texaco source)

Fuel cell passenger cars originated in the desire for pollution free power plant, but it has since been driven by the need for a pollution free, efficient power plant. The need of a new technology that could mitigate the problem to Global Warming led to the development of the fuel cell technology. There are a number of ways by which fuel cells can reach commercial production and these are set in the following figure taken from a Texaco study:



For passenger cars, a methanol fuelled system offers the easiest on board processing of a liquid hydrocarbon fuel. Work is continuing on the improvement on the on board fuel processors so that Methanol Fuel Cell Vehicles could be available by 2004 – 2005. The infrastructure to make methanol available at a limited number of filling stations could be set up within 5 years.

Establishing a complete supply and service chain for real numbers of Methanol Fuel Cell Vehicles would take roughly another 5 years and this would dependent on political rather than technical factors.

A similar evolution towards production status is possible for Gasoline Fuel Cell Vehicles and, although the reduction in CO_2 would be less than methanol, this route would be much simpler as far as safety is concerned.

The route to the pure hydrogen Fuel Cell has already been partly explored. Hydrogen filling stations have been set up for experimental bus fleets in several cities and a decision is needed whether compressed or cryogenic liquid hydrogen is the best solution to store the gas at the filling station before wider use of this fuel in municipal or commercial fleets is possible. The supply of hydrogen from existing commercial processes is already sufficient for this to be possible for a large number of bus fleets. The storage problem is not nearly so severe for such vehicles as it is for passenger cars and current bus demonstrators store the hydrogen as compressed gas in roof or chassis mounted tanks. For use in the normal passenger car the solution to the storage problem is needed and it could take some time to overpass it.

The future could see general move towards Fuel Cell Vehicles with methanol or gasoline used as transitional fuels on the route towards a hydrogen fuelled vehicle within the hydrogen economy. It is only a move towards highly efficient, low CO_2 vehicles that will permit the passenger car industry to reduce Global Warming and move away from an oil based primary energy supply.

The Concept

A brief overview

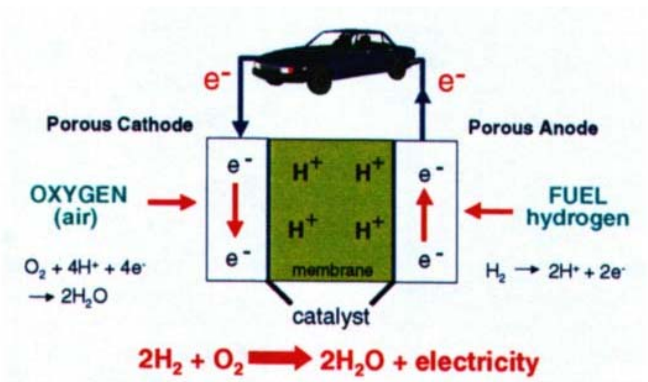
Automobile makers are currently investigating the use of an alternative energy source that could replace the existing method of producing energy from the burn of fossil fuels. Fuel Cell technology is the most likely technology to yield a solution to the matter above.

Fuel Cell Vehicle prototypes have already been built and tested from many car manufacturers. The results, obtained from testing, seem to be encouraging for the abidance of the research and development of such technology. Yet, it should be kept in mind that Fuel Cell technology is currently in a development phase and its application is considered to be very expensive at the moment.

Theory

Almost all the research on Fuel Cell Vehicles is concentrated on the Proton Exchange Membrane (PEM) fuel cell.

The basic operating principles and construction of the above membrane are shown on the following figure:



Hydrogen, the fuel is supplied to the anode of the cell. There, in contact with the catalyst, hydrogen atoms are converted to positively charged hydrogen ions and electrons are released.

This chemical reaction is the following one:

$$2H_2 \rightarrow 4H^+ + 4e^-$$

The hydrogen ions flow across the membrane as protons to the cathode. There, catalysis of the oxygen and water and the electrons from the external circuit has resulted in hydroxyl ions.

Chemical reaction:

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

The hydrogen ions come into contact with the hydroxyl ions at the cathode to produce water.

Chemical reaction:

$$4H^+ + 4OH^- \rightarrow 4H_2O$$

From the movement of the protons through the membrane and from the movement of the electrons through the external circuit an electric current is generated.

