POLITECNICO DI TORINO

Corso di Laurea Magistrale

in Automotive Engineering

Master degree thesis

Investigate the Scientific and Commercial Literature about the Use of Fuel Cells in Hybrid or Electric Vehicles

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Abstract

Now a days, reducing transportation emissions is one of the biggest challenges of our society. Development of various technologies in recent times and utilizing them to reduce emissions and to maximize the productivity, Automobile manufacturers have turned their attention not only to Electric and Hybrid Vehicles but also from the perspective of Fuel cells. The primary objective of this Thesis is to present the Fuel Cells and their Technologies as one of the alternative drive systems. Present generations are realizing the importance of the environment and avoiding the emissions of pollutants with Fuel Cell Vehicles along with the Electric vehicles.

This thesis also focuses on Fuel cell electric vehicles, which are integrated with Hybrid storage systems and operation and performance parameters which are compared with typical electric and Conventional engines and also deals with the analysis of the various types of fuel cells and Fuel cell vehicles which are available in the commercial market and their economic analysis of the Fuel cell technology with respect to other electric and hybrid technologies.

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1.INTRODUCTION

In Fuel cell, generation of the electricity is due to the electrochemical reaction. It utilises chemical energy and runs endlessly, as long as it is provided with a source of hydrogen and a source of oxygen (i.e. air). The Fuel is regarded as the source of hydrogen. Although, there is no combustion involved. Instead Oxidation of the hydrogen happens electrochemically in a very efficient Manner. During oxidation, reaction between Hydrogen and Oxygen atoms results in the formation of the water; In the process, electrons released are flow through an external circuit as an electric current.

1.0 Fuel Cell : Basic Structure

A fuel cell is an electrochemical device which converts fuel chemical energy into electrical energy. The basic structure of the single cell consists of the electrolyte layer in the contact with the porous anode and cathode on the either side.[1]

Fuel is fed continuously to anode (negative electrode)and an oxidant (oxygen from the air)is fed to the cathode (positive electrode) continuously. The electrochemical reactions takes place at the electrodes to produce an electric current through the electrolyte. The battery will cease to produce electrical energy when the chemical reactants are consumed.[1]

Operating Principle of the Fuel cell:

The electrochemical reactions are

Anode reaction : $H_2 \rightarrow 2H^+ + 2e^-$

Cathode reaction : $\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$

Overall reaction : $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$ + heat (exothermic reaction, $\Delta H = -286\ kJ\ mol^{-1}$)

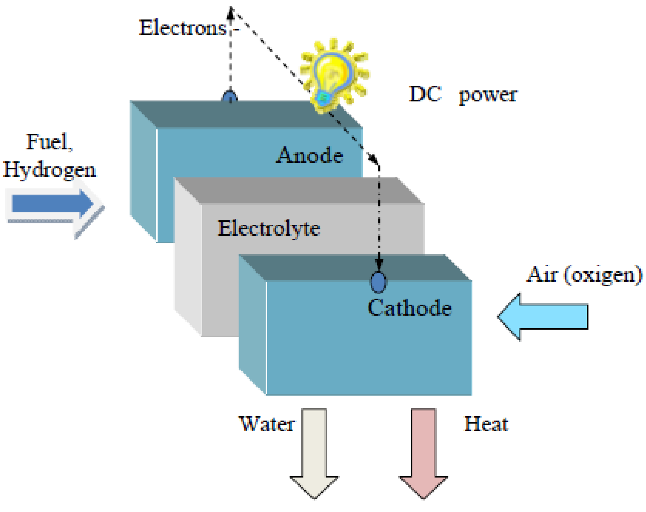


Figure 1.1 schematic diagram of typical fuel cell

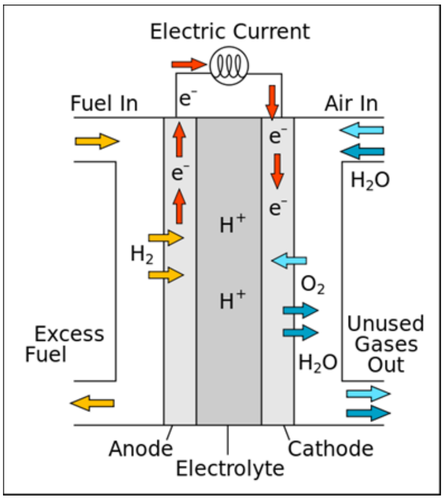


Figure 1.2 Operation of Fuel cell

The thermodynamic Voltage of the Fuel cell is closely associated with the energy released and the number of the electrons transferred in the reaction. The energy released by the cell reaction is given by the change in Gibbs free energy, Δ*G*, usually expressed in per mole quantities. [2]

$$\Delta G = \Sigma G_i - \Sigma G_j$$

where *Gi* and *Gj* are the free energies in species *i* of products and species *j* of reactants. In a reversible process, Δ*G* is completely converted into electric energy, that is[2]

$$\Delta G = -nFV_r$$

where *n* is the number of electrons transferred in the reaction, *F* = 96, 495 is the Faraday constant in coulombs per mole, and *V*r is the reversible voltage of the cell. At standard conditions (25◦C temperature and 1 atm pressure), the open-circuit (reversible) voltage of a cell can be expressed as[2]

$$V^0r = -\Delta G0/nF$$

, where Δ*G*0 is the change in Gibbs free energy at standard conditions. Δ*G* is expressed as

$$\Delta G = \Delta H - T\,\Delta S$$

The "ideal" efficiency of a reversible Fuel cell is related to the enthalpy for the cell reaction by[2]

$$\eta_{id} = \Delta G/\Delta H = 1 - (\Delta S/\Delta H)T$$

Fuel cell vehicles (FCV) use fuel cells to drive the vehicle's electric motor by supplying the power necessary to run it. Many FCVs use a fuel cell combined with a battery and supercapacitor to efficiently start-up, power, and utilize the best energy source for constant and peak power[3]. In FCVs, the fuel cell utilises oxygen (air) and compressed hydrogen. These vehicles emit water and heat as by-products. The major reason for developing automotive fuel cell technology is due to their efficiency, low or zero emissions, and fuel production from local sources rather than imported sources.

There are three methods for storage of hydrogen on-board:

1. Compressed hydrogen in a container at ambient temperature,
2. Cryogenic liquid hydrogen at low temperature and
3. The metal hydride method.

For our analysis, our investigation of Fuel cells is mainly focussed with respect to electrical and hybrid vehicles.

1.1. Electric vehicle

An electric vehicle (EV) operates on an electric motor, which is the substitute for an internal-combustion engine that generates power by combustion of the mixture of fuel and gases. Therefore, Electrical vehicle is seen as a promising replacement for modern automobile, in addressing the issue of Rising pollution, global warming, Hydrocarbon emissions etc.

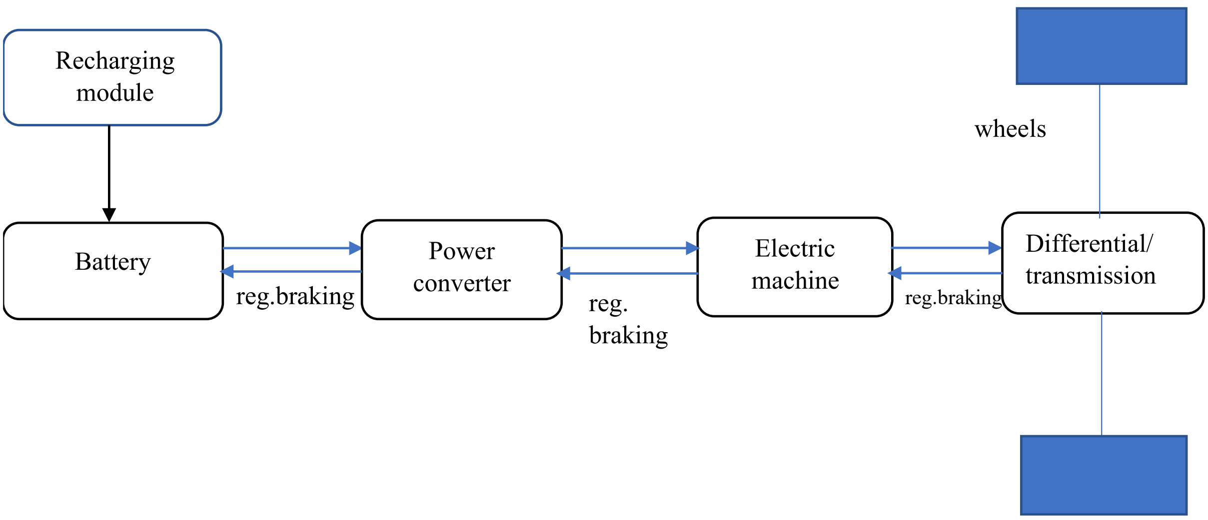


Figure 3. Block diagram for the powertrain of electrical vehicle

General electric vehicles are comprised of a battery, power converter electrical machine, or motor. Electrical energy is stored in the battery is converted into mechanical power employing an electrical machine. Which is driven by the power converter. Power converters draw electrical energy from the battery and generate voltages which supplied to the input of the electrical machine.so that it delivers mechanical power. The mechanical energy of the moving vehicle can be reconverted into electrical energy which can be used to recharge the battery. the operation mode is regenerative braking which is achieved by properly driving the power converter.

Classification of Electric Vehicles

Electric vehicles are categorized into

1.Battery electric vehicles(BEV)

2.Fuel cell Electric Vehicles(FCEV) and

3.Hybrid electric Vehicles(HEV).

1. Battery electric vehicles(BEV)

Generally they called as Electric vehicles(EV), as they are completely eelectric with rechargeble batteries and no Internal Combustion engine is involved. Energy is generated from the battery in order to run the vehicle which is recharged from the Electric Grid. They are Zero emission Vehicles, as they don't have any emissions and pollution hazard components generated by the involvement of Gasoline engines(ICE). The source uses a battery-motor system.

1 Battery electric vehicle components

2 Car power section

3 Battery management system part

4 Drive motor and drive system section

5 Control technology section

6 Body and chassis part

7 Security protection system section[7]

2. **Fuel cell electric vehicles (FCEVs)** runs by hydrogen in which energy stored as hydrogen converted to electricity by the fuel cell. FCEVs, like a BEV system, use electricity to supply to the engine. They produce their electricity through the fuel cell powered by hydrogen, unlike BEVs [8]. Therefore, fuel cell supplies electricity to a BEV by acting like a generator(from Figure 1.4)

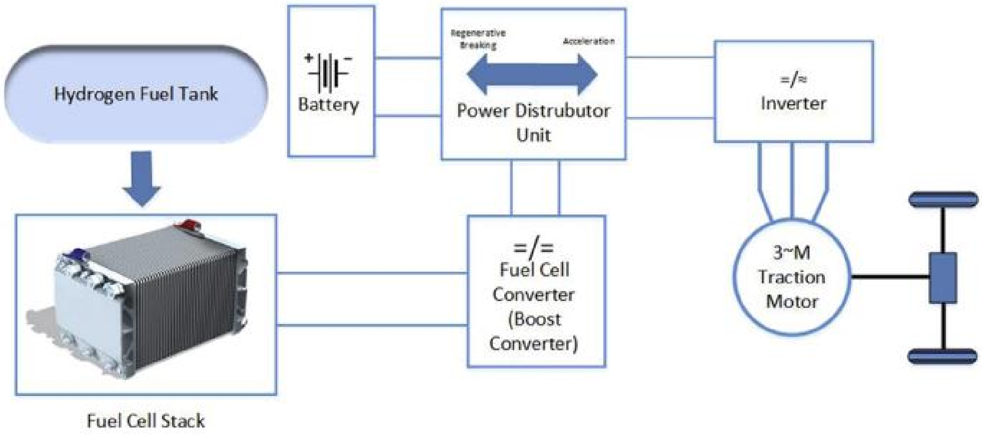


Figure 1.4 schematic of Fuel cell electric vehicle

An FCEV Typically comprises of a

1. Fuel cell system

2.An electric motor with its controller

3.the battery

4.controller for whole vehicle and a smart control unit(Power distribution network) between the battery and the fuel cell system[7,8].

5. Fuel cell converter .

The vehicle controller is responsible for controlling the output power of the motor and the energy transfers among the battery, the fuel cell stack and the drive train [9,10]. Both the fuel cell and the battery provide power to the traction motor drive for a sudden acceleration command [10]. In the case of breaking, as if the structure of electric motor transformed into a generator, it converts the breaking energy of wheels into electrical energy and this energy is sent to storing in the battery.[8]

1.2 Hybrid Vehicles

To overcome the limitations of using Internal combustion engines and battery electric vehicles (BEVs), the most possible solutions are Hybrid vehicles (HEVs). A hybrid electric vehicle (HEV)uses two power sources to power the vehicle. There are many methods to connect the two power sources, each of which has its special operation characteristics. For different vehicles that have different mission requirements and operation environments, a special architecture should be used to fully use its advantages and avoid its shortcomings.

Hybrid electric vehicles divided into two types based on the arrangement i.e. 1.Series-HEV and 2.Parallel-HEV

Hybrid electric vehicles are divided into three types based on the range. they are Mild-HEV, Full-HEV and Plug-in HEV.

1.2.1 Series hybrid vehicle-configuration

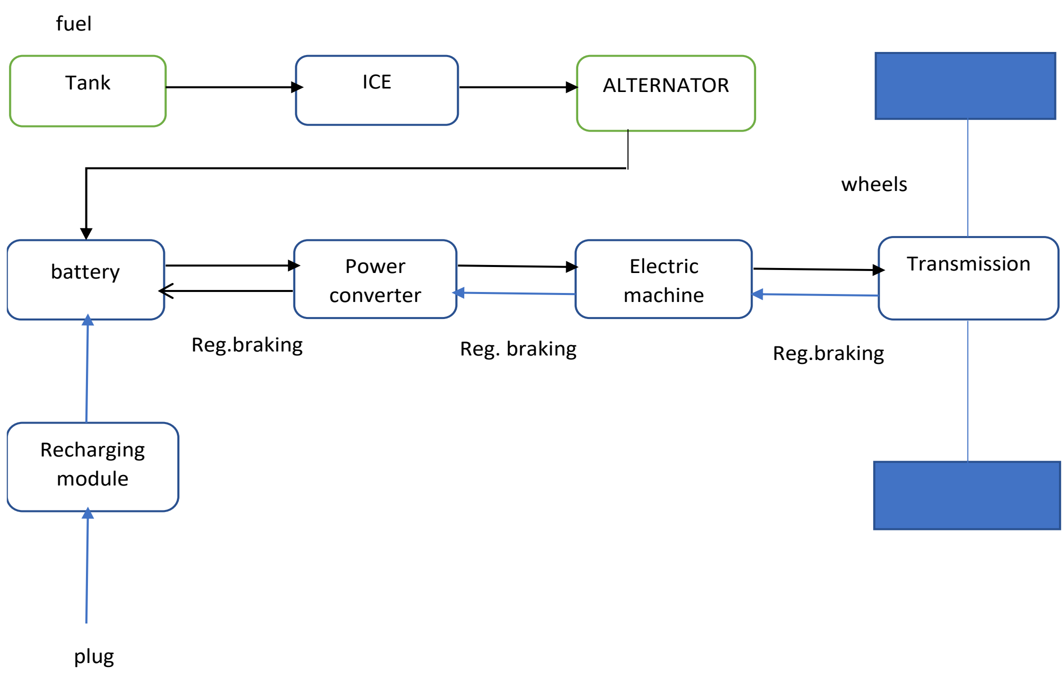


Figure 1.5 Block diagram for the Series powertrain of Hybrid electrical vehicle

Series electrical vehicle power train comprises a battery pack, power converter, and an electric machine Which electrical part of the powertrain. An IC engine is mechanically coupled to the alternator to generate the electrical power due to the combustion of the fuel from the reservoir which is a mechanical part.

The electric power is used to recharge the battery and the same time used as a power supply to the electrical machine. The presence of an IC engine in Series HEV gives rise to non-zero pollutant emissions when ICE is active.