Reaction:

$$2H_2 + O_2 \rightarrow 2H_2O + \text{Electricity}$$

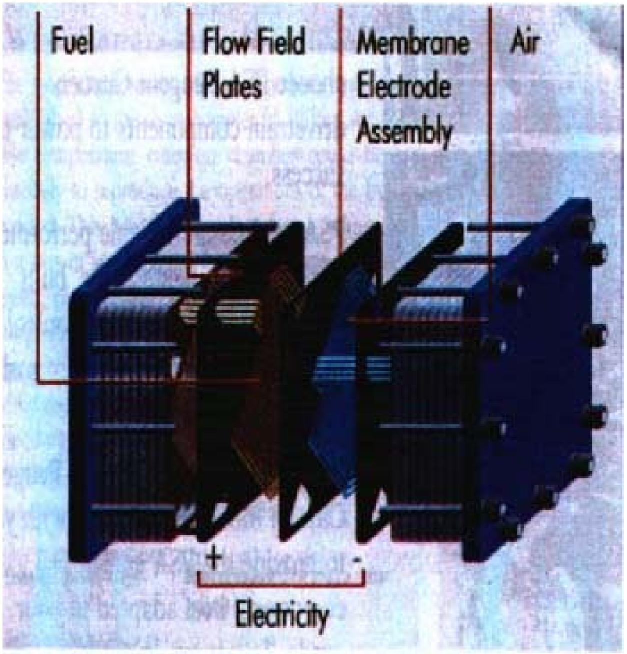
This electricity produced from the fuel cell operation is then used to power the car.

Specifications

In order for the fuel cells to yield an acceptable power output they are put together to form a 'stack'. Stack is the term applied to the assembly of fuel cells used to make up a complete fuel cell power unit. The cells are stacked against each other and connected in series to give the maximum of its performance. The theoretical open circuit voltage is 1.23V. In practice, about 200 cells are required to give an output voltage of 200V in order to power a passenger car.

The thickness of each cell separately ranges from 0.5 to 1cm. Hence a typical 50 kW fuel cell stack would measure about 30cm by 30cm by 60cm.

A typical automotive fuel cell stack is shown on figure below:



The fuel, hydrogen, and air are fed in at the end of the stack at a pressure of about 3 bar and they are distributed to the appropriate side of each cell through interconnected tubes.

The Project – Case Study

The aim of the project was first, to investigate fuel cell technology and its application to the transportation domain as an alternative energy source. Thus, establishing a better view of that technology. And secondly, to suggest a feasible fuel cell application, again in the transport sector, as an early stage of fuel cell development.

As already been discussed, fuel cell technology offers a better, more efficient, cleaner and quitter at the same time, source of energy than the existing internal combustion engines. Its application in passenger cars is just a few moments before production. Almost all car manufacturers have considered this kind of technology under research and development. Unfortunately, due to the fact that this new technology is currently, very expensive and it is still under development, its application to replace the existing car engines may not be profitable at the moment.

The suggestion

For all of the above reasons, the author believes that Fuel Cell technology could be applied partially in the transportation sector just by first replacing the normal car battery, that supplies with energy all the electric parts of the vehicle. Thus, the efficiency of the car engine could be improved since more power would be available to the driving wheel of the car.

Various electric parts of the car could easily be powered by the installed on-board fuel cell system. Consequently, many conclusions, regarding the application of fuel cell technology on passenger cars, could then be achieved.

The author believes that such an application would profit fuel cell technology since it would be a very good example of fuel cell application, in its very early stages of development, in transport without worrying much about the total installation cost. Apart from that, people could establish a better view on this domain, since only then, good commercialisation of the fuel cell technology could be obtained.

The implementation - Methodology

In order to replace the existing car battery with a fuel cell system powering the various electric parts of the car, many cases had first to be discussed.
At first, the fuel cell type had to be selected for the above application. Then, fuel and its storage method were next to be considered.

Finding the most suitable Fuel Cell Type

From all the fuel cell types, discussed earlier, the most likely one to be used in the transportation industry is the Proton Exchange Membrane (PEM) Fuel Cell type. This type of fuel cells is the most advanced and therefore the most preferable one for use in vehicles. Its high power density allows flexibility to the design of it. A generally small PEM fuel cell may give the desired energy output and being compact in size simultaneously.

Also another parameter that emphasises the use of PEM fuel cell is that its repeated operation and shut down does not affect the life span of it. Moreover, the solid structure of a PEM fuel cell may withstand and absorb any possible vibrations caused by the movement of the vehicle.

Another key factor that reinforces the use of such fuel cell type is that PEM fuel cell may operate on hydrogen – air fuel. And hydrogen is preferable among other fuels (see related paragraph).
Most of the car manufacturers prefer PEM fuel cell to power their cars for all of the above reasons. Hence, for the project, the use of a PEM fuel cell was also selected.

PEM Fuel Cell design characteristics

The basic characteristics of the PEM fuel cell have already been discussed in earlier chapter. At this part of the report, the design characteristics that determine the performance of the PEM fuel cell are specified.

- Cell size and shape: The size of PEM fuel cells varies from 5cm^2 to 1180 cm^2 while its shape is rectangular.
- Membrane type and thickness: The membrane material is perfluorosulfonic polymer. The thickness of the membrane varies from 50μm to 175μm.
- Electrode properties: Electrodes are the most important part of a fuel cell. Many experiments have been carried out so that the electrode properties could reach a certain value to benefit the efficiency of the whole fuel cell.

Temperature: plays a very significant role affecting the fuel cell performance. As the temperature increases the conductive resistance decreases while the exchange current density increases to improve the efficiency of the fuel cell. The operating temperature for the PEM fuel cell is about 80°C.

Pressure: Increasing the pressure at the anode and the cathode sides of the fuel cell, a voltage gain may be recorded. The operating pressures are between 300 – 500 kPa when hydrogen is used as fuel and oxygen as the oxidant. **[7,42]**

Comparison with other Fuel Cell types

In comparison, PEM fuel cell with other fuel cell types, the following advantages and disadvantages may be recorded:

Advantages:

- There is no volatile liquid contents in other types
- Minimal material corrosion
- Simple fabrication and assembly
- Long life due to the operating temperature and materials involved
- High efficiency
- High specific power (kW/kg) due to lightweight materials

Disadvantages:

- Membrane is expensive
- High platinum loading is required
- Fuel anode is intolerant to carbon monoxide
- Low temperature running requires an extremely clean type of fuel

The following table has been constructed by taking into account some of the basic characteristics that describe the operation of the fuel cells:

Characteristics of fuel cells for transportation

Type of fuel cell	Status[b] (1991)	Specific power[c] kW/kg	Specific power[c] kW/liters	Operating temp °C	Contam. by	Startup time min
Phosphoric acid	CA	0.12	0.16	150–250		300
Alkaline	CA	1.49	1.47	65–220	CO, CO_2	120–720
Proton exchange membrane	D	1.33	1.20	25–120	CO	5
Molten carbonate	D	–	0.7	650		500
Monolithic solid oxide	L	8.3	4.0	700–1,000		100

Where

b. CA = commercially available, D = development of prototypes, L = laboratory

c. Specific power includes only the fuel cell stack but no auxiliaries

From table someone may observe that the start-up time in the case of the PEM fuel cell is the lowest one and therefore its use in transportation is reinforced among the other types of fuel cells. It is very important for a fuel cell application the preparation process until the moment that the fuel cell may operate in its optimum condition.

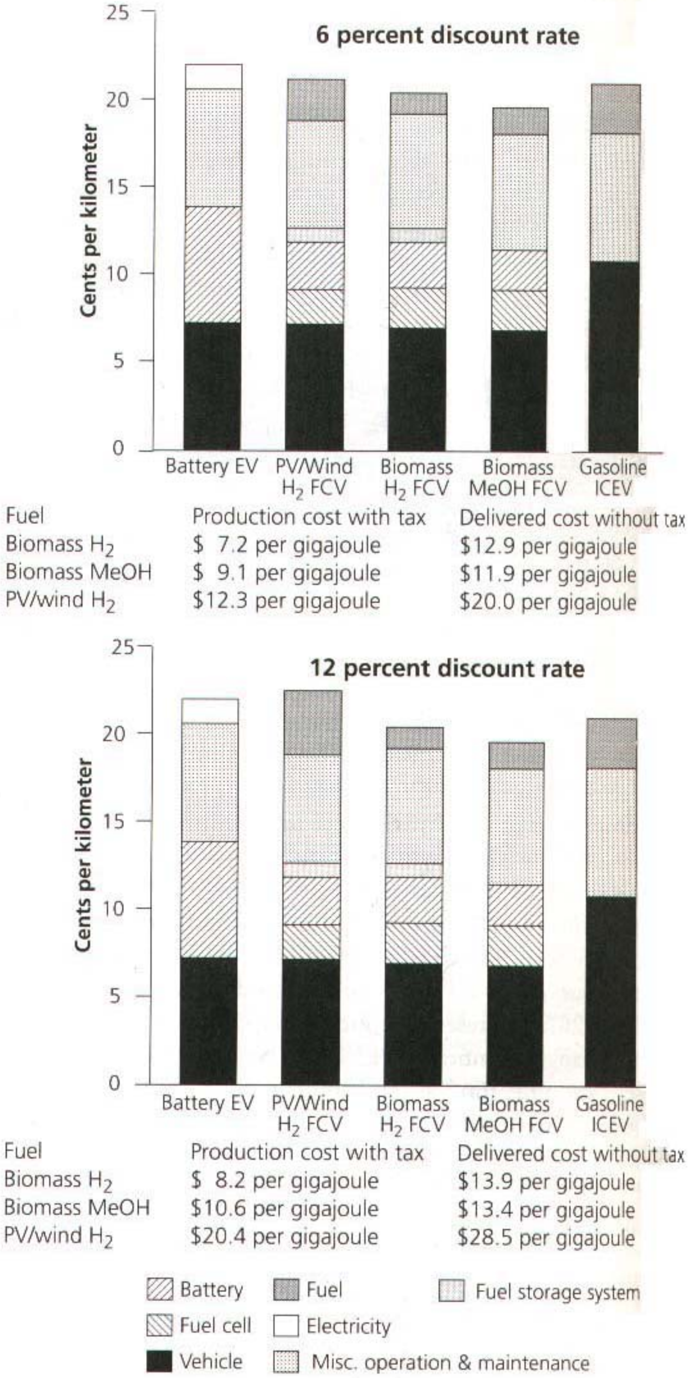
Selecting the fuel

The PEM fuel cell requires hydrogen or a hydrogen rich gas as fuel and oxygen or air as oxidant to operate and produce electrical power. Therefore, hydrogen was considered as fuel.