1.2.2 Parallel hybrid vehicle-configuration:

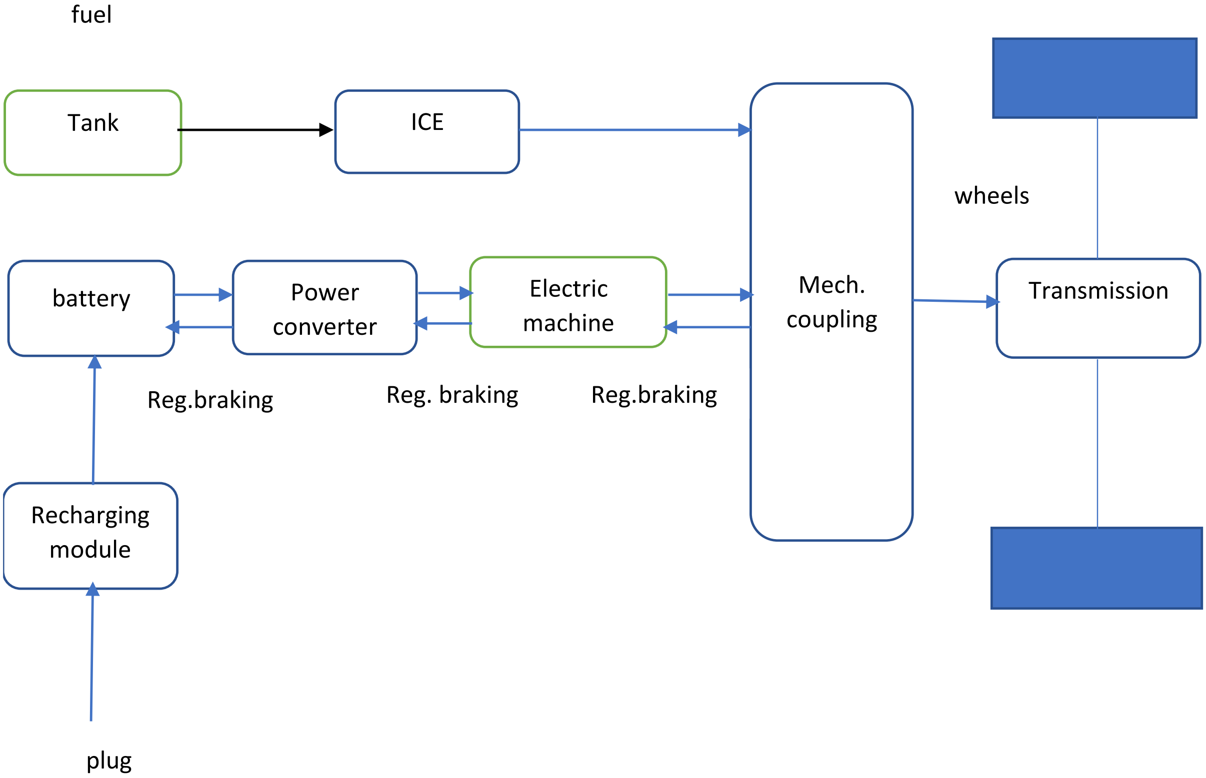


Figure 1.6 Block diagram for the Parallel powertrain of Hybrid electrical vehicle

According to the parallel hybrid vehicle, The powertrain is classified as one section which comprises Fuel tank, IC engine which is similar to standard vehicle powertrain. Whereas the other section consists of a battery pack, power converter, and electric machine which is similar to the power train of an electric machine.

IC Engine is mechanically coupled to the same shaft likewise the electric powertrain is connected.

They can cooperate in delivering the tractive power to the wheels. In this IC engine can be disconnected in order to deliver the complete tractive power by the electric machine like pure EV.

There are many degrees of freedom in control of both ICE and electrical machine in order to obtain optimal operation in terms of pollutant emissions, fuel economy, and battery management.

1.2.3 Types of Hybrid Vehicles

The Primary goal of Hybrid Electric Vehicle is to maximize the electric portion usage of the drivetrain because electric motors produce no emissions and more efficient. So today automobile manufacturers are trying to substitute the gap towards pure electric vehicles.

Based on this bridge gap these technology can be classified as

1) MILD Hybrid

2) FULL Hybrid

3) PLUG-IN hybrid

1) <u>MILD Hybrid</u>

A Mild Hybrid car is very similar to a Self-Charging Hybrid car, but with a smaller battery [11]. So, it can't drive on battery power alone. The battery is there to help the Internal combustion engine perform more economically.[12]

mild hybrid is limited to parallel mode as having a battery and helper motor. The electric motor is not so powerful to drive the wheels at any real speed without the assistance of the IC engine[13].

Mild hybrids typically have stop-start and regenerative braking,

2) <u>Full hybrid</u>

They are also called as Strong Hybrid technology and operates on IC engine or on an electric motor or with combination of both powertrain. In these types of vehicles, Split power allows higher flexibility characteristic by reciprocating mechanical and electric power in the drive train.

Highly powered motor and large (or) High-capacity batteries can drive the vehicle with electrical energy at lower speeds and short distances.

Most fuel efficient among regular hybrids they can automatically choose to operate in series mode, parallel mode, or all-electric mode[14]. All-electric mode is Unambiguous and is typically used by FHEVs at low speed .

Series mode also uses the electric motor to drive the wheels but the combustion engine is used at the same time as an on-board generator.

Parallel mode uses the electric motor and the IC engine and together to drive the wheels[15]

Examples: Examples : Toyota Prius ,Ford Fusion Hybrid, Honda Accord Hybrid.

3) **Plug-In Hybrid**

Plug-In Hybrid technology powered by means of Electric motor and IC engine. In this

1. Using of Conventional or alternative fuel by IC engine.
2. Battery is charged by means of external power source or by regenerative breaking mechanism.

During urban driving, most power comes from stored electricity[16]. Long trips require the engine. Fully charged battery allows them to run on more distance on fully electric mode Can run on EV only mode six to 14 miles for the Toyota Prius PHEV, to 38 miles for the Chevy Volt.[17]

Plug-in Hybrid electric vehicle in combination with the Biofuels will reduce the fuel consumption and produce electricity which may help to limit the greenhouse gas emissions.

The hybrid electric vehicles and plug-in electric vehicles both reduce Green House Gases emissions, if the vehicles still with the IC engines will not be adequate to limit the GHG below 80%.

Adding hydrogen-powered FCEV or battery EV gradually, we can curb GHG emissions substantially.

Typically, Plug-in hybrids use all the technology of a FHEV but have a larger capacity battery which can be plugged into the mains to charge, The range they can drive in all-electric mode is higher than the average FHEV and also eliminate the "range anxiety" associated with all-electric vehicles, because the combustion engine works as a backup when the batteries are depleted. Examples: Audi A2 E-Tron, BMW i8, Ford C-Max Energi, Kia Optima, Porsche Cayenne S, McLaren P1

1.3 Fuel cell hybrid electric powertrain configuration

The incorporation of Fuel cells into the hybrid electric drive is advantageous in terms of energy efficiency and lower the emissions. The integration of a fuel cell system with a peaking power source is to overcome the negative effects caused by fuel cell alone powered vehicles.

Fuel cell hybrid electric drive has the following construction and configuration.it comprises of fuel cell system as a primary source of power, aa peaking power source, electric machine(motor), vehicle controller, and electronic power interface.

Energy flows from the fuel cell(or)peaking power source(PPS), and drive train. The vehicle controller controls the power output. For peak power usage, both fuel cell systems and PPS provide power to the electric machine. for breaking, the electric motor acts as a generator that converts part of energy into electrical energy and stored in PPS. PPS restore energy from the fuel cell system when loading powerless than the rated power of fuel cell.

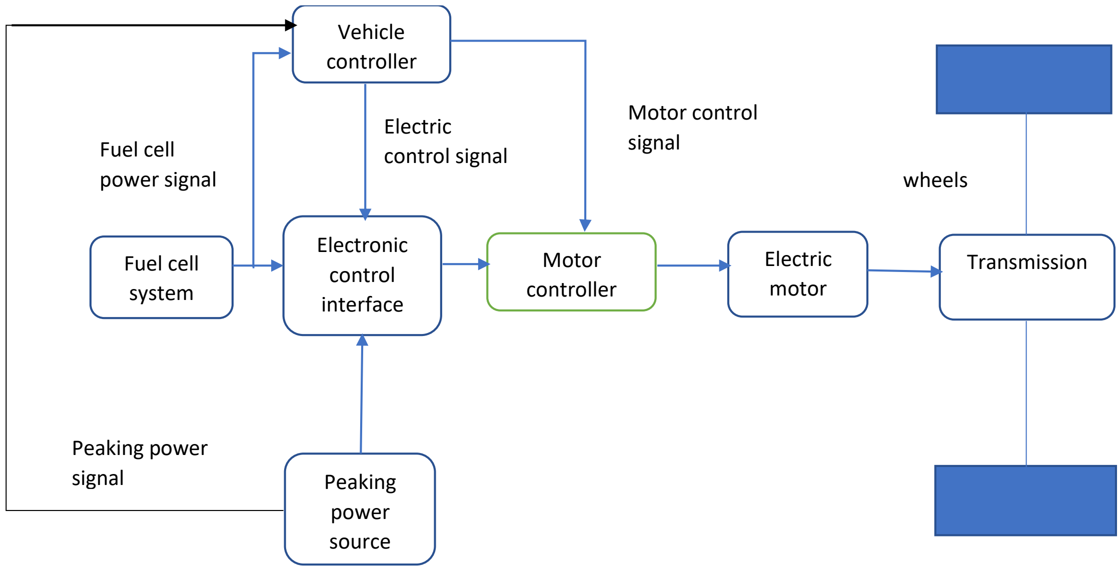


Figure 1.7 Fuel cell Hybrid Electric Configuration

1.4 Batteries and Fuel Cells Comparison

The Principle option of energy sources for the all-electric vehicles are:

a) Batteries

b) Fuel cells

FCEV are superior to batteries in terms of Mass, volume, refueling time, cost, reduction of greenhouse gases etc. Fuel cells obtain their energy from the hydrogen stored in the vehicle, whereas the battery vehicles derive their energy from batteries charged by the electrical power generation grid.

As an alternative to the conventional IC engine, Gasoline Hybrid electric vehicles (HEV) are already having an impact in the light duty vehicles, consequently Plug-in Hybrid electric vehicles (PHEV) obtain energy by charging the batteries from the electric source started to show its impact in the market.

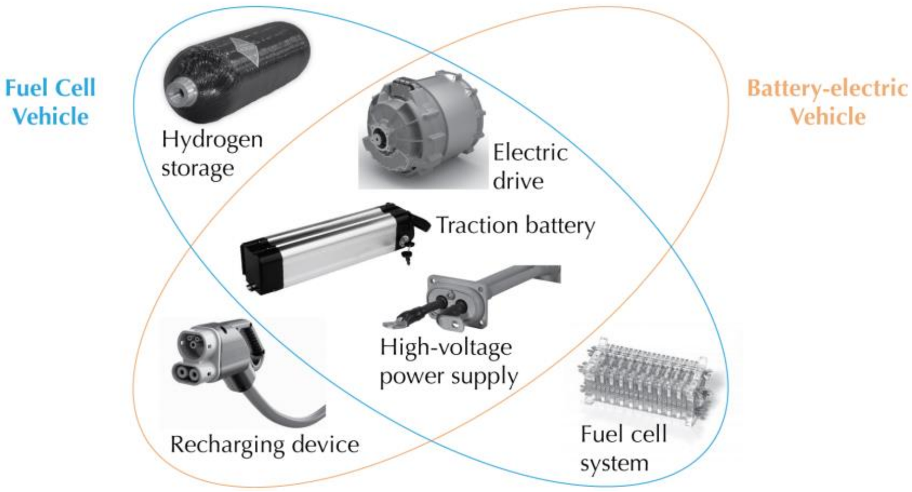


Fig 1.8 Concept defining components for BEV and FCEV

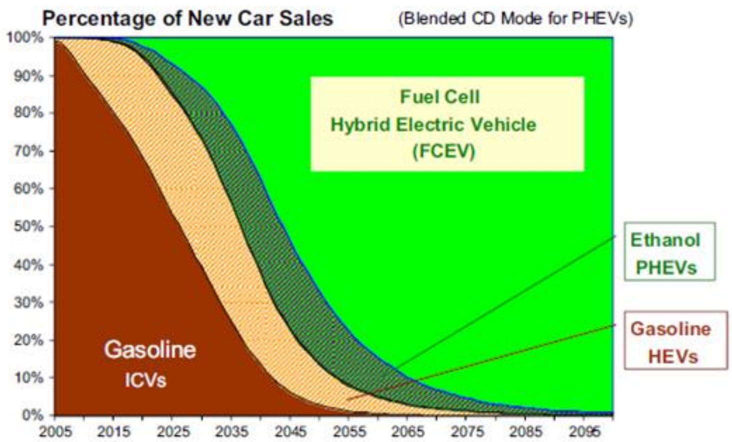


Fig. 1.9 – Percentage of new cars sold over the 21st century for the hydrogen-powered fuel cell electric vehicle (FCEV) scenario, showing the mixture of gasoline internal combustion engine vehicles (ICV), followed by gasoline-powered hybrid electric vehicles (HEV), (cellulosic) ethanol-powered plug-in hybrid electric vehicles (PHEV) and finally the hydrogen-powered FCEV

Table 1.0 Characteristic differences between Battery and Fuel cells

Characteristics	**Batteries**	**Fuel cells**
Charge time	1h-4h	1-30min
Operating temperature/◦C	−20 to +65	+25 to +1000
Operating cell potential (ΔV)/V	1.25–4.2	0.6–1.0
Lifetime	150–1500 cycles	• Stationary upto 40,000 h • Automobile

		1500h-10,000h
Weight/kg	0.001–10	0.02–10
Power density/kW kg^{-1}	0.005–0.4	0.001–0.1
Energy Density/Wh kg^{-1}	5–600	300–3000

1.4.1 Batteries

Two main types of batteries were in use for Battery Electric Vehicles(BEV) are

1)Nickel Metal Hydride

2)Lithium -ion batteries.

NMH batteries used as a secondary energy source in Hybrid electric vehicles e.g. Toyota Prius

Where as Li-ion used as primary energy source in Battery electric vehicles e.g. Nissan leaf

1) NiMH(Nickel Metal Hydride Battery)

In 1986 Stanford Olshansky patented NiMH battery when researching hydrogen storage materials now a days, NiMH batteries are used in over 95% of Hybrid electric vehicles. From the manufacturing point of View, NiMH batteries are preferred for consumer and industrial applications due to the following properties

i) Environmental acceptability

ii) Low maintenance ,

iii) High power and the energy density

iv) Cost

Charge/discharge efficiency: 66%–92%

Nominal cell voltage: 1.2 V

Self-discharge rate: 13.9% –70.6% at room temperature

Energy density: 140–300 W·h/L

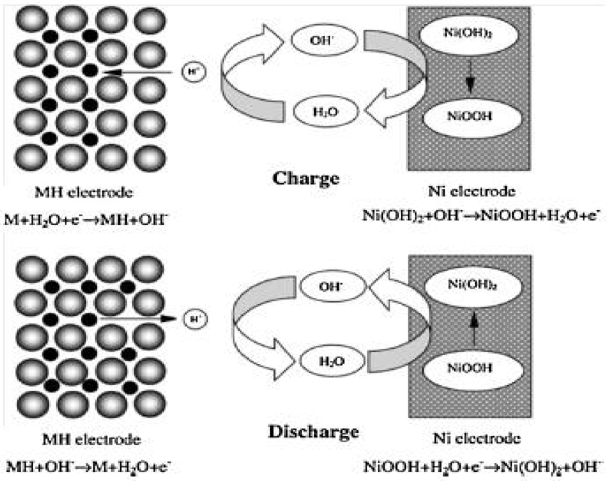


Fig 1.10 Operation of NiMH battery

2) Lithium-ion batteries

The components of NiMH batteries include an anode of hydrogen absorbing alloys (MH), a cathode of nickel hydroxide ($Ni(OH)_2$) and a potassium hydroxide (KOH) electrolyte.