Hydrogen fuel cells could offer a number of advantages over other kind of fuel cells. First, because hydrogen storage is less heavy and bulky than electric batteries and offers more energy than the battery.
Secondly, hydrogen could be stored in pressure cylinders that could be refuelled in just a few moments, in contrast to batteries that require several hours to recharge. **[35]**

Recent studies, have compared the performance and economics of hydrogen fuel cell automobiles to other options, gasoline internal combustion engine vehicles, methanol fuel cell vehicles and battery powered electric vehicles, based on post 2000 projections for fuel cell, battery, solar electric and biomass technologies.
Surpassingly, these studies show that fuel cell vehicles fuelled with hydrogen from wind or PV could have lifecycle costs comparable to those of gasoline or battery powered vehicles. If hydrogen or methanol derived were derived from biomass, costs would be even lower. **[33,34]**

The following table illustrates graphically the lifecycle cost of transportation for various fuels. **[40]**



Lifecycle cost of transportation for various fuels.

Lifecycle cost of transportation
per kilometer

Vehicle type					Cost component
Battery EV	PV/wind H_2 FCV	Biomass H_2 FCV	Biomass MeOH FCV	Gasoline ICEV	
1.47					Purchased electricity
7.09	6.72	6.72	6.73	11.17	Vehicle (excluding fuel cell, battery, H_2 storage)
6.71	2.67	2.67	2.52		Battery
	0.83	0.83	0.02		Fuel storage system (compressed H_2 gas)
	2.25	2.25	2.60		Fuel cell system
0.05					Home recharging sta.
	2.15	1.39	1.50	2.89	Fuel for vehicle (excluding fuel taxes)
1.70	1.90	1.90	1.97	2.89	Maintenance
4.95	4.77	4.77	4.72	4.56	Misc. other costs
21.97	21.29	20.53	20.06	21.51	Total cost ¢ *per km*
					Breakeven gasoline price
1.42	1.11	0.80	0.60	–	*$ per gallon*
0.38	0.33	0.21	0.16	–	*$ per liter*
	22.19	20.63	20.25		Total cost *cents/km*
	1.49	0.84	0.68		Breakeven price *$ per gallon*
	0.39	0.22	0.18		*$ per liter*

Even though the initial fuel cell car would be significantly higher than that of a gasoline car, and the delivered fuel cost for hydrogen or methanol would be several times that of a gasoline the overall lifecycle costs for fuel cell vehicles are about the same as those for gasoline or electric battery vehicles.

The reasons why the costs are comparable are as follows: **[45]**

➢ Hydrogen can be used in a fuel cell vehicle about three times as efficient as gasoline in an internal combustion engine vehicle, so that the fuel cost per km is less than for gasoline.

➢ The lifetime of a fuel cell vehicle is about 50% longer than that of the gasoline vehicle, so that the contribution of the vehicle to the lifecycle cost is only slightly higher than for gasoline (refer to following table).

➢ Maintenance costs are lower for fuel cell cars than for gasoline cars, due to the fact that fuel cell vehicles employee less moving parts and hence are exposed to minimum chance of failure.

Lifecycle costs for alternative motor vehicle systems
cents per kilometer

	Alternative fuel cell vehicle/fuel combinations for vehicle lifetimes					**Gasoline ICEV**
	50% longer than for ICEVs			**10% longer than for ICEVs**		
	MeOH	Biomass H_2	PV/wind H_2	Biomass H_2	PV/wind H_2	
Vehicle	6.73	6.72	6.72	8.43	8.43	11.17
Fuel Cell	2.60	2.25	2.25	2.80	2.80	–
Battery	2.52	2.67	2.67	2.58	2.58	–
Fuel storage	0.02	0.83	0.83	0.83	0.83	–
Misc. O&M	6.69	6.67	6.67	7.24	7.24	7.45
Fuel	1.69	1.49	3.05	1.49	3.05	2.89
Total	20.25	20.63	22.19	23.37	24.93	21.51
Breakeven gasoline price						
$ per liter	0.179	0.221	0.393	0.527	0.700	
$ per gallon	0.68	0.84	1.49	1.99	2.65	

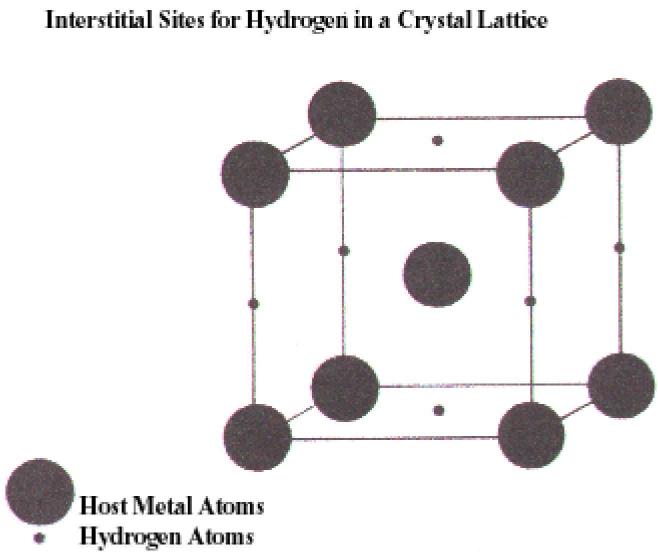
Hydrogen Storage

Many hydrogen - storing techniques are available, but the most promising ones for the on-board vehicle storage are: Compressed Gas, Liquid or Hydride Storage.

Gaseous Hydrogen Storage:
This method is the most commonly used due to its simplicity since hydrogen is stored in its natural form as a gas.
This technique involves high – pressure gas storage in cylinders at pressures ranging from 150 to 400 atmospheres at ambient temperature of approximately 298 K° (25 C°).
This storage technique is very reliable but on the other hand it can be proved inefficient for large storing quantities of hydrogen.

Liquid Hydrogen:
The liquefaction of hydrogen is a complex process due to hydrogen's physical properties. Hydrogen has a density of 0.071g/cm^3 and it boils at 20.4 K° (-252.6 C°).
There are various negative factors in storing hydrogen in liquid form, the most important ones are that the liquefaction of hydrogen results in energy loss and the storing temperature that has to be lower than 20 K° (-253 C°). Also, there is risk associated with low temperature due to the high expansion ratio of liquid hydrogen to gaseous hydrogen. Damage or an explosion may occur if no careful control is employed.

Hydride Storage: Hydrogen has the capability to be absorbed in metals or metal – alloys, where it is stored by chemical combining to form a metal hydride. It is a physical chemical process that involves the hydrogen atoms diffusion through the crystal structure of a solid metal or alloy where a reaction occurs forming a chemical compound as figure below illustrates:



The most common metal hydrides, for the above hydrogen storage application, appears to be that formed by the intermetalic compound iron – titanium, FeTi.
This method is not suitable for mobile storage system due to its heavy weight. **[34,35,36]**

Safety issues

The use of hydrogen creates the need for the investigation of such a substance on safety aspects. The lack of knowledge in this domain has produced the fear that hydrogen is a 'dangerous' gas due to its high flammability.

Gasoline, natural gas and hydrogen can all be ignited causing fire and explosions. Comparing though all these fuels, it can be said that hydrogen is the most difficult one to be ignited due to its higher ignition temperature (585 °C) among the other two (258 °C for gasoline, 556 °C for natural gas). Hence, hydrogen is more difficult to be ignited by heat.

On the other hand, hydrogen is more easily ignited by electric sparks, than gasoline or natural gas. It is completely colourless, odourless, tasteless making its leakage hard to be detected. But even in the case of a fire, hydrogen is less dangerous than a fire produced by the use of hydrocarbon fuels. Its buoyancy drives the fire almost straight up than in the case of hydrocarbon fuels. Apart from that no smoke is produced or any other hazardous substances like carbon monoxide, during its extinguishing.

Consequently, comparing hydrogen with other fuels it has to be said that hydrogen is no more dangerous under the proper and careful handling.

The table below compares hydrogen, methane and gasoline by summarising some of their properties: **[40]**

Safety–related properties of hydrogen, methane, and gasoline

		Hydrogen	Methane	Gasoline
Flammability limits in air	*percent volume*	4.0–75.0	5.3–15.0	1.0–7.6
Detonability limits in air	*percent volume*	18.3–59.0	6.3–13.5	1.1–3.3
Minimum energy for ignition in air	*mJ*	0.02	0.29	0.24
Diffusion velocity in air	*m s⁻¹*	2.0	0.51	0.17
Buoyant velocity in air	*m s⁻¹*	1.2–9.0	0.8–6.0	nonbuoyant
Leak rate in air (relative to methane)		2.8	1.0	1.7–3.6
Toxicity		nontoxic	nontoxic	toxic in concentrations > 500 ppm

Safety aspect	Relevant physical properties	Implications
Fire/explosion hazard		
Leak rate	Density, absolute viscosity	Hydrogen has a leak rate 2.8 x that of methane, 0.6–7.3 x that of gasoline
Ignitability	Minimum ignition energy, flammability/detonability limits, buoyant velocity, diffusion velocity	All three fuels ignite easily, hazard persists longest with gasoline, then methane and hydrogen
Physiological hazard	Toxicity	Gasoline toxic, hydrogen and methane nontoxic

In conclusion…

In conclusion, it has to be pointed out that all of the above methods are feasible for the storage of hydrogen but the most suitable one depends on the application question.