Li-ion batteries store more energy than NiMH, however they suffer from major issues such as costs (1000$/kWh), wide operational temperature ranges, materials availability (e.g. Li), environmental impact and safety. For example, $LiCoO_2$ batteries are unsafe as they are thermodynamically unstable although they are kinetically stable in practice.[24]

Lithium-ion batteries are light, compact and operate with a cell voltage of ~4 V with a specific energy in the range of 100–180 Wh/kg. In these types of batteries, both the anode (graphite e.g. mesocarbon microbeads—MCMB) and cathode (lithium metal oxide—LMO2 e.g. LiCoO2) are materials into which, and from which, lithium (as Li+) migrates through the electrolyte[24]

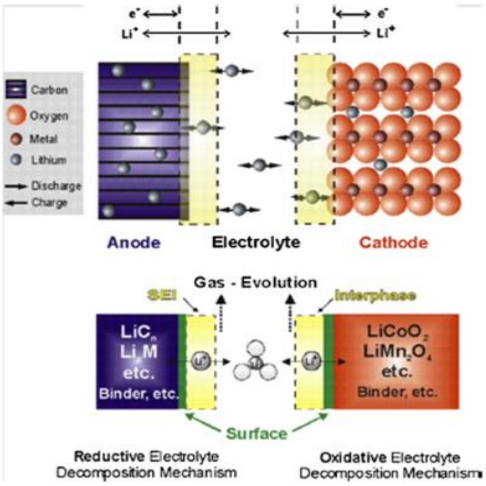


Fig 1.11 Li-ion Battery operation

1.4.2 Comparison of battery and fuel cell electric vehicles

we compare hydrogen-powered fuel cell electric vehicles (FCEV) with battery-powered electric vehicles (BEV) in terms of mass, volume, greenhouse gases, fuelling time, energy efficiency, fuelling infrastructure and cost.

a) **Vehicle mass(or weight)**

In terms of specific energy, figure 1.11 shows the comparison between batteries and fuel cells in field of transport applications. Two hydrogen pressures 5000psi(345 bar) and 10000 psi(700 bar).the energy plotted on this graph is useful energy delivered to vehicle controller

The mass in the specific energy calculation includes the hydrogen tanks, a high power battery pack to capture the regenerative braking and helps in boost the acceleration and fuel cell stack with auxiliary fuel cell components.

Similarly for the batteries in specific energy calculation, we include only energy delivered to the motor not the total battery energy stored.[25]

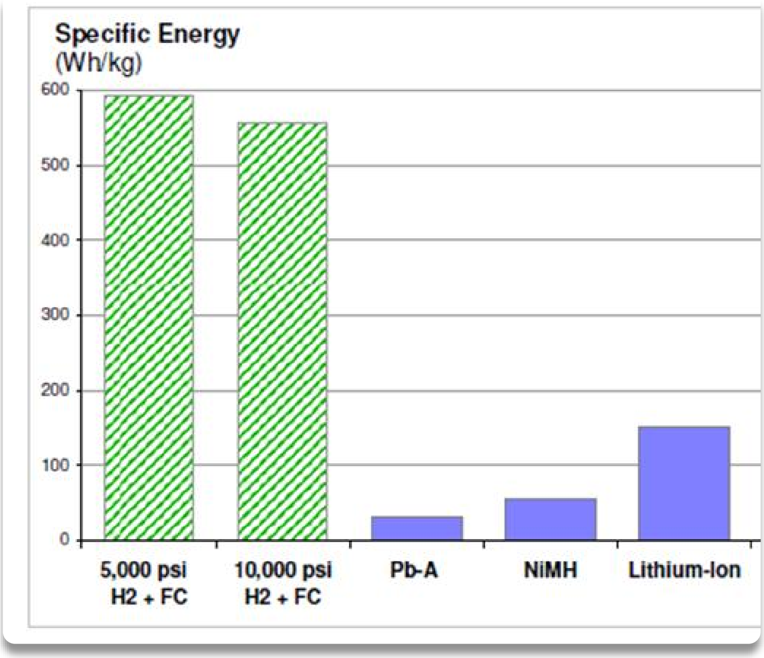


Figure 1.12 The specific energy of hydrogen and fuel cell systems compared to the specific energy of various battery systems

fuel cells can provide electricity to a vehicle traction motor with weights that are between eight to 14 times less than current batteries, As a result, EVs must be much heavier than FCVs for a given range, as shown in Figure 1.12

The Extra weight to increase the range of the fuel cell EV is negligible, while the battery EV weight escalates dramatically for ranges greater than 100 to 150 miles due to compounding weight. Each extra kg of battery weight to increase range requires extra structural weight, heavier brakes, a larger traction motor, and in turn more batteries to carry around this extra mass, etc.[25]

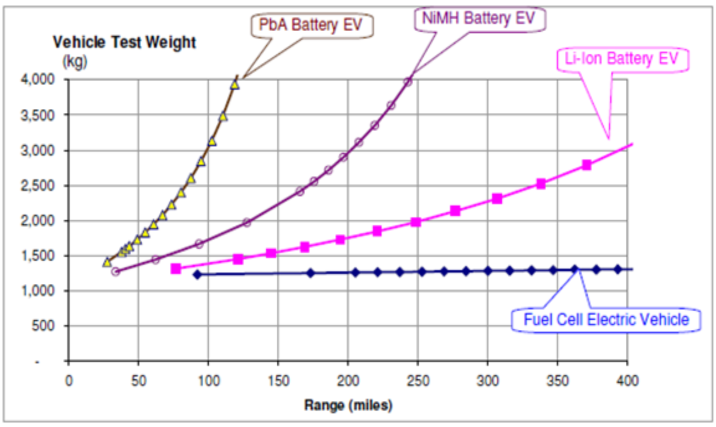


Figure 1.13. Calculated weight of fuel cell electric vehicles and battery electric vehicles as a function of the vehicle range

b) Storage volume

In FCEV, Compressed gas hydrogen tanks plus fuel cell system together take up less space than batteries per unit of useful energy.

The total volume required for the hydrogen tanks and fuel cell system is compared with battery packs in Figure 1.14

Since the BEV weighs more than the FCEV for ranges greater than 80 km (50 miles), a long-range BEV requires more energy storage to travel a given distance despite the two systems having nearly identical useful energy densities, requires more space on the car. The space to store lead acid batteries would prevent a full passenger vehicle with a range of more than 160 km (100 miles), while a NiMH EV would be limited in practice to less than 240 km (150 miles) range.[25]

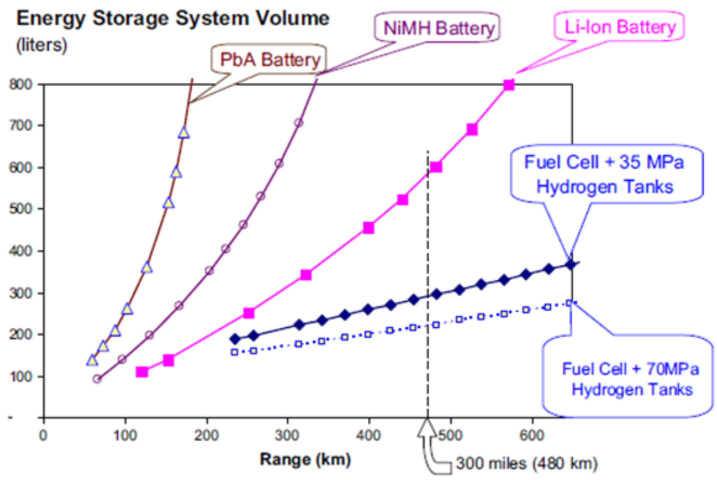


Figure.1.14 Calculated volume of hydrogen storage plus the fuel cell system compared to the space required for batteries as a function of vehicle range

c) Effect of Greenhouse gas

The implications of greenhouse gas (GHG) in charging battery Electrical Vehicles(EVs) with the electrical grid in the 2010–2020 time period will be serious in most parts of the world.

GHGs would be greater for EVs in most parts of the US than for hydrogen powered FCEV in the early start-up years, assuming that most hydrogen was made by reforming natural gas for the next decade or two.

longer range EVs are heavier and less efficient for any given battery type, a 5-passenger lead acid battery EV that achieved more than 100–110 km (60–70 miles) range would generate more net GHGs than the same gasoline version.[25]

A NiMH battery electric vehicle with range of more than 200-240 km and Li-ion BEV with the range of 430 km would generate more GHG emissions than Comparable IC engine vehicles and Fuel cell vehicles.

Hydrogen fuel cell electric vehicle can achieve 480-550 km range with consistent GHG reductions. They reduce emissions by approximately 47% compared to gasoline cars.

Advanced Li-ion BEVs with 320 km (200 miles) range are projected to have approximately the same GHGs as fuel cell EVs initially when hydrogen is made from natural gas.

From this analysis, a 5passenger battery EV range would be limited to about 60 to 70 miles before that EV with lead acid batteries would generate more net GHGs than the gasoline version of the same car.[25]

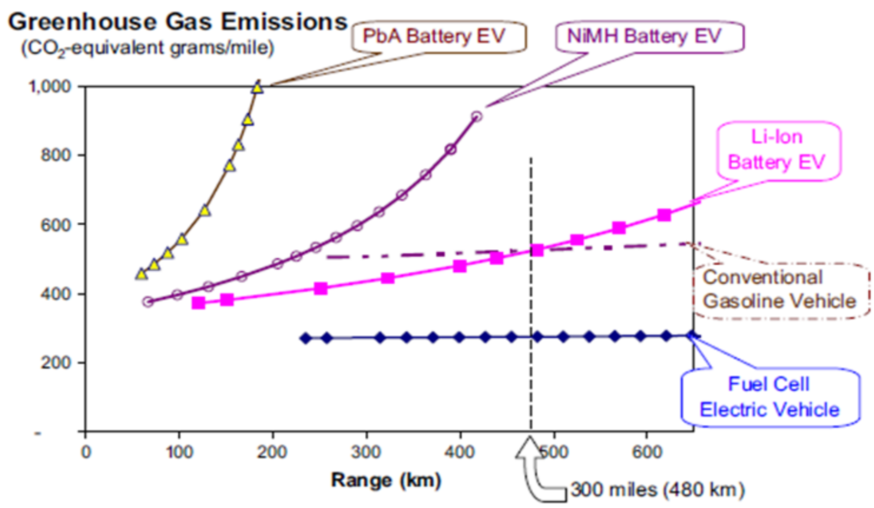


Figure 1.15 Estimated well-to-wheels greenhouse gas emissions as a function of vehicle range for the average US marginal grid mix in the 2010–2020 time period.

d) Fuelling time

Charging batteries for an all-electric vehicle will take much longer. One of the challenges facing battery companies is to design and manufacture batteries that can accept rapid charging currents without overheating the battery cells or disrupting the voltage balance between cell banks.[25]

It will take from 36 min to 1.4 h to fully charge a 320-km BEV battery bank, and 1–2.5 h to charge a 480-km. On the other hand, It will take few to 30 min to recharge the fuel cell, which cosidered to advantageous with respect to BEV.

Table 1.1 Estimated minimum fuelling time for battery EVs and Fuel cell EVs

		Battery electric vehicles		**Fuel cell electric vehicles**
Vehicle range (km)	Energy required from grid (kWh)	Point1 charging time (h) 120V,20A/1.9KW	Point2 charging time (h) 240 V, 40 A/7.7 kW	Hydrogen tank filling time (hours)
250	56	29.2	7.3	0.08
322	82	42.7	10.68	0.10
483	150	77.6	20	0.15

e) Vehicle cost

Costs of various alternative vehicles in Mass production analyzed by Kromer and Heywood at MIT. BEV with 200 miles range would cost approximately $10,200 more than a conventional car by 2030, where as FCEV with 350 (553 km) range is projected to cost only $3600 more in mass production. From the figure 1.16 All electric range would cost less than FCEV [25]

Fuel cell electric vehicle could have the range demanded by modern drivers for good function vehicles. All electric battery powered electric vehicles will probably for city cars and limited range distance covered vehicles.

Incremental Cost Compared to Advanced FCEV by 2030

Figure 1.16 Estimated mass production incremental cost of hybrid and electrical vehicles compared to a conventional gasoline internal combustion engine vehicle by the 2030 time frame

f) Efficiency

Fuel cell electric vehicles are less efficient than battery electric vehicles i.e. fuel cell system efficiency of a driving cycle will be around 55% where as the round trip efficiency of Battery system will be around 75-80%. [25]

The BEVs are heavier than FCEVs for any given range, The BEV will require more energy per km.

For full cycle of Well-to-wheel basis , the hydrogen -powered fuel cell electric vehicle is between 1.5 to 2.2 times more efficient energy than a battery EV in case of natural gas to hydrogen to run a fuel cell electric vehicle.

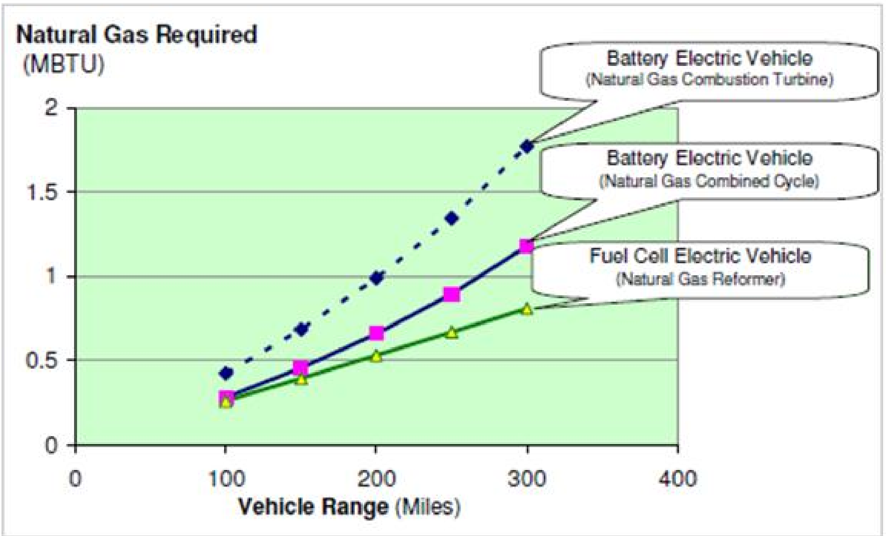


Figure.1.17 Quantity of natural gas required to power an advanced Li-ion battery EV compared to a hydrogen-powered fuel cell EV as a function of vehicle range

By the effect, the increased weight of a long range BEV, even assuming advanced Li-ion battery systems, almost eliminates the improved round trip efficiency of the battery pack compared to the fuel cell system.

As shown in Figure 1.17, efficiency of BEV with 100 miles range is identical for total system efficiency of the FCEV. assuming that the electricity is generated by a modern combined cycle turbine with 48% total system efficiency. [25]

g) Biomass utilization efficiency

Converting biomass to hydrogen uses 35% less energy than generating electricity for a BEV used to travel 400Km, which grows to 40% less bio mass energy with 480 Km.

With natural gas, the advantage of FCEVs reduced if both vehicle ranges are reduced to approximately 160 km (100miles)

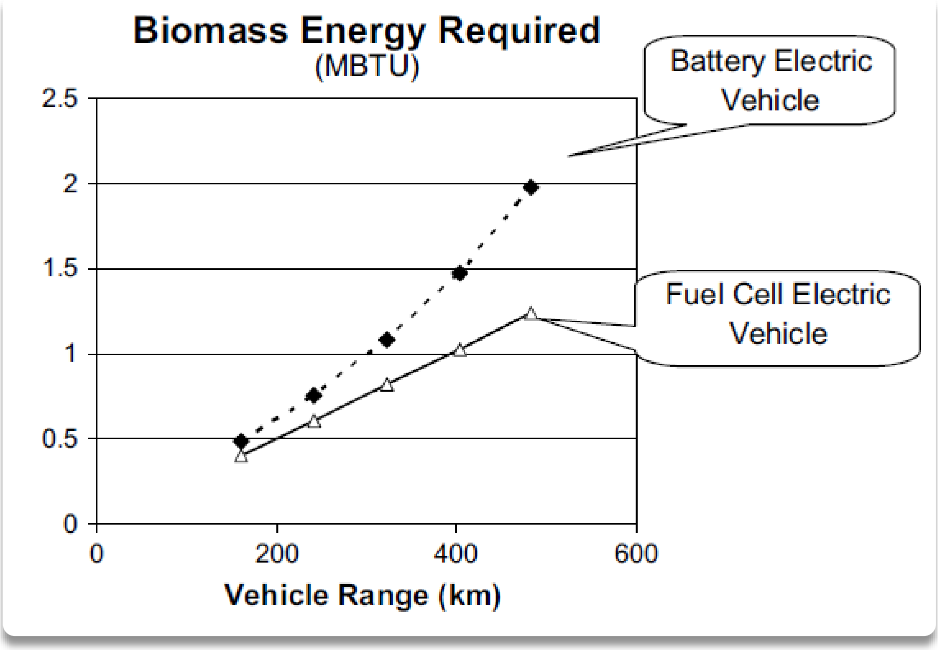


Fig. 1.18 Biomass energy required for battery EVs and for fuel cell EVs as a function of vehicle range

Table 1.2 Comparison of the major characteristics of EVs, HEVs, and FCVs.