More specifically, in the case of replacing the existing battery of a passenger's car with a fuel cell system, the most promising method for the hydrogen storage is the case where hydrogen is stored in its gaseous form. This is because the capacity of hydrogen required is not very large. Apart from that, simplicity of this method reinforces its use in transport.

Summary

Up to this point of the thesis report, the Fuel Cell type, the fuel cell fuel and its storage method have all been selected for their application on-board a vehicle.

Therefore, Proton Exchange Membrane Fuel Cell type has been selected for the advantages that offers in transport industry.
The fuel was selected to be hydrogen and the storage method would be the one that involves the storage of hydrogen in its natural form of gas.

Car Battery replacement

A typical 1.6-liter car engine produces about 110 horsepower. This value is equal to 82 kW. Therefore in order to replace such engine with a fuel cell system, this system should be able to power the same car with almost the same energy of 82 kW or more for the application above to be efficiently feasible.

Due to the fact now that replacing the whole car engine is highly costly at the moment, only the battery of it is selected to be replaced by a fuel cell system in such a way to power the various electric parts of the car as the battery did earlier.

This fuel cell application can be regarded as non-expensive while people on the other hand could then become familiar with this kind of technology.

The generator is the basic source of energy for the various electric parts of the automobile. An alternator that is belt driven from the engine crankshaft is also used. The design is an alternating current type with built – in rectifiers and a voltage regulator to match the generator output to the electric load and also to the charging requirement of the battery regardless of the engine speed.
To store excess output power of the generator, a lead – acid battery is used which serves as an energy reservoir.

Therefore, by replacing the car battery with a fuel cell system, some other parts of the engine may also be disregarded, like the belts used to recharge the battery or the engine's dynamo. Hence, lesser losses are now occurring due to less moving parts of the engine. Thus, making the whole engine to operate in lower noise levels with fewer vibrations.

The electric circuit of a car consists of a 12-voltage battery.
In order to replace the existing battery now, the same voltage output has to be attained from the fuel cell system for the replacement to be efficiently feasible.

System Configuration

The configuration of the PEM fuel cell system plays a very significant role. The best way for the fuel cell system to yield a 12 - voltage output is the use of 12 individual Fuel Cells all connected in series together to form a fuel cell stack.

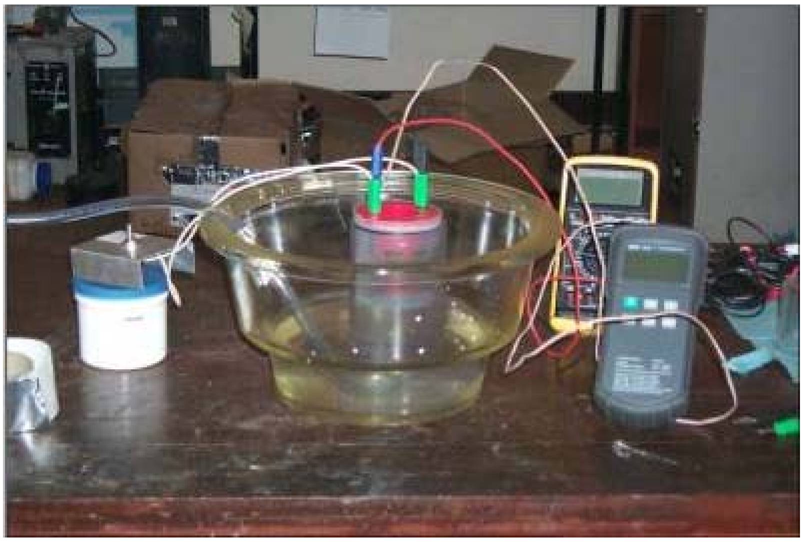
As in theory a single fuel cell may provide us with 1.23V, in practice the voltage output from a single fuel cell is closer to 1V. Therefore a single stack of 12 fuel cells all interconnected, in series, together would be enough to yield the same voltage output as the battery.

Such a fuel cell system would be compact in size since each cell is of 0.5cm to a maximum of 1cm in thickness. Therefore, the thickness of the fuel cell stack would measure from about 6cm to a maximum 12cm in thickness. Hence, the total size of the PEM fuel cell system would be no more than 12cm by 12cm in volume.

Thereupon, in replacing the car battery with a fuel cell system, dimension of it would not cause any critical problem due to the fact that the fuel cell system would be smaller than the existing battery and hence many system modifications may take place until the most convenient is found.

The fuel (hydrogen) and air would be fed in at the end of the stack at a pressure of about 3 atmospheres and they would be distributed to the appropriate side of the cell by the means of interconnected tubes.

The following photograph, taken from an experiment carried out in one of the laboratories of Strathclyde University, demonstrates a single hydrogen fuel cell in operation.



The fuel cell stack system employees the use of 12 single fuel cells, as the one above on picture, all interconnected together to yield the desired energy output.

The operating temperature of the fuel cell system would lie on the range of 80 °C – 90 °C. For cooling purposes, water that is used from the car refrigerator to cool down the engine may also be used on the fuel cell system to keep its operating temperature to the desired range for optimum operation.

The storage of hydrogen on-board the vehicle is not a great difficulty since the hydrogen quantity required is not very large. More specifically, for the production of 1 kW of electric power, 1 Nm^3/h of hydrogen is needed.

Consequently, a small cylindrical vessel of about 0.3 m^3 would be just enough to serve as a hydrogen reservoir. Such a vessel can easily be stored under the hood of the car.

The supply of hydrogen to the fuel cell requires the use of special hydrogen tubes hard to produce any gas leak.

Moreover, to avoid any possible hydrogen leak, the hydrogen 'reservoir' may be placed very close to the PEM fuel cell system thus eliminating the chances of having a leak due to smaller tubes used.

Large quantities of hydrogen may also be stored on board the vehicle, as shown on the picture that follows.

However, this application has the disadvantage that the reservoir occupies a great volume of the vehicle's trunk but its use is necessary when hydrogen is used as the only fuel to power the car alone (in the case where fuel cells replace the car engine).

Nonetheless, start up time for automotive applications must be less than a few seconds to reach full power. Until faster fuel cells are developed, vehicles may be designed so that energy stored in on-board batteries can be used during the first few minutes of operation while the fuel cell system reaches required power levels.

On – board hydrogen storage systems are heavier and bulkier than those for liquid fuels such as gasoline or methanol, although they are lighter and more compact than electric batteries.

The following table refers to the on – board energy storage systems for automobiles.

These values apply for much larger reservoirs than the one used in the thesis proposal but the differences among these values are analogue and therefore may be used to compare all these energy storage systems. **[40]**

Onboard energy storage systems for automobiles

Storage system	Installed energy density[b] MJ/liter	Installed energy density[b] MJ/kg	Container cost[c] $	Refuel time[d] min	Filling station markup[e] $/GJ
Hydrogen storage systems					
Carbon wrapped aluminum cylinder 55 MPa (8,000 psia)	3.4	7.0	4,000	2–3	5
Liquid hydrogen Dewar (–253 °C)	5.0	15.0	1,000–2,000	>5	11
FeTi metal hydride	2–4	1–2	3,300–5,500	20–30	3
Cryoadsorption (Carbon at –150 °C)	2.1	6.3	2,000–4,000	5	4–5
Thermocooled pressure vessel	2.5	8.0	4,000+	5+	5–8+
Organic liquid hydride	0.5	1.0	?	6–10	?
H-Power system (proprietary)	5.8	5.0	500?	2–3	?
Storage systems for other automotive fuels					
Gasoline	32.4	34.0	20	2–3	0.6
Methanol	15.9	14.9	20	2–3	1.2
Batteries:					
Lead–acid	0.187	0.115	$100/kWh	60–360	0.5[f]
Nickel–iron	0.407	0.18	$100/kWh	60–360	0.5[f]
Sodium–sulfur	0.432	0.378	$100/kWh	60–360	0.5[f]
Bipolar lithium alloy	0.925	0.511	15,000	60–360	0.5[f]

Where a, b, c, d, e, f:

a – It is assumed in all cases that enough energy is stored to travel 400 Km.

b – Energy density is based on the weight and volume of the full container.

c – Cost to the original equipment (automotive) manufacturer.

d – Time to deliver fuel only.

e – The mark- up (the cost in excess of the hydrogen cost to the filling station operator) is needed to cover the full cost of owning and operation the refuelling station.

f – The cost of the home recharging station for the electric battery car does not include the price of electricity.

Comparison, Fuel Cell – Battery

It is well known that fuel cell offers an emerging technology that has a lot to contribute worldwide.

In transportation sector now, and more specifically in trying to compare a fuel cell system with the existing car battery the following points are met.

Dimensions

A 12 – voltage power output fuel cell system is very compact in size. Its dimension would measure no more than 12cm by 12cm in size. PEM fuel cells are of rectangular shape and its weight also remains low for small applications.

On the other hand, a normal car battery is about 25cm by 17cm by 20cm in size and weights about 15kg to 20kg depending on the battery.

Efficiency

The efficiency of the PEM fuel cell is about 40% nowadays and it is forecasted to reach values close to 50% or even 60% in the near future. Further developments in the material used for this technology would increase fuel cell efficiency more.

This value is considered to be very high for transportation applications since the Internal Combustion Engines have already reached their maximum of their development and their efficiency lies in the range 10% - 15%.

The PEM fuel cell has power density 240mW/cm^2 while it is strongly believed that this value will be increased to 300 mW/cm^2 in the following years.

Battery has proved to have JUST enough energy for powering the car and fulfil its electrical needs. While the power density of a car battery can reach values up to 130 mW/cm^2, value which is much lower than that of the PEM fuel cell power density.