Type of EV's	BEV	HEV	FCEV
Propulsion	• Electric motor drives	• Electric motor drives • IC engines	• Electric motor drives
Energy System	• Battery • Ultracapacitor	• Battery • Ultracapacitor • ICengine Generating Unit	• Fuelcells • Need battery/Ultracap-acitor to enhance power density to start
Energy source &	• Electric Grid chargimg	• Gasooline	• Hydrogen

infrastructure	facilities	Stations • Electric grid charging facilities(plug-in hybrid)	• Hydrogen production and transportation infrastructure.
Characteristic -s	• Zero emissions • High energy density • Independence on crude oils • Short range • Initial cost is High • Commercially available	• Very low emissions • Fuel economy is higher when compared with the ICE • Long driving range • Crude oil dependent (non plug-in hybrid) • High cost as compared with the ICE • Commercially available	• Zero emissions • High energy efficiency • Crude oil Independence(if not using gasoline to produce hydrogen) • Higher cost • Commercially avaialable
Major issues	• Battery Management • Charging facilities • Cost	• Mulitple energy sources control,optimization and management • Battery sizing and management.	• Fuel cell cost,cycle life and reliabilty • Hydrogen infrastructure.

1.5 Evolution of the Fuel cells and their perspective towards vehicle.

The conceptualization of the fuel cell was first put forward by Humphry Davy in 1801. But the invention of the first working fuel cell is credited to William Grove, which was succeeded by pioneering work on what were to become fuel cells by the scientist Christian Friedrich Schönbein in 1838. In 1839, William Grove was credited with inventing the fuel cell. Grove conducted a series of experiments with what he termed a gas voltaic battery, which ultimately proved that electric current produced from an electrochemical reaction between hydrogen and oxygen over a platinum catalyst. In 1842, Grove's experiments proved that an electrochemical reaction of breaking the hydrogen atom delivers electric current.[18]

Around 1959, the First modern fuel cell vehicle was produced by altering an Allis-Chalmers farm tractor, equipped with a 15KW fuel cell. The Cold War Space Race tugged further development of fuel cell technology. In 1966, General Motors developed the first fuel cell road vehicle. It had a Proto-exchange Membrane fuel cell, with a range of 120 miles and a speed of 70 mph. There were only two seats, as the fuel cell stack and fuel tanks took up the rear portion of the van[18]. one of them was built because the project was deemed cost-prohibitive. General Electric went working on PEMFC in the 1970s. In the 1980s, Fuel cell stacks were confined to space applications.

By the 1990s, automobile manufacturers were interested in fuel cell applications and demonstration of vehicles geared up. In 2001, the first 700 Bar (10000 PSI) hydrogen tanks demonstrated, abridging the size of the fuel tanks that could be used in vehicles and extending the range.

In 1889, Charles Langer and Ludwig Mond had first mentioned the term scientifically as Fuel Cell. In 1932, Cambridge engineering professor Francis Bacon modified Mond's and Langer's equipment to develop the first Alkaline Fuel Cell. But in 1959, that Bacon demonstrated a practical 5kW fuel cell system. Simultaneously, Harry Karl Ihrig equipped an altered 15 kW Bacon cell to an Allis Chalmers agricultural tractor. Allis-Chalmers, in collaboration with the US Air Force, subsequently developed many fuel cell-powered vehicles. By 1970, emersion of increasing environmental awareness among governments, businesses, and individuals. Incited by concerns over air pollution, clean air legislation passed in the United States and Europe. It ultimately mandated the reduction of harmful vehicle exhaust gases and was eventually adopted in many countries around the world. By the 1970s, Clean air and energy efficiency were to become two of the principal drivers for fuel cell adoption in subsequent decades, in addition to the recent concerns about climate change and energy security. Also, in the 1980s, Research, Development, and Demonstration (R&D) work continued into the use of fuel cells for Automobile applications. The US Navy commissioned studies into the utilization of fuel cells in submarines, where highly efficient, zero-emission are offered considerable operational advantages[19].

In 1983 the Canadian company Ballard commenced research into fuel cells and to become a crucial player in the manufacture of fuel cell stacks and systems for stationary and transport applications in the following years. Attention turned towards The Proton-exchange membrane fuel cell (PEMFC) and Solid oxide fuel cell(SOFC) technology in the 1990s, particularly for small stationary applications. It seems to offer a more imminent commercial possibility due to the cost per unit is lower compared to others and then greater the number of potential markets.

In 1990, California Air Resources Board (CARB) introduced the Zero Emission Vehicle Mandate (ZEVM). It was the first vehicle emissions standard in the world predicated not on improvements to the internal combustion engine (ICE) but the use of alternative power trains. Carmakers such as Daimler Chrysler, General Motors and Toyota, all of which had substantial sales in the US, responded to this by investing in PEMFC research. Companies other than carmakers, such as Ballard, continued PEMFC research for automotive. Ballard went on to supply PEMFC units to Daimler and Ford. The programs initiated in the 1990s still recapitulate, although with some changes to the strategic focus of some key players.[19]

3.Fuel Cell Technologies

Fuel cells are categorized primarily based on the type of electrolyte employed. This classification figures out:

1. Kind of electrochemical reaction in the cell.
2. Kind of catalysts required.
3. Range of temperature in which fuel cell operates.
4. Fuel type required in the operation.

According to Batosky, Fuel cells are classified into three types based on

1. Reactant type (i.e., Hydrogen, methanol and other organic substances and oxidizing agent, use pure oxygen, hydrogen peroxide and other substances)
2. Electrolyte type (general electrolytes of acids, alkali + salts or solid electrolytes which serves as separators, holding the reac6tants from reacting the wrong electrode)
3. Operating temperature.

- Low-temperature (50°C–150°C): alkaline-electrolyte (AFC), proton-exchange membrane (PEMFC) and direct-methanol (DMFC) fuel cells.
- Medium-temperature (around 200°C): phosphoric-acid fuel cells (PAFC).
- High-temperature (600°C −1000°C): molten-carbonate (MCFC) and solid-oxide (SOFC) fuel cells.

The major types of fuel cells employed in various fields of science and technology are

1. Proton-exchange membrane Fuel cell
2. Alkaline fuel cell
3. Direct methanol fuel cell
4. Phosphorus Acid Fuel cells
5. Solid-oxide fuel cells
6. Molten-carbonate fuel cell

1. **Alkaline fuel cells**

Alkaline Fuel cell comprises of 40% of the aqueous solution of Potassium hydroxide(KOH) as an electrolyte. It conducts ions between Two electrodes i.e. Anode and Cathode. On the anode side, Oxidation reaction takes place which results in turning Hydrogen into positively charges ion and negatively charged electron. It is one which is widely used in Space applications.

Some advantages made it promising for different applications.

1. Low operating temperatures ranging between 50-200°C.
2. Quick startup.
3. Low catalyst required which results in reduced content costs .
4. Efficiency will be around 50 -60%.

2. **Polymer Electrolyte Membrane Fuel cell**

The basic structure of PEMFC is a solid membrane with natural material(for example polystyrene sulfonic acid) is used as an electrolyte. The membrane is sandwiched between the anode and cathode which allows protons only to move between the electrodes. Oxidation reaction of the hydrogen makes hydrogen into positively charged ion and electron. Ions(or) protons reach the cathode combine again with electrons and reaction with oxygen results in the formation of water.

Key advantages of PEMFC

1. Low operating temperatures ranging(50 °C-100 °C)
2. Efficiency range around (40%-60%)
3. Power density is highest comparing with all available types of Fuel cells
4. Start quickly, less wear on system components and better durability

Lots of big companies such as Ballard, General Electric, Toshiba and Sanyo produce PEMFCs commercially. Leading Automotive makers such as Honda, Toyota, Hyundai, Daimler-Chrysler, General Motors, BMW, Nissan, Ford and Renault use the technology for their own commercial purposes. [20]

3. **Direct Methanol Fuel cells**

They have the close resemblance with PEMFC(uses poly styrene sulfonic as electrolyte).Operation of Direct Methanol Fuel cell (DMFC) is based on oxidation of Water with methanol. DMFC's use Liquified Methanol for the quick transportation. DMFC's became least preferrable because of Low density, Slow Power response and Low Efficiency compared with direct hydrogen. Generally The Operating Temperature will be around 50-100◦C. They are preferably used for emergency Power supply and Portable electronics. Due to its Low density and efficiency characteristics, it is not a primary option for Automotive Technology and other means of applications.

4. **Phosphoric Acid Fuel Cell**

Invention of Phosphoric Acid Fuel Cell(PAFC) takes place in 1980s. It consists of Porous silicon carbide matrix (i.e. conducting material)in which Phosphoric acid is contained between the two electrodes to function as electrolyte. The reactions of the anode and cathode resembles PEMFC reactions. The rate of reaction is increased by incorporating the Platinum catalyst. The electrolyte temperature of the PAFC is to be above 42°C(Freezing point).which adds extra weight, cost, volume etc,. which makes not compatible for Automotive applications.

Advantages of PAFC systems

1. Electrolyte used is cheap
2. Low operating temperature and reasonable startup time.

5. **Solid Oxide Fuel Cells**

Solid oxide fuel cells use a hard ceramic material or membrane conducts ions at high temperature usually at 700-1100ºC. the ceramic membrane is used as a solid electrolyte called Yttria-stabilized Zirconia (YSZ). On the anode(Porous Nickel)side, fuel is applied and oxygen flows to the cathode (metal oxide) side. The solid electrolyte membrane only permits the transition of negative charged oxygen ions from cathode to anode. When oxygen ions reach anode, they react with hydrogen ions to form water.[21]

SOFCs have about 45% efficiency that can reach 85% by capturing and utilizing the heat/exhaust. Additionally, the SOFC systems have low gas emissions[21]

Advantages of SOFC systems can be specified as follows

1. High efficiency
2. Reliability of the solid electrolyte is high compared to Liquid Electrolyte
3. Low corrosion problems.

6. Molten Carbonate Fuel Cell

Molten Carbonate Fuel cell depends on Molten Carbonate salts to conduct ions. Ion conduction mechanism is Like in concentrated AFCs. Operation of the Fuel cell takes place over the melting point i.e. 600-700°C of the carbonates and does not require a catalyst because of the high temperature. MCFCs use Hydrocarbons rather than pure hydrogen.

MCFCs do not demand an external reformer; thus, the primary fuel used may not be hydrogen gas. The basic components of natural gas, methane, and steam are processed at a reformer in the MCFC system, and electricity will be produced. The internal reformer reduces the costs compared with the other FC technologies with external reformers.[22]

Advantages of MCFCs

1. Require low cost catalysts
2. Fast response to the load changes
3. Lower sensitive to poisoning.

Overview of Fuel cell Technologies.

From the available fuel cell types, Polymer electrolyte membrane Fuel cells(PEMFC) is most suitable and working characterized for the Automotive applications because of its prominent features like Low operating temperature, quick start-up, packaging and low cost relative to other fuel cell types.

The Stand-alone fuel cell system is not suitable for the power demand of the vehicles due to the load variation. Then the Fuel cell system is to be combined with driving motor, ESS and various auxiliary components In order to meet the power demand when vehicle is subjected to significant variation due to acceleration and Road surface[23]. A suitable strategy is to be adopted to meet the power demand of the vehicle in order to eliminate the limitations and maximize the performance of the Fuel cell by adopting the Hybrid system Technology.

Let us discuss in detail the main Fuel cell technologies which are adapted for the Distributive power generation, Mobile electric generation, storing the energy mainly for our study on the automotive propulsion system and transportation applications.

2.1 Alkaline Fuel cell

2.1.0 Introduction

Alkaline fuel cell technology is one of the first developed technology and is widely used in space applications. Because of the electrolyte is alkaline, the ion conduction mechanism has differences with PEMFC. At the anode hydrogen undergoes oxidation (turns hydrogen to positive charged ion and negative charged electron) At the cathode, negatively charged electrons travel through an external circuit generate electricity. Voltage applied between the anode and the cathode of a single fuel cell is between 0.9V and 0.5V depending on the load.[26]

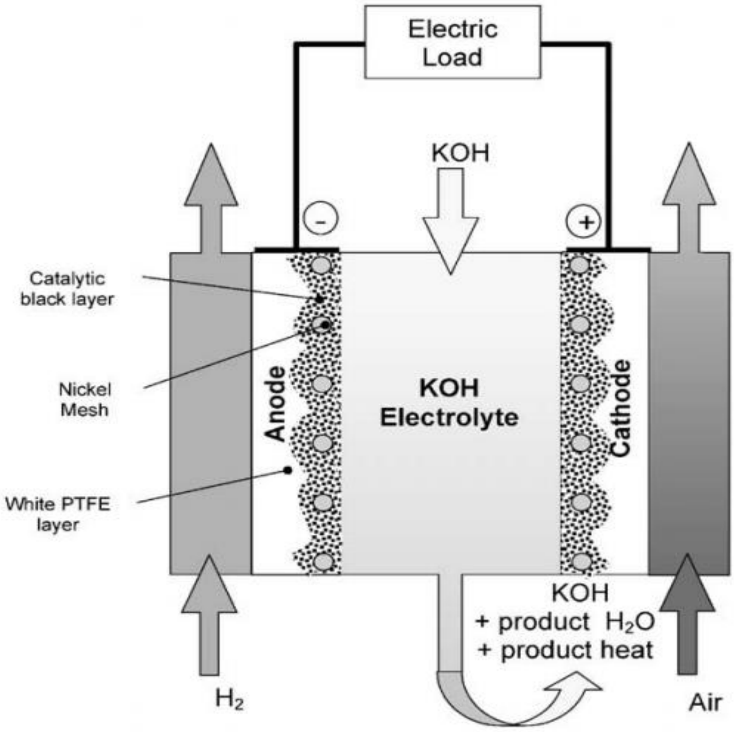


Fig. 2.1 Operation of the Alkaline Fuel cell

Principle of operation:

Anode reaction: $2H_2 + 4OH^- \longrightarrow 4H_2O+4e^-$

Cathode Reaction: $O_2+2H_2O+4e^- \longrightarrow 4OH^-$

Overall reaction: $2H_2+O_2 \longrightarrow 2H_2O$ + Electric Energy+ Heat

The Aqueous solution of KOH as the electrolyte having the concentration of 30%.the electrodes consist of a double-layer structure. i.e. Active layer and Hydrophobic layer.[26]

The active layer consists of an organic mixture i.e. carbon black, catalyst and PTFE at room temperature to form a supporting sheet. The hydrophobic layer prevents electrolyte from leaking into the gas flow channels and ensures diffusion of gases to the reaction site. The two layers are then pressed onto a conducting metal. The process is eventually completed by sintering. The total electrode thickness is of the order of 0.2–0.5 mm[27]

The major constraint is the requirement for low CO_2 concentration. The presence of the carbonates leads to blockage of electrolyte pores and pathways.

2.1.1 Evaluation of current density and potential

It is useful to compare the electrochemical performance of AFCs and PEMFCs in terms of the relationship between cell potential, E, and current density, i. When mass transport limitations are negligible (low to intermediate current density), E and i are approximately related by Blomen and Mugerwa [33]

$$E = E0 - \beta \log i - Ri \ldots\ldots(1)$$

With

$$E0 = Er + \beta \log i0$$

where, Er is the reversible thermodynamic potential, β and i_0 are the Tafel slope and the exchange current density for the oxygen reaction, and R is the differential resistance of the cell.

Differentiating Eq. (1) provides further insight into the relative importance of losses associated with electrode kinetics and electric resistance:

$$\frac{\partial E}{\partial i} = -\frac{\beta}{i} - R.$$

At low current densities, the 4rst term on the RHS is dominant and corresponds to the typical steep fall of the cell potential with increasing current.

At higher current densities, β <<R and the second term becomes dominant, resulting in a quasi-linear drop of cell potential with current until mass transport limitations become important.

Optimal performance is obtained for low β and cell resistance (R), and high exchange current density (i_0). The better electrode kinetics of AFCs results in β lower by about 30% than for PEMFC, when Pt is used as a catalyst in both AFC and PEMFC

The main contribution to cell resistance is due to the ionic=protonic resistivity of the electrolyte. Again AFCs appear to have lower electrolyte resistivities (0.05 Ω/cm^2 vs. 0.08 Ω/cm^2 for PEMFC).

Nonetheless, AFCs have an intrinsic advantage over PEMFC on both cathode kinetics and ohmic polarization.[29]

Optimum electrochemical results

Voltage (V) = 0.67

Current Density (mA/cm2) = 574.316

Power (mW/cm2) = 325.19

2.1.2 Power density

Evaluation of the power density must be based on overall system volume or weight, thus making it difficult in assessing power density based on the defined performance of the fuel cell electrochemical reaction.

In the absence of absolute volumetric or gravimetric system power densities, polarization information is often used to assess the merits of particular fuel cell designs.[26]

This approach is reasonable in providing a Figure of relative merit as a cell with higher current density, at an equivalent voltage, will provide higher overall power density so long as the stack geometry and ancillary systems remain constant, which is a reasonable assumption for the majority of PEM and AFCs.[26]

2.1.3 Performance information of Power density in Space applications.

A matrix type alkaline H_2–O_2 fuel cell is elaborated by Matryonin.[30]

The cell is defined to be operating at 100◦ C and pressures of 4 –4.5×10^5 Pa.