Lifetime

The lifetime of the PEM fuel cell is huge. This type of fuel cell has been tested in laboratories and its lifetime has exceeded 40,000 hours of, almost, continuous operation without any critical damages to the cell itself.

For the battery again, its lifetime is estimated to be 1 or 2 years depending on the use of it. Apart from that, battery may rust or even cause a fire in the case of a battery acid leakage.

Service – Recharge

PEM fuel cell require a typical inspection every 10,000 or 15,000 hours of operation and even then no service may be necessary while refuelling occurs in just a few moments just by feeding the storage reservoir with hydrogen by the means of interconnected tubes.

Likewise, battery requires inspection every 3 to 6 months so that its condition is recorded and be replaced if needed.

Recharging of the battery usually occurs in 12 – 14 hours if not replaced with a new one.

The major fuel cell drawback for its use in transportation is its start – up time. Any fuel cell system requires a few minutes until it can reach its operating temperature. PEM fuel cells are considered to be the fastest ones to be able and produce valuable energy and that is something that makes them more preferable over other types of fuel cells.

Battery on the other hand is always ready to supply us with energy without any delay.

Discussion – Conclusions

It is believed that fuel cells have the power to change the future. A breakthrough 'clean machine', the fuel cell harness the chemical energy of hydrogen and oxygen to generate electricity without combustion or pollution. Fuel cells will power the car of tomorrow, quieter, cleaner and more energy efficient, with equivalent range and performance. The benefits would be extraordinary, in national energy security, clean air, and economic opportunity.

Fuel Cell development for application in the transport sector includes components and subsystems development, and technology integration for fuel cell stack systems, fuel processors, on board hydrogen storage systems, and integrated power systems.

There are still many things to be accomplished first, before fuel cell technology finally replaces the existing sources of electrical power.

Some of these things that still should be done include: **[3,4,6]**

- Low cost components are necessary for the system to be competitive
- Low cost, high volume manufacturing methods have to be developed
- Lightweight, compact, and affordable hydrogen storage system technologies must also be developed
- Develop full scale fuel cell and processor system and demonstrate practicality, performance, and durability in a vehicle
- Reduce system start up time
- Increase power output either by making larger fuel cell stacks or by combining smaller stacks

The major development thrust now is aimed at reducing the cost of the system and the sensitivity of the cells to impurities in the hydrogen resulting in catalyst poisoning. At present, the cost of producing 1 kW is about 3000 Euro and the goal is 100 Euro per kW or even less by the year 2010. This value may only be achieved if fuel cell industry go on large mass production so that the total cost of purchase would eventually drop.

The best PEM Fuel Cells degrade quickly if the hydrogen contains more than 100ppm (parts per million) of CO. This implies that expensive gas clean up treatment is required on board the car. The goal of companies like Ballard Fuel Cells to improve the tolerance to 100ppm.

The replacement of the car's battery with a fuel cell system is feasible and it's a very good way for this technology to achieve good commercialisation since people would become familiar with this kind of technology.

'Commercialisation is easier when customers accept the product rapidly, which they are more likely to do if marketers can make them aware of its benefits.'

Wide commercial use of fuel cell power is only few moments far. Fuel cell power plants should break into mainstream first in the stationary power market, where their cost competitiveness is currently nearest to what the market demands.

Within a few years, several companies will push their demonstration units to full commercial viability by cutting manufacturing costs and making this technology available and affordable for general use.

Transportation applications of fuel cells will likely follow the establishment of a commercial stationary power market. Fuelled by high efficiency, ever dropping installation costs, and increasing public recognition, fuel cells could supersede the internal combustion engine as the power train in cars around the world.

In conclusion, it has to be pointed out that Fuel Cell technology is undoubtedly a new technology able to provide us with useful 'green' energy for various applications. This technology is at its development stage and only prototypes have been developed and tested so far. Its use is considered to be expensive until this technology is developed further more in the following years and people can become familiar with the benefits that fuel cell industry offers.

Hence, fuel cell may be slowly introduced to the market in a way that people could establish a better view over this kind of energy production and therefore adopt its use in greater applications.

The thesis suggestion is economically, plus efficiently, feasible while on the other hand it is believed that this replacement would profit fuel cell commercialisation for all of the above reasons.
Car battery replacement by a fuel cell system is something that does not require a great amount of money, in order to be accomplished, and hence it is not considered to be a risky choice.

The major drawback for its use in transportation is that the fuel cell requires a few moments until it reaches its operating temperature and be able to produce useful energy, thing that would force the driver to wait before starting the vehicle. This is only a temporary problem until faster fuel cells are developed in the future and start – up time for any fuel cell would be just an instant.

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Department of Mechanical Engineering

ENERGY SYSTEMS & THE ENVIRONMENT

Title: *FUEL CELLS: An Emerging Technology – Its application in the transport field – A feasible Suggestion*

Name: *Lekkas Nikolaos*

Reg. No. *200054023*

Supervisor: *Dr. A Gilchrist*