The performance is impressive, showing 3.2 A/cm^2 at 600 mV. The results show very good current density at high voltages with pressures between 30 and 60 psi.

Martin and Manzo [31] present performance data from Operating with gas pressures of 200 psi and temperatures of 300 F and a 50% weight KOH electrolyte solution they report current densities up to 9 A/cm^2 at just over 0.7 V. Their Orbiter data reports 1000 mA/cm^2 at 900 mV. Similarly, the Siemens fuel cells indicates 1 A/cm^2 at 0.74 v. with an operating pressure of 30 psig.

Although these reported results for AFCs which are based on the space applications, do not typically provide complete polarization curves, they nonetheless indicate very high current densities. performance information from these space-based approaches is shown in Table 2.1.

Table 2.1 Summary of space application AFC performance

Operating point		**Power**	**Pressure**	**Temperature**
mV	**mA/cm²**	**(W/cm²)**	**(psig)**	**(ºC)**
950	140	0.133	29	98
950	220	0.209	58	98
950	310	0.2945	116	98
950	150	0.1425	58	65
950	280	0.266	58	96
950	440	0.418	58	130
600	3200	1.92	58	98
600	4200	2.52	58	121
800	6730	5.384	299	149
740	1000	0.74	29	80
900	320	0.288	29	80

The second distinct class of AFCs is based on operation at atmospheric pressure. Current densities of 100 mA/cm^2 are reported there. The ZEVCO published performance recently [27] indicates normal operation at 100 mA/cm^2 range at 0.67 V per cell.

The Performance of an Alkaline Fuel Cell using a solid ionomer alkaline membrane is discussed in Swette.[32]The system was operated at 44 psi gas pressures at 40◦C, which is a unique operating point. Using a Platinum–Iridium catalyst produced the best results, but still only 100 mA/cm^2 was produced at 800 mV. Unfortunately, no further developments were achieved with this technology.

An Alkaline Fuel Cell stack developed for operation with Biomass produced hydrogen specifically is discussed by Kiros[33]. For Both H_2–air and H_2–O_2 performance were reported, but the operating data is incomplete with no gas pressure information being provided. Considering together, the atmospheric performance reported results in the literature suggests that power densities are between 100 and 200 mA/cm^2 under atmospheric pressures. results are summarized in Table 2.2.

Table 2.2 Summary of terrestrial application AFC performance

Current density 0.7v(mA/cm^2)	**Power at** 0.7(w/cm^2)	**Operating point 2** mV	mA/cm^2	**Power at point 2**	**Pressure at (psig)**	**Temperature**
290	0.203	800	260	0.208	Atm H_2-air	75
450	0.315	800	280	0.224	Atm H_2-air	75
90	0.063	800	35	0.028	Atm H_2-air	40
108	0.076	800	102	0.082	Atm H_2-air	40
115	0.081	570	225	0.128	Atm H_2-air	40
125	0.088	700	125	0.088	Atm H_2-O_2	40
88	0.062	700	88	0.062	Atm H_2-air	40
157	0.110	700	157	0.110	Atm H_2-air	40
87	0.061	670	100	0.067	Atm H_2-air	70
40	0028	-	-	-	Atm H_2-air	60

2.1.4 AFC hybrid car

AFC hybrid can have the operating life of about 4000h by draining the circulating KOH electrolyte. The early model is the hydrogen/air fuel cell lead-acid hybrid car, built by K. Kordesch.

The Austin A40 is incorporated with Low-cost alkaline Fuel cell-Hybrid system. It is connected with seven lead acid batteries that are connected in series for supplying the peak power when accelerating the vehicle and hill climbing. An Electrovan is used for propulsion only and The performance of this 150 kW H2/O2 system connected to A.C. motor.[33]

Fig.2.3 Austin A40 Hybrid vehicle.

The complete system was fitted into the Austin A40. 6 lightweight pressurized hydrogen tanks are mounted on the roof contained with the hydrogen for driving about 300 km in the city and these could be refilled in 2 min using quick-connection hoses from a hydrogen tank.

The AFCs Life expectancy is increased by emptying the electrolyte from the battery between operating periods. Shutting down the Hydrogen gas exposes the negative electron to the air(catalyst regenerative effect)

The six hydrogen tanks contained a total of 25 m^3 of hydrogen at a pressure of 150 bar. This is equivalent to 45 kW h (at 0.7 V per cell). The car used an average of 6 kW in the city but less than 5 kW on the open road at 60 km/h .The specific energy of the fuel cell system (W= 250 kg) was 140 W h/Kg. The calculated efficiency about 60%. Operating at high speeds with capacity from the lead acid batteries which could be replaced by the fuel cell during idling periods.[33]

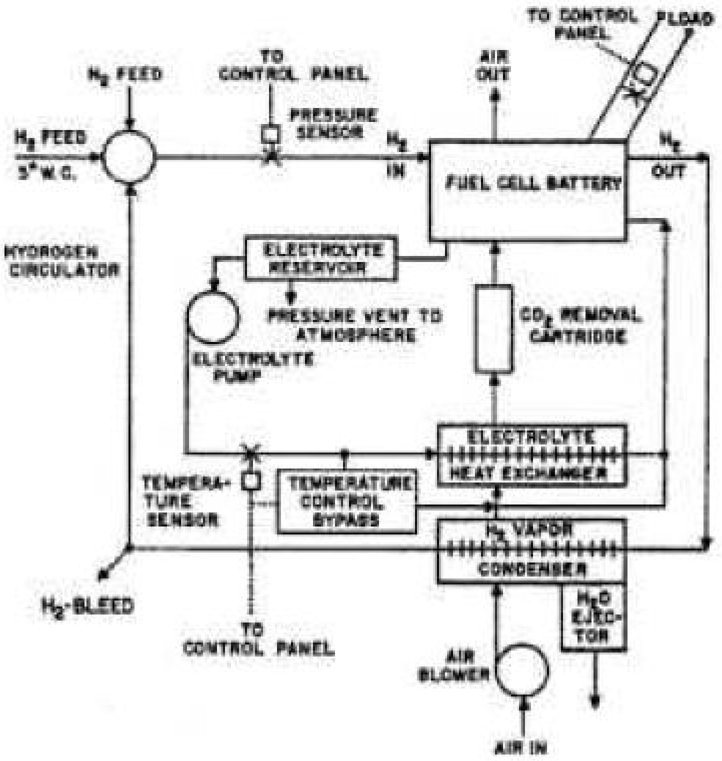


Fig 2.4 *6* kW alkaline fuel cell system.

Typical fuel in Fuel cell electric vehicles

a) Reformer fuels, hydrides and liquid hydrogen storage

Methanol and hydrocarbons are candidates as reformer fuels. For AFCs, the $C0_2$ content must be removed by

1. A shift reactor
2. A swing adsorption process, or
3. By a new method, using sponge iron

Unlike PEM cells, CO is no problem for noble metal catalysts on carbon in alkaline cells, The fuel storage also involve the use of metal hydrides which act as a buffer until the reformer starts.

Liquid hydrogen has been used too, but the liquification lowers the fuel efficiency by 30%. Only the Direct Methanol FC gets around the reformer problems.

It could be the future competitor for reformer fuel cells. Interestingly, JPL also report a longer life (4000 h vs. 200 h) by intermittent usage.[33]

b) Iron sponge

Iron sponge is produced by the reduction of iron ores and is used in steel furnaces for cooling purposes. It was H-POWER who suggested its use as a source of hydrogen plus steam produces clean hydrogen and iron oxide.[33]

c) Ammonia as a fuel for AFCs

Anhydrous liquid ammonia is an interesting carrier of hydrogen and its transportation in low pressure cylinders is a commercial practice.

The specific energy is 3.3 kW h/kg. From this value, 15% was lost in a catalytic cracker, producing 75% hydrogen. Low temperature (i.e. 350°C) crackers are also possible, and early designs with Raney-metal catalysts date back to the 1970s.[33]

d) RAM batteries in a hybrid system.

In 1994, it was suggested that the lead-acid battery could be replaced by the Rechargeable alkaline manganese dioxide i.e. RAM batteries capable of producing high currents and high storage life even at high temperatures. Assembly of cylindrical cells in series and parallel arrays could replace even Ni/Cd batteries in both power output and capacity.[33]

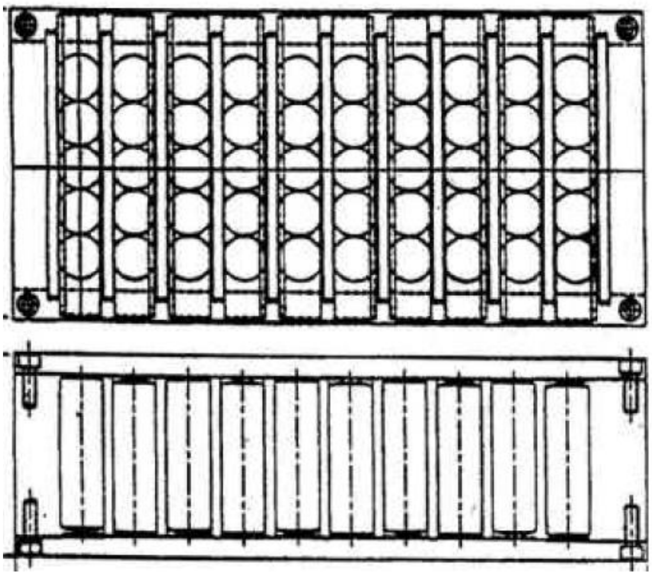


Fig 2.5 Parallel-series assembly of RAM batteries

Table 2.3 : Projected performance of a hybrid system using a hydrogen/air alkaline fuel cell and a series/parallel array RAM cells

Performance parameter	**Value**
12-15 kW hydrogen/air fuel cell, weight	220kg
5 kW h rechargeable battery, weight	100kg[a]
Vehicle curb weight + 4 persons (or 2 + luggage)	500kg
150 kW h lightweight H2 cylinders, weight	150kg[b]
Hydrogen consumption per 100 km	1.5kg
Driving range of the vehicle at 75 km/h	300kg[e]
Efficiency of the system	60%
Acceleration, time from 0 to 70 km/h	10 s
Maximum speed	100 km/h

20-minute high power output	30kW
1 -minute peak power output	60kW
Fuel cell working temperature	69-90°C
Readiness of the secondary battery	instantly
Cycle life of the secondary battery	500 cycles[d]
Time to full output from the fuel cell	3-5 min
Actual operating life on intermittent duty cycles	4000 h
Maximum current density for the air electrodes	150 mA cm $^{-2}$
Noble metal catalyst loading for each electrode	0.1 mg cm $^{-2}$

[a] This assessment uses 5000 AA cells, each weighing 20 g, in an assembly of 50 parallel strings, each with 100 cells in series

[b] If liquid ammonia at low pressure is used, the energy output would double for the same weight.

[c] Accordingly, the range with ammonia would increase to 600 km.

[d] This is based on an average depth of discharge (DOD) of 50%.

2.1.5 Expectations on AFCs

1. The life expectancy of the system must be sufficient to drive for 200,000 km, (intermittent operation with complete shutdown possibility when the car is not in operation, is observed)

2. The design of the fuel cell system must be such that its operation is fully automatic.

3. The load capability should be sufficiently high (200 mA cm^{-2}) to give a specific energy of 150 W h/kg for the total system (without fuel tanks)

Table 2.4 Comparison with AFC with PEMFC

FC TYPE	Alkaline Fuel cell (AFC)	Proton Exchange membrane(PEMFC)
Anode	Platinum or Carbon	Platinum
Electrolyte	Potassium Hydroxide(KOH)	Polymer membrane
Electrolyte type	Liquid	Solid
Fuel	• Hydrogen • Ammonia	Hydrogen
Temperature	60-70 ^{o}C	• 80-100 ^{o}C • 200 ^{o}C
Efficiency	60-70 %	30-50%
Power	0.5-200kW	0.12-5 KW
Startup time	< 1minute	<1 minute
Merits	• Quick startup • Temperature resistant • Low-cost ammonia liquid fuel	• Quick startup • Small • Light-weight
Demerits	• Liquid crystal adds weight • Relatively large	• Sensitive to humidity or dryness • Sensitivity to salinity • Sensitivity to low temperatures
Uses	• Backup generator (Long-duration UPS) • Primary Power	• All automobile vehicles like

	generators • OFF-grid telecom	• Cars • Buses • Trucks etc.

Typical PEM fuel cell performance describes a system in which current densities are greater than 1 A/cm^2 at 0.6 V or higher, volumetric densities exceed 1 kW/l and gravimetric densities exceed 1 kW/kg. PEM fuel cell technology is producing high power densities compared with the ambient AFC fuel cell technology. However, the PEM systems are typically pressurized to at least 30 psig. In pressurized AFC systems similar or even higher power densities were reported.[26]

The ambient air operated PEM systems suggest performance that is on the same order of magnitude as ambient air alkaline systems. The current density achieved at 0.7 and 0:6 V for each case is presented in Table 2.5. Note that these data are gathered from available literature and do not necessarily reflect state of the art performance of ambient air PEM systems.[26]

Table 2.5 Summary of ambient air PEM fuel cell performance

Current density 0.7 V	**Power at 0.7 V**	**Current density 0.6 V**	**Power at 0.6 V**
(mA/cm^2)	(W/cm^2)	(mA/cm^2)	(W/cm^2)
200	0.140	425	0.255
250	0175	500	0.300
125	0.088	450	0.270

Comparing the Tables and from the results, it is that available alkaline and PEM technologies achieve roughly equivalent current densities when working on ambient air oxidant streams.

AFCS with higher current densities can outperform PEMFC and with pressurized AFC systems than the current PEMFC technology. AFC technology has the great potential to yield major improvements for R& D investments.[26]

Present AFC systems have been demonstrated to easily meet the 5000 h lifetime required for traction applications. On the other side, Electrolyte management issues in AFC's imply a degree of ongoing maintenance which is not necessary with PEMFC technology. Minimizing maintenance in AFCs is an important topic for productivity of fuel systems.

For low power applications, including hybrid vehicles, AFCs are least competitive with the cost of any equivalent system constructed using PEMFC technology. The AFC system has a low cost stack and low cost peripheral components. An ambient air operated PEM system, while having low cost peripheral components has prohibitively high stack costs. A high pressure PEM system, while enjoying low stack costs, requires expensive peripheral components. Further improvements in AFC technology will only strengthen this competitive position.[26]

2.1.6 Poisoning and contamination issues

Like all fuel cells, Alkaline Fuel cells have the limitations to the amount of impurities can be tolerated in gas streams. The " poisoning of the fuel cell" by impurities can be caused by any number of different gases. The effect of carbon dioxide, as well as carbon monoxide and oxygen, on the anode side of Alkaline fuel cell are as follows.[35]

a) Effect of carbon dioxide on the cathode

1. Terrestrial application AFCs will in all likelihood operate on ambient air, this is a significant issue. Poisoning reaction involves the alkaline electrolyte directly by the following reaction(s):[35]

$$CO_2 + 2OH^- \rightarrow CO_3^{2-} + H_2O$$

$$CO_2 + 2KOH \rightarrow K_2CO_3 + H_2O$$

2. This has the effect of reducing the number of hydroxyl ions available and therefore reducing the ionic conductivity of the electrolyte solution.
3. Al Saleh showed that concentrations of up to 1% CO_2 in the oxidant stream of Ag/PTFE electrode at 72^{O}C did not significantly affect the cell performance over a period of 200 h. However, at 25^{O}C the CO_2 did adversely affect the performance. the solubility of K_2CO_3 is lower at 25^{O}C and therefore precipitates out and blocks the electrode pores[35]

b) Effect of impurities on the anode

CO_2 adversely affected the performance; the effect was entirely reversible under all experimental conditions. the cell was tested with and without CO2 a number of times in a cyclic manner. At 40 mA/cm^2 they found a 75 mV polarization effect between 0% and 4% CO_2in the hydrogen stream[35]

c.) Contamination effects

CO_2 in the oxidant stream has a distinct effect on the performance of AFC systems There is strong evidence that a large amount of this poisoning is reversible, and that effective electrolyte management will mitigate a large part of the problem. This could be done in a similar manner as an oil change is performed on vehicles today.[35]

2.1.7 AFC lifetimes

The lifetime of an AFC can be over 5000 h for inexpensive terrestrial AFCs and has been significantly over 10,000 h for space application AFCs. Operating duty cycles and procedures for alkaline cells is provided by Kordesch, in the context of the Austin A40 fuel cell powered car. The electrolyte was drained nightly, and a nitrogen purge was used to neutralize the cells during the shutdown and into inactive operation.

From the predictions to the developments on the electric fuel cell, Alkaline fuel cell may have greater chance than PEMFC due to following.

1. Alkaline space vehicle are best performing fuel cells since 1970, They have been performing on hydrogen and oxygen at high current densities i.e. 1 A cm^{-2} at 0.75V[165]
2. Catalyzed carbon substrates are used in air electrodes successfully, which have delivered current densities between 100 and 150 $mAcm^{-2}$ at 0.75V since 1960. PEMFC electrodes can perform better. But there is a significant increase in the complexity and cost of the system.
3. The alkaline OXY was an excellent prototype system, already geared for mass production before the company went out of business. The ELENCO alkaline system is still the only publicly demonstrated fuel cell which looks economically affordable. In this connection it should also be mentioned that no large funding has gone into the development of alkaline systems for street vehicles during the last 15 or 20 years.[165]

As we discussed earlier on Austin A40 AFC hybrid car, Professor Kordesch showed the use of liquid ammonia as fuel for his car. At that time only 2KW size NH_3 converts were available[34].alkaline Hydrogen/Air fuel cells with circulating KOH electrolyte operate directly upon the dissociated ammonia catalytically and effluent gas contains few percent of hydrogen used to heat the converter.

2.1.8 Cost analysis

AFC technology evaluated from a purely technical perspective, has the potential to compete with other low fuel cell technologies. Although the alkaline technology has been largely neglected in the last ten years, mostly due to the apparent CO_2 poisoning issue, there are no obvious technical reasons to discount its potential for useful applications. [26]

Table 2.6 Summary of low power fuel cell prices[36]

Company (Fuel Cell Product)	Nominal Power	Type of Fuel Cell	Price (US$)
Astris (LC200-16)	240 W	AFC	2400
H-Power (PowerPEM-PS250)	250 W	PEMFC	5700
DAIS-Analytic (DAC-200)	200 W	PEMFC	8500

2.1.9 System cost estimates

The AFC system estimates have a total cost range with a factor of 6, compared to a range of 28 for the ambient air PEM estimate. Gulzow proposed a figure of $400–$500/kW for an AFC system using the technology for high volume production. This analysis indicates AFC systems are cost competitive with comparably sized PEMFC systems, at least for low power. This advantage remains for all production volumes but is most significant at low and medium production volumes. However, it should be noted that the 7-kW alkaline system would be competing with a 50 kW PEMFC system. Directed Technologies has estimated that the total system cost for a 50 kW PEMFC system would be about $2100 for production volumes of 500,000. Extra components required to complete the alkaline hybrid power system (namely batteries) must cost no more than about $670.[26]

a) AFC stack materials

Potential improvements in the AFC stack materials include the reduction of the catalyst loadings, as well as development of cobalt oxide-based catalysts and replacement of the nickel mesh current collectors with a cheaper metal mesh.

The cost of final assembly, especially for larger volume manufacturing, is assumed to be minimal.

Table 2.7 Costs of AFC stack components

Component	**Current(US$/KW)**	**Projected**(US$/kW)
Stack costs	1750	205

on a 1:0.925 basis

Table 2.8 Materials and manufacturing processes for AFC stacks [29,37]

Component	**Materials**	**Manufacturing Processes**
Anode	PTFE powder graphite powder catalyst: (Pt or Pd 0.12–0:5 mg/cm^2) Ni–Al, Ag	Mechanical process involving grinding, dispersion, filtering, rolling and drying
Cathode	PTFE powder graphite powder catalyst: Pt	Mechanical process involving grinding, dispersion, filtering, rolling and drying
White layer (for both anode and cathode)	PTFE powder	Pre-forming and rolling
Module Current collectors	Nickel mesh	Pressed to black and white Layers
Plastic frames	ABS plastic	Injection moulding and manual assembly with electrodes
Stack assembly		Plastic frames are friction-welded to module casing for sealing

b) PEMFC stack costs

PEMFC stack costs have been reported in several papers, with current stack cost estimates ranging from $500/kW to $5000/kW[39]

Optimistic cost projections for a 70 kW stack, for a typical automotive production volume of 50,000 units per year, produce a lower bound cost estimate of $20/kW[26, 38]

Ekdunge assumed a catalyst loading of 16 g/kW, which corresponds to around 8 mg/cm^2. With today's catalyst loadings, this could be decreased by nearly an order of magnitude, reducing the cost estimate by around $200.[39]

2.1.10 Impact of production volume

No study presenting cost estimates of AFC stacks at very high volumes has been found. To estimate low volume production costs, we have used the lowest power density ZEVCO costs

There are many sources providing high volume mass production cost estimates of PEMFC systems. All these results are within the US$ 20–50/kW range. Directed Technologies completed one particularly thorough report for the FordMotor Company[26]

The Report provided cost estimates for PEM fuel cell systems in the 30–90 kW range. These cost estimates have been extrapolated to estimate the costs in the 7 KW range[26]

2.2 Polymer Electrolyte Membrane Fuel Cells(PEMFCs)

2.2.1 Introduction

PEM fuel cells are used primarily for transportation applications and some stationary applications In any case, the PEMFC is commonly viewed as the most ideal alternative for mobile applications because of its low operating temperature, high effectiveness, high power density, quick beginning up, and potential for ease for high volume creation.

The PEMFC can be categorized into two classifications,

Low-Temperature PEMFC (LTPEMFC), and High Temperature PEMFC(HTPEMFC).

The LTPEMFC is known as the conventional PEMFC, but the HTPEMFC is another sort, which is worked over 100°C. The HTPEMFC is easier to control than the LTPEMFC, and it can endure a higher CO focus. The Drawback of the HTPEMFC is lower productivity, and the higher temperature requires greater levels of demand for the materials, and the initiation time turns out to be longer.

Table 2.9 Differences between the Low Temperature and High Temperature PEMFC.

	Polymer electrolyte membrane FC	
	Low Temperature	**High Temperature**
Electrolyte	Solid polymer membrane (Nafion)	Nafion/PBI doped in phosphoric acid
Catalyst	Platinum supported on carbon	Platinum–ruthenium supported on carbon
Operating temperature	60–80 °C	110–180 °C
Fuel	Hydrogen (H_2)	Hydrogen (H_2)
Charge carrier	Hydrogen ion (H^+) (proton)	Hydrogen ion (H^+) (proton)

2.2.2 Scenario of PEMFC in the view of Automobile industry

Because of the higher tolerances of CO poison , improved methanol can be utilized as a fuel rather than compressed hydrogen, which is more suitable for automotive application. Thus and because of the less complex framework activity, the HTPEMFC is utilized in this one.

The significant utilization of PEMFC concentrates on transportation primarily due to their possible effect on the climate, for example the control of discharge of the greenhouse gases (GHG).

Different applications incorporate dispersed/stationary and conventional power generation. Most significant motor organizations work exclusively on PEM energy units because of their high power density and amazing dynamic characteristics as compared and different sorts of Fuel cells.

Fuel-cell vehicles (FCV) have been created and illustrated, for example GM Hydrogen 1, Ford Demo IIa (Focus), DaimlerChrysler NeCar4a, Honda FCX-V3, Toyota FCHV, Nissan XTERRA FCV, VW Bora Hy Motion, and Hyundai Santa Fe FCV. [166]

Auto manufacturers, for example, Toyota, Honda, Hyundai, Daimler, and General Motors (GM) have reported plans of commercializing their power device vehicles by 2015 . Distributed PEM Fuel cell power system is basically concentrated in taking small scale things (50–250 kW for decentralized use or <10 kW for home appliances). the significant cost of PEMFC remained to be a Major barrier that disallows their far reaching applications in this area. Back-up power for banks and telecommunications organizations gets developing interests as of late in view of the amazingly significant expense related with power breakdowns.

Some units like Plug Power GenSys and Ballard FCgen 1020 ACS energy unit frameworks have been created and conveyed in numerous fields. Another promising territory is the portable power supply. Taking into account that the restricted energy limit of batteries unlikely meets the quickly developing the energy interest of the modern portable electronic devices such as PCs, mobile phones, and military radio/specialized devices.

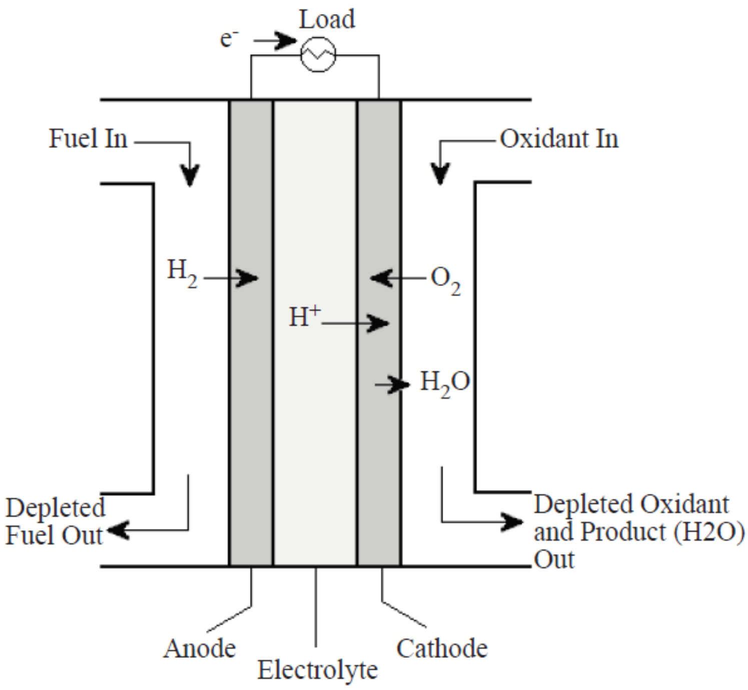


Fig. 2.5 Operation of PEMFC

2.2.3 Cell Components

Typical components of a PEMFC stack include:[41]

• The Ion Exchange Membrane

• An Electrically conductive porous backing layer

• An Electro-catalyst at the interface between the membrane and the backing layer and

• Cell interconnects and flow plates that deliver the fuel and oxidant to reactive sites via flow channels and electrically connect the cells.

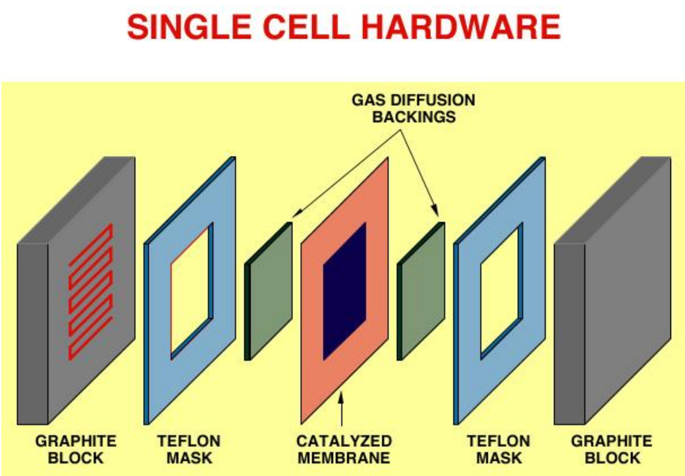


Fig 2.6 Single Cell Structure of Representative PEFC

2.2.4 Construction and operation

The fundamental structure of a PEMFC fuel cell can be described as electrodes (anode and cathode) separated by a solid membrane acting as an electrolyte figure 2.5

• PEMFCs are built out of membrane electrode assemblies (MEA) including electrodes, electrolyte, catalyst, and gas diffusion layers

• Hydrogen is delivered to the anode side of MEA and is catalytically split into protons (H+)and electrons (oxidation half-cell reaction):[42]

Anode reaction: $H_2 \longrightarrow 2H^+ + 2e^-$

The protons permeate through the polymer electrolyte membrane to the cathode side. The electrons travel along an external load circuit to the cathode side of the MEA, creating the current output.

Oxygen is delivered to the cathode side of MEA and reacts with the protons and the electrons to form water (reduction half-cell reaction)

Cathode reaction: $\frac{1}{2} O_2 + 2H^+ + 2e^- \longrightarrow H_2O$

Total cell reaction: $H_2 + \frac{1}{2} O_2 \longrightarrow H_2O$

The products of this process are water, DC electricity and heat.

Hydrogen fuel courses through an organization of channels to the anode, where it separates into protons that, in turn, flow through the film to the cathode and electrons that are gathered as electrical flow by an external circuit connecting the 2 terminals.

The oxidant (air) flows through a similar network of channels to the cathode where oxygen consolidates with the electrons in the outer circuit and the protons coursing through the layer, subsequently creating water.[42]

2.2.5 Mathematical model for analysis of potential and efficiency

At the point when current flows , there a deviation from the thermodynamic potential happens comparing with the electrical work performed by the cell. The deviation from the equilibrium is known as the overpotential.[42]

expression of the voltage of a single cell is

$$Vcell = E + \eta_{act} + \eta_{ohmic} + \eta_{diff}$$

The over potentials originate primary from activation over potential (ηact), ohmic over potential ($\eta ohmic$) and diffusion over potential ($\eta\ diff$) and equilibrium thermodynamic potential (E)[42]

The ideal voltage of a fuel cell is reversibly with pure hydrogen and oxygen in standard condition is 1.229V.A decrease in current density is resulting in an increase in cell voltage and thus increase the efficiency of the fuel cell. The reversible thermodynamic potential of the $H_2 + O_2$ reaction previously described is given by the Nernst equation:[43]

$$E= E_O + \frac{RT}{zF} \ln [P^*_{H2} (P^*_{O2})^{0.5}]$$

where the reversible standard potential E^0 of an electrochemical reaction is defined as

$$E^O= -\frac{\Delta G°}{nF}$$

Activation overpotential is directly identified with the idea of the electrochemical responses shows the magnitude of activation energy, at the point when the response spreads at the rate requested by the current. [43]it arises due to kinetics of energy transfer reaction across the electrodes. The activation overpotential happening at the cathodes of a PEMFC is given by which is known as the Tafel equation

$$\eta_{act} = (\frac{RT}{\alpha nF})ln(i_o) + (\frac{RT}{\alpha nF})ln(i)$$

Ohmic overpotential results from electrical resistance losses in the cell. These resistances can be found in practically all fuel cell components: ionic resistance in the membrane, ionic and electronic resistance in the electrodes, and electronic resistance in the gas diffusion backings, bipolar plates and terminal connections. [43]This could be expressed using Ohm's Law equations such as

$$\eta_{ohmic} = -i\, R_{internal}$$

Diffusion overpotential is brought about by the mass exchange restrictions on the accessibility of the reactants close to the anodes. The electrode reactions require a constant supply of reactants to continue the current stream. when the diffusion constraints diminish the accessibility of a reactant, part of the available reaction energy is utilized to drive the mass transfer, in this way making a corresponding loss in output voltage. similar issues can be created. if a reactant item collects close to the terminal surface and limits the diffusion path or weakens the reactants. [43]The diffusion overpotential can be communicated as

$$\eta_{diff} = \left(\frac{RT}{\alpha nF}\right) ln\left(\frac{il-i}{il}\right)$$

2.2.6 Thermodynamic efficiency of fuel cell

The thermodynamic efficiency of the fuel cell *Efc* can be determined as the ratio of output work rate to the product of the hydrogen consumption rate *and* the lower heating value of hydrogen,[43]

$$E_{fc} = \frac{Wgross}{mH2\,.LHVH2}$$

The output current is correlated with the hydrogen mass flow rate by the equation

$$m_{H2} = \frac{IMWH2}{2F}$$

Thus, the thermodynamic efficiency of the fuel cell can be simplified as follows:

$$E_{fc} = \frac{2V_{cell}F}{MW_{H_2} \cdot LHV_{H_2}}$$

2.2.7 Fuel Efficiency

The fuel cell efficiency is a function of power density.

Efficiency ∞ 1/ power output and the financial aspects relies upon:

1) capital cost of fuel cell
2) cost of hydrogen.

Since the Fuel cell productivity diminishes with expanding power output, their efficiency and financial aspects are interrelated. For a similar power output, a more productive fuel cell is greater and expensive. There is an ideal efficiency for every application which directly brings about inexpensive power delivered by the fuel cell.[44]

Efficiency [19]

$$\eta_{fc} = \frac{electrical\ poweroutput}{Fuel\ input}$$

Electrical Power Output

$$P_{fc} = V.I$$

Fuel Input

$$F_{in} = Q_h.\ \Delta h$$

Where $Qh = mI/nF$ is hydrogen consumption rate , Δh= enthalpy

2.2.8 Relationship Between Power Density And Efficiency

Power density is inversely proportional to Fuel efficiency. If power is maximum, efficiency depletes and at part load efficiency is maximum. This attribute of a PEMFC makes it extremely appealing and feasible for applications with variable loads.[45]

Power density = V*Current Density

Table 2.10 a Relationship Between Power Density And Efficiency

Cell potential(V)	0.4	0.45	0.5	0.55	0.6	0.65	0.7	0.75
Power density(W/cm^2)	0.4	0.394	0.38	0.358	0.3375	0.325	0.306	0.2334
Efficiency	0.269	0.304	0.337	0.3711	0.405	0.439	0.472	0.506

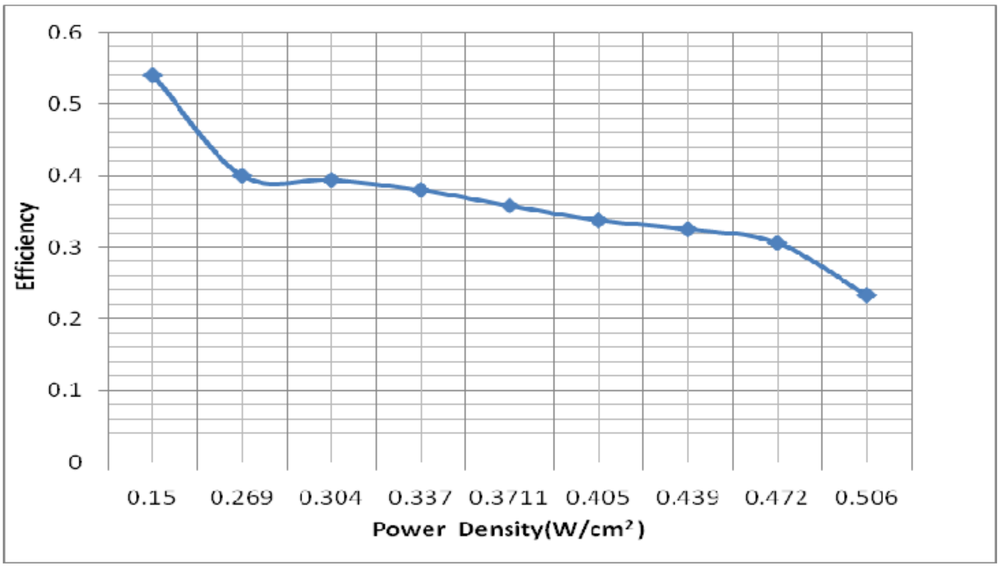


Fig 2.7 Relationship between efficiency and power density

when the power density gets higher, the output power of the fuel cell is high the efficiency is typically lower.[45]

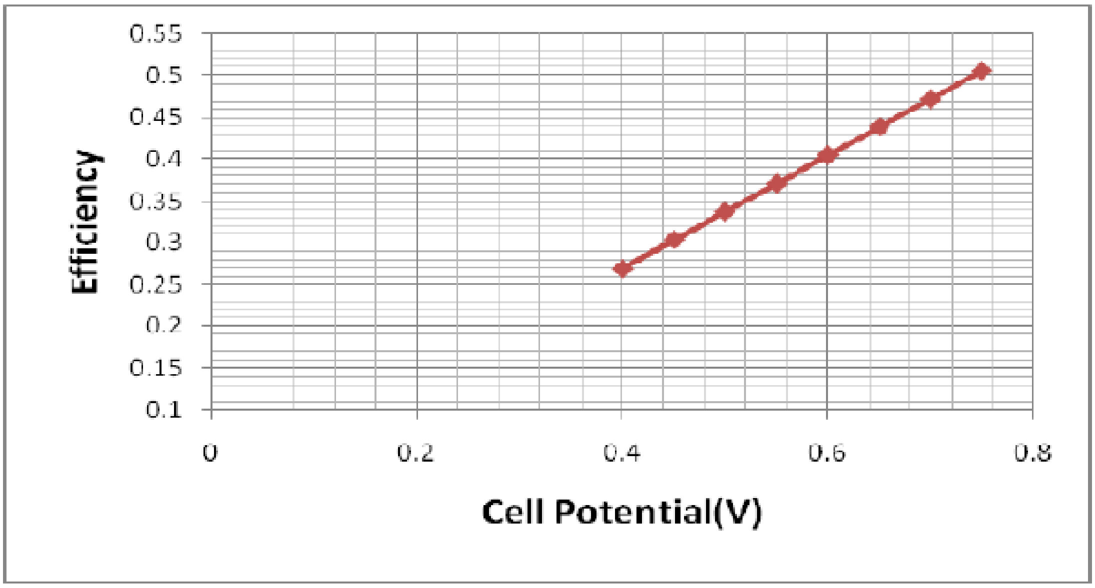


Fig 2.8 Relationship between efficiency and cell potential

2.2.9 Improvements In Fuel Cell Performance

Table 2.10 b Relatonship Between Power Density And Efficiency Through Improvement In Fuel Cell Performance

Cell potential(V)	0.4	0.45	0.5	0.55	0.6	0.65	0.7	0.75
Power density (W/cm^2)	0.8	0.7875	0.81	0.756	0.7125	0.65	0.569	0.4588
Efficiency	0.269	0.304	0.337	0.3711	0.405	0.439	0.472	0.506

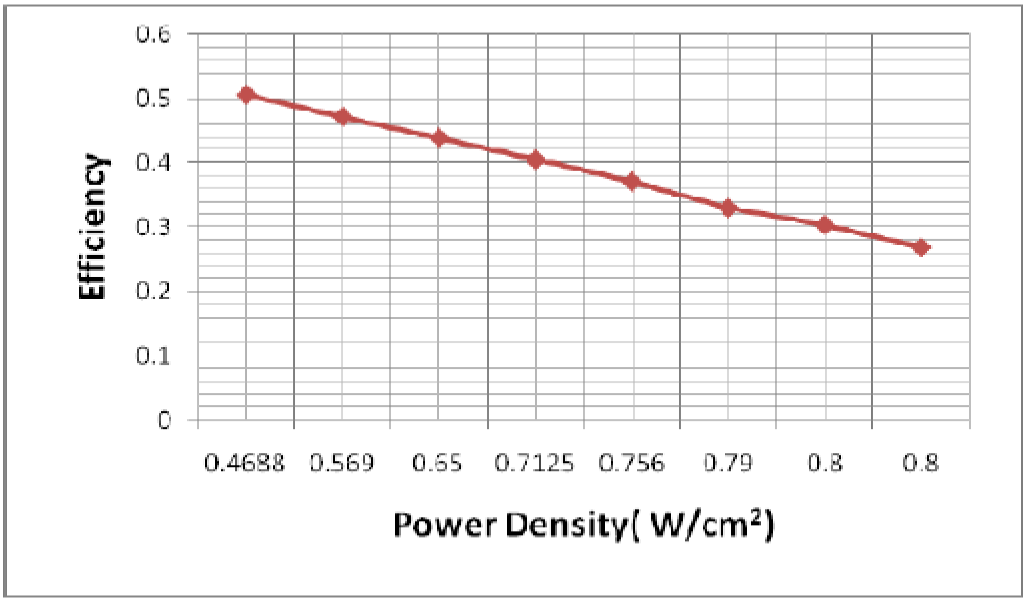


Fig 2.9 Relationship between efficiency and power density under performance improvements.[45]

The power density has altered due to the change in the Current density under performance improvements.[45]

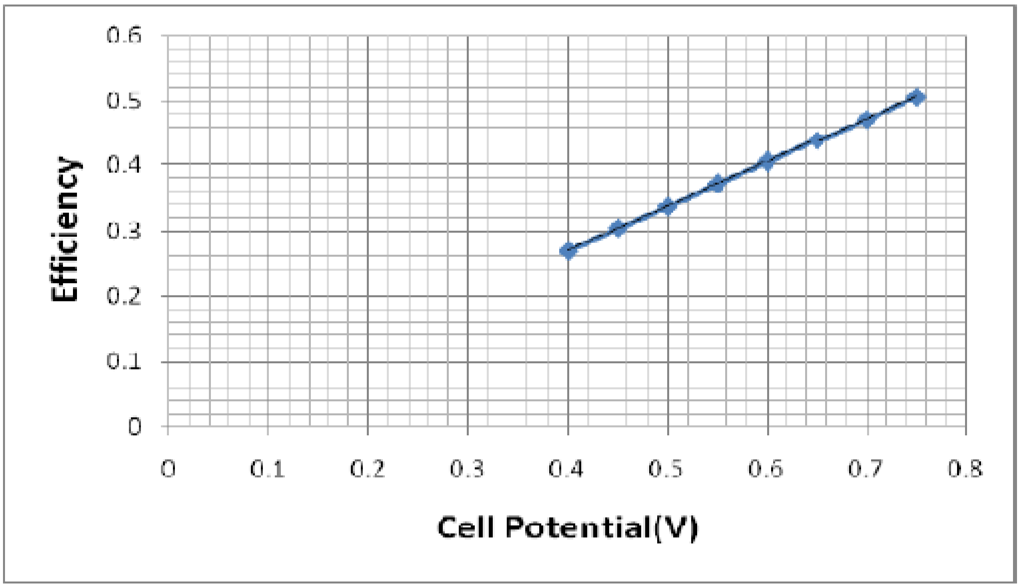


Fig 2.10 Relationship between efficiency and cell potential under performance improvements

It signifies that despite the fact that the exhibition of the Fuel cell is expanded there in no change in its efficiency[45]

Table 2.11 Improvement In Fuel Cell Performance

Cell Potential	0.45	0.5	0.55	0.6	0.65	0.7	0.75
Fuel Cell Efficiency	0.304	0.337	0.3711	0.405	0.439	0.472	0.506
CF = 0.9 Electricity Cost	0.294	0.2708	0.2512	0.235	0.2212	0.2097	0.1995
CF=0.5 Electricity Cost	0.339	0.3166	0.297	0.2807	0.26699	0.2555	0.2453

CF=0.15 Electricity Cost	0.5801	0.557	0.5374	0.5211	0.5073	0.4959	0.4856

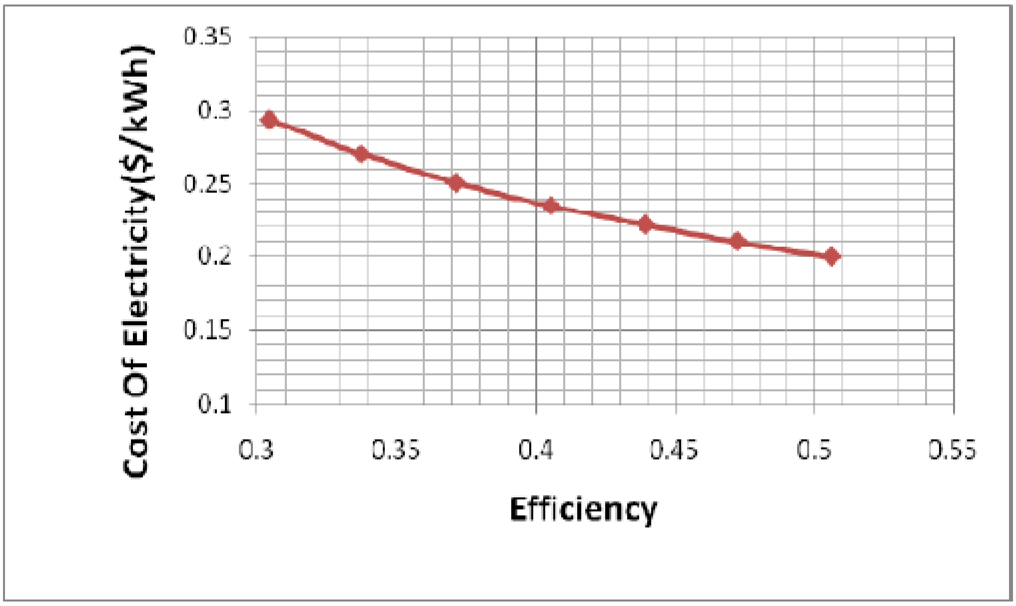


Fig 2.11 Relationship between cost of electricity and efficiency for fuel cell performance improvements CF:0.9.

Fuel cell performance improvements with Capacity Factor 0.9 , electricity cost is between 0.29$/kWh and 0.2$/kWh for efficiency between 0.3 and 0.51.[45]

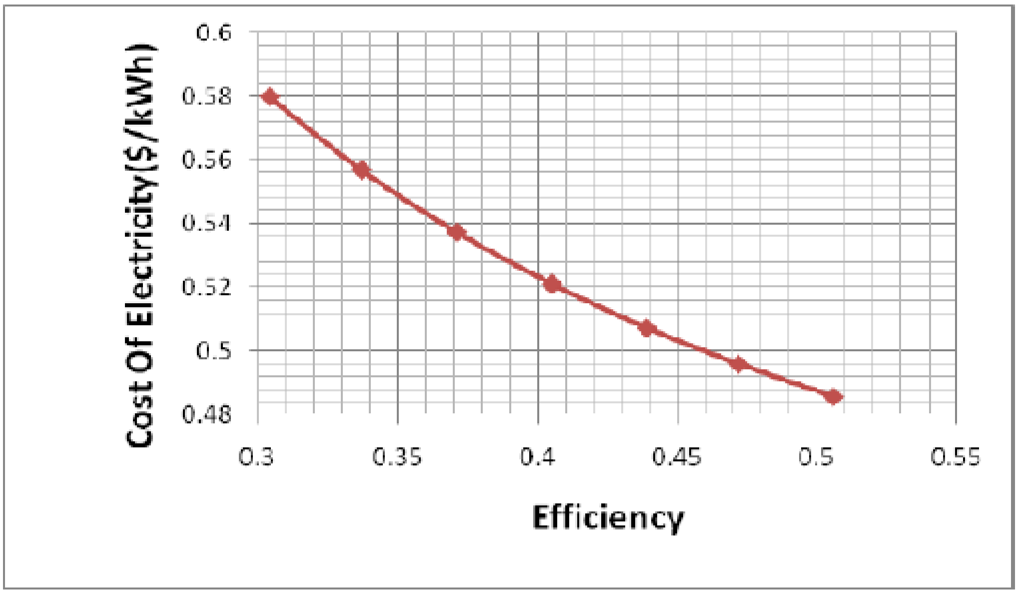


Fig 2.12 Relationship between cost of electricity and efficiency for fuel cell performance improvements CF:0.15.

fuel cell performance improvements with Capacity Factor 0.15 , the cost of electricity is between 0.58$/kWh and 0.49$/kWh for efficiency between 0.3 and 0.51. greatest expense of power is being charged by limit factor 0.15 if the Fuel Cell performance is expanded[45]

It's obvious from the table that the profound factor load profile CF=0.15 conveys the greatest expense in all situations when differentiated and Steady load profile (CF=0.5) and modestly variable load profile (CF=0.9).But the enhancements in Fuel cell performance and decrease in fuel cell cost results in lower electricity cost is contrasted with Base case and decrease of hydrogen cost in the high variable load profile. Essentially, for each of the 3 capacity factors considers the reduction in fuel cell cost will bring about least financial cost when compared with other 3 situations. In view of the graphical data appeared above, it is obvious that as the electricity cost diminishes, the efficiency increases.[45]

2.2.9 Properties and advancements of the PEMFC

Through continuous global research and development (R&D) over the past decade, the important operational factors of PEMFCs, such as energy efficiency, volumetric and mass power density, and low temperature start ability, have been greatly improved. Research and development of novel basic materials and parts have been a way to deal with improve the strength also, cost proficiency of PEMFCs.[46] Some critical materials for PEMFC incorporate proton exchange membranes, catalysts, and support materials.

Over the previous many years, the main mechanical advancement in the field of PEMFCs was the development of ultra-thin improved proton exchange membranes.

Table 2.12 shows the U.S. Department of Energy (DOE) technical targets for 2020 for the key membrane properties.

Characteristics	**Units**	**Status**	**2020 target**
Maximum Oxygen crossover	mA/cm^2	<1	2
Maximum hydrogen crossover	mA/cm^2	<1.8	2
Area specific proton resistance	Ω-cm^2	0.017 (25 KPa)	
Maximum operating temperature	°C	120	120
Minimum electrical resistance	Ω-cm^2	-	1000
Cost	USD/m^2	18	20
Durability	Cycles	>20,000	20,000

Table 2.13 Technical targets for electrocatalysts

Characteristic	Units	Status	2020 Target
Platinum group metal (PGM)	g/kW rated	0.14	0.125
PGM total loading	mg/cm^2	0.15	0.125
Loss in catalytic (mass) activity	%	37	<40%
Mass activity	A/mg	0.47–0.67	0.44
Non-PGM catalyst activity per volume of supported catalyst	A/cm^3	60	300

Since the utilizations of proton exchange membrane fuel cell (PEMFC) systems at first revealed in the New Generation of Vehicles program (PNGV) in the US in 1993 , it has taken over 10 years to arrive at the current test-stage or fractional commercializing stage.

2.2.10 Challenges for The Commercialization of PEMFC

a) Stable high purity hydrogen supply

It is essential to have a stable high purity supply of hydrogen for perfect commercialization of PEMFC system. Today scarcity and repeatability on this challenge for a long time makes it complicated for the usage in recent times.

Hydrogen is mechanically delivered by the steam transforming of hydrocarbons, for example, petroleum gas or by coal gasification. In any case, these techniques cause the inevitable CO_2 discharge, which can prompt greenhouse impact. Furthermore the creation of CO can cause serious poisoning of the anode electrocatalysts in PEMFC. It is likewise critical to build up the more secure and more efficient hydrogen storage system. traditionally used system for example, tank, metal hydride and synthetic hydride.

b) Cost reduction of PEMFC system

At present, the complete expense of a PEMFC is roughly 500–600$/kW. At the point when a vehicle is using this system, the total expense of the FCV is multiple times that of a traditional vehicle with an (ICE).

The cost of a normal PEMFC is comprised of the cost with of the membranes, platinum, cathodes, bipolar plates, peripherals and the assembly measure.

Among them, the expenses of the bipolar plate and the terminal including platinum make up around 80% of the complete expense of a PEMFC. To limit the cost, it is characteristic that there be a more proficient and economic advancement of every segment in a PEMFC.

Tsuchiya detailed the cost structure of PEMFC and the chance of its decrease by large scale manufacturing of PEMFC using the expectation Their references for analysis were based on the following case:

the typical performance of a single fuel cell has a 0.6–0.7V and 0.3–0.6 A/cm^2 cell current density, which equals the power density of 2 kW/m^2 or more. In any case, the stack execution is lower than that of a single cell. if an automobile has a 50 kW rated output, at that point the cell region for 2 kW/m^2 of power density should be 25m^2,

2.2.11 Applications of The PEMFC

Table 2.14 Various applications of PEMFC

Application	Function	Power	Fuel	Comments
Hybrid power bus	Power supply	50kW	Compressed hydrogen in cylinder	Efficiency: 40%, Mean power consumption: 17–24kW
Powered	Power	300W	Hydrogen stored	Efficiency: 35%,

bicycle	supply		in the metal hydrides	Distance to-fuel ratio: 1.35 km/g
Lightweight powered vehicle	Power supply	5 kW	High pressure gaseous hydrogen in cylinder	Drive over a 100km run at a speed of 18 km/h
Stationary power generator	Power supply	5 kW	Commercially available 15MPa hydrogen cylinder	• Efficiency: more than 30% in fully loaded operation. • Operated 3 h at 5 kW with two 50 litre hydrogen cylinders
Uninterrupted power supply	Power supply	2 kW	Hydrogen produced by methanol via fuel processing	Total cost was strongly dependent on the service time.
Portable computer	Power supply	46W	Hydrogen stored in the metal hydrides	Trouble-free start-up of the portable computer

Transportation applications

Applications going from compact/micropower and transportation to enormous scope stationary power systems for structures and distributed generation. numerous organizations including Fuel cell innovation (Ballard, UTC, Nuvera, GE-FCS, Plug Power, Toshiba, Sanyo, and Hydorgenics), in automotive (Daimler-Chrysler, Ford, Renault, Toyota, Nissan, GM, BMW, Hyundai), and power (NTT, Sanyo, Samsung and IBM) have reported different applications, new advances and prototype vehicles utilizing on-board PEMFCs. Also, numerous advancements using PEMFC for various applications are as of now being worked on , and are before long-expected enter the market in power around the world[47]

The present and future specifications of PEMFC for FCV can be explained by the technology roadmap which was published by Ballard in May 2005shows the cumulative installed capacity of PEMFCs by application in 2006. Although some stationary applications exist for this technology, most PEM fuel cells are used to provide electricity to portable items and different types of vehicles[47]

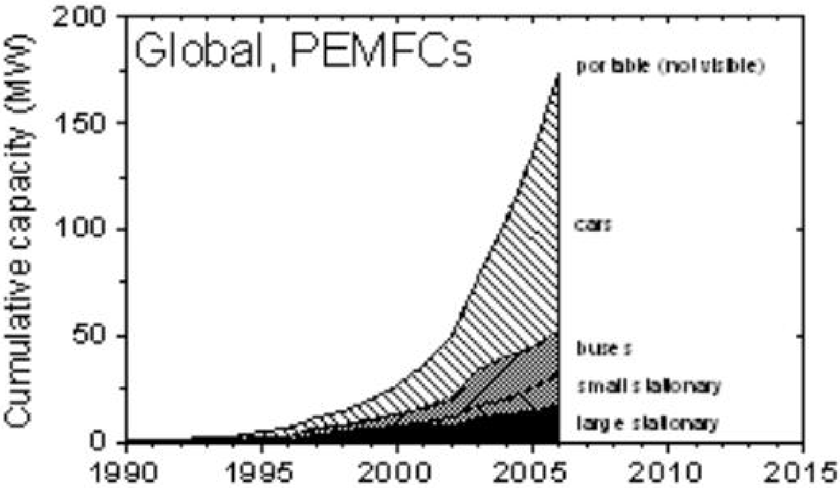


Figure 2.13 Cumulative capacity of PEMFCs by application (Schoots et al., 2010)

Several car manufacturers were planning the deployment of PEMFC vehicle fleets. However, As electric and hybrids vehicles have been receiving more attention in the last couple of years, it is possible that some of the PEMFC plans announced by car manufacturers have been postponed.[47]

Table 2.15 launch dates for fuel cell vehicles by manufacturer (Crawley, 2006)

Manufacturer	**Year**	**Number of Vehicles**	**Notes**
Daimler Chrysler(Germany)	2012 2015	10000	Initial Launch, Mass Market
Ford (USA)	2015		Commercial readiness
GM(USA)	2010-2015 2025		Commercial viability Mass market
Honda (Japan)	2010	12000(in USA)	Start production

	2020	50000(IN USA)	
Hyundai (Korea)	2010	30000(by 2021)	Road tests 2009
Toyota(Japan)	2015	11,016(upto august 2021)	Will cost US$ 50,000

The four areas that are basic for the business variation of automobile PEM stack innovation: durability, cost, freeze-start and volumetric power density. The fundamental focuses are:

- A lifetime of 5000 h by 2010. Ballard already demonstrated a durability of more than 2200 h in simulated testing.
- A stack cost of US$ 30/kWe net at a volume of 500,000 units.
- A freeze-start capability down to -30 ^{o}C, reaching 50% of the rated power in 30 s.
- A volumetric power density of 2500Wnet/l.

Table 2.16 Relative prospects of PEMFC in various applications based on the current status of PEMFC technology

Application	**Main reason**	**Competition**	**Comments**
Bus, Lightweight vehicle	More space for equipment of the fuel processor	None	PEMFC-based hybrid system
Passenger car	Positive impact for uniform spacing of people	ICE-based hybrid system without PEMFC	PEMFC-based hybrid system
Sailing yacht	Bottled LPG is widespread	DMFC, DBFC	Used as APU
Powered bicycle	Inconvenient for hydrogen supplies	Battery	Batteries or hybrid system
Stationary power generator	Challenge of stable hydrogen supplies with high purity	MCFC, SOFC	MCFC, SOFC

Uninterrupted power supply	Possible for long blackout periods	Battery	Hybrid system desired

Considering these issues, Bus, lightweight vehicles fueled by PEMFC is the most encouraging applications.

2.3 Phosphoric Acid Fuel Cell (PAFC)

2.3.1 Introduction

The First commercialized fuel cell technology is Phosphoric acid fuel cell. They are Developed in in mid-1960s, and field tested since 1970s. most of the plants are in the 50 to 200 kw capacity range and the large plants are in the range of 1MW AND 5MW. Due to the early improved characteristics significantly in stability, performance and cost make them good for stationary applications. The key industrial participants around the world are International Fuel Cells Corporation in the U.S, Fuji Electric Corporation, Toshiba Corporation and Mitsubishi Electric Corporation in Japan. [48]

In this highly concentrated phosphoric acid (H_3PO_4) saturated in silicon carbide matrix is taken as electrolyte. During mid-1960s electrodes were polytetrafluoroethylene(PTFE)-bonded Pt black. But during past two decades, Pt supported on carbon black has replaced previous one as the electrocatalyst.[48]

The Pt loading is about 0.10 mg Pt/cm^2 in the anode.

0.50 mg Pt/cm^2 in the cathode

Operating temperature range is 150^o C to 210^{o}C.

Acid concentration of PAFCs have increased to achieve maximum cell performance i.e. 100%H_3PO_4.

2.3.2 Operation of the PAFC system

PAFC stack contains electrically connected cells in series to obtain the desired level for delivery of the load. Arrangement involves individual cells are stacked with the bipolar plates between the cells. The all graphite bipolar plates are sufficiently corrosion resistant for a projected life of 40,000 hours in PAFCs, but they are still relatively costly to produce. Adjacent cells in the stack separate the reactant gases by a thin impervious plate and the gas flow is directed by separate porous plate. Provisions adopted to remove the heat generated in the operation. [48]

In a cell stack, the impenetrable plate is partitioned into two sections, and each goes along with one of the permeable plates. The electrolyte disintegrates so a bit of H_3PO_4 escapes from the cell noticeable all around stream over the long run. An electrolyte repository plate (ERP), made of permeable graphite, gives enough electrolyte to accomplish a 40,000-hour cell life (there is no electrolyte substitution). The ERP too accepts increments in electrolyte volume because of an expansion in H_2O, so the permeable graphite anodes don't flood.

These vacillations in electrolyte volume happen during fire up and during transient activity. The permeable structure, which permits fast gas transport, is additionally used to store extra corrosive to recharge the stock lost by vanishing during the phone working life.

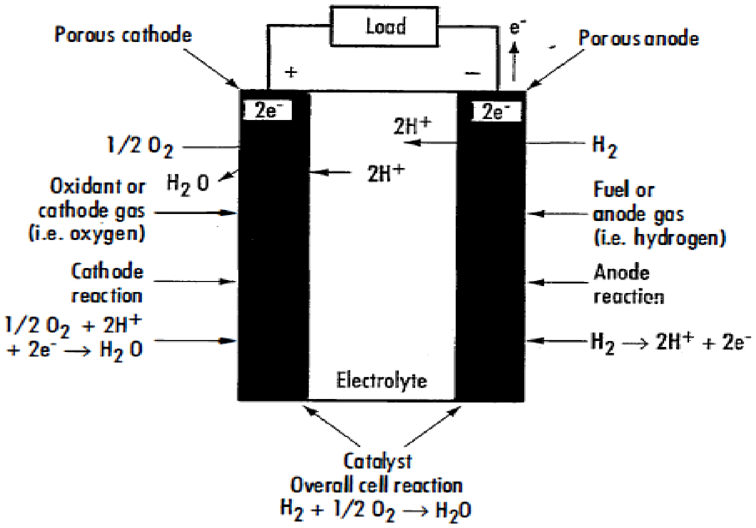


Fig 2.14 Operation of phosphoric acid fuel cell

The electrochemical reaction occurring in PAFC.

Anode reaction: $2H_2(g) \longrightarrow 4H^+ + 4e^-$

Cathode reaction: $O_2(g) + 4H^+ + 4e^- \longrightarrow 2H_2O$

Overall cell reaction: $2H_2 + O_2 \longrightarrow 2H_2O$

The electrochemical responses on exceptionally scattered electro-catalyst particles upheld on carbon black. Platinum (Pt) or Pt alloys are utilized as the catalyst for both electrodes.

2.3.3 Evolution and Performance

Table 2.17 Evolution of Cell Component Technology for Phosphoric Acid Fuel Cells

Component	**1965**	**1975**	**Current status**
Anode	PTFE-bonded Pt black	PTFE- bonded Pt/C	PTFE-bonded Pt/C

		Vulcan XC-72[a]	
	9 mg/cm^2	0.25 mg Pt/cm^2	0.25 mg Pt/cm^2
Cathode	PTFE-bonded Pt black	PTFE- bonded Pt/C	PTFE-bonded Pt/C
		Vulcan XC-72[a]	
	9 mg/cm^2	0.5 mg Pt/cm^2	0.5 mg Pt/cm^2
Electrode support	Ta mesh screen	Graphite structure	Graphite structure
Electrolyte support	Glass fiber paper	PTFE- bonded SIC	PTFE -bonded SIC
Electrolyte	85 percent H_3PO_4	95 percent H_3PO_4	100 percent H_3PO_4
Electrolyte Reservoir		Porous graphite plate	Porous graphite plate
Cooler			1per 7 cells embedded(SS) tubes in graphite plate

a - *Over 40,000 hour component life demonstrated in commercial power plants.*

PAFC Fuel cell stack

In PAFC stacks, arrangements should be incorporated to eliminate heat generated during cell activity. Practically, heat has been removed by one or the other fluid (two-stage water or a dielectric liquid) or gas (air) coolants that are steered through cooling channels located (mostly about each fifth cell) in the phone stack.

Liquid cooling requires complex manifolds and associations; however, preferable warmth evacuation is accomplished over with air-cooling. The benefit of gas cooling is its simplicity, dependability, and relatively low cost. Nonetheless, the size of the cell is limited, and the air-cooling entries should be a lot bigger than the liquid cooling sections.[48]

Table 2.18 Advanced PAFC Performance

	Average Cell Voltage, V	Current Density mA/cm²	Power Density W/cm²
IFC Pressurized:			
Project Goal			0.188
Single Cells	0.75 to 0.66	431 to 645	0.323
	0.71	431	
Full Size Short Stack	0.75	190	0.307
11 MW Reference			0.142
IFC Atmospheric:			
Single Cells	0.75	242	0.182
Full Size Short Stack	0.65	215	0.139
Mitsubishi Electric Atmospheric Single Cells	0.65	300	0.195

A conceptual design of an improved stack, working at 8.2 atm and 207 °C, was created depending on cell and stack advancement tests. The stack was intended for 355 10 ft^2 (around 1 m^2) cells to deliver more than 1 MW DC power in a similar actual envelope as the 670 kW stack utilized in the 11 MW PAFC plant worked for Tokyo Electric Power. The enhancements made to the plan were tried in single cells and in subscale and full size short stacks.[48]

Single cells accomplished an underlying performance of 0.75 volts/cell at a current density of 400 A/ft^2 (431 mA/cm^2) at 8.2 atm and 207 °C. The power density of 300 W/ft^2 (0.323 W/cm^2), was well over the project objective. A few cells were worked to 600 A/ft^2 (645 mA/cm^2), accomplishing up to 0.66 volts/cell. The flat plate component designs were checked in a subscale stack preceding creating the full-size short stack.[48]

The pressurized short stack of 10 ft^2 cells achieved a performance of 285 W/ft^2 (0.307 W/cm^2). In spite of the fact that the average cell performance, 0.71 volts/cell at 400 A/ft^2 (431 mA/cm^2), was not as high as the single-cell tests, the performance was 65 percent higher than the project. Tokyo Electric Power Company's 11 MW power plant which is operational in 1991, had a normal cell execution of roughly 0.75 volts/cell at 190 mA/cm^2 or 0.142 W/cm^2.[48]

The atmospheric pressure quick stack, which include 32 cells, received a preliminary overall performance of 0.65 volts/cell at 200 A/ft2 (215 mA/cm2) or 0.139 W/cm2.The performance degradation rate changed into less than 4 mV/1,000 hours all through the four,500 hour test. unmarried cells, examined at atmospheric conditions, achieved a 500 hour overall performance of approximately 0.75 volts/cellular at 225 A/ft2 (242 mA/cm2) or 0.182 W/cm2.[48]

Mitsubishi electric corporation investigate alloyed catalysts, strategies to supply thinner electrolytes, and expanded utilization of the catalyst layer. those advancements resulted in an initial atmospheric performance of 0.65mV at 300 mA/cm2 or 0.195 W/cm2, which became higher than the UTC gas fuel Cells' performance.

2.3.4 Performance of PAFC

- Performance of any fuel cell is a function of the parameters such as Pressure, Temperature and gas composition and behaviour.
- In addition, performance can be adversely affected by impurities in both the fuel and oxidant gases.[48]

Typical PAFCs will normally operate within the range of 100to 400 mA/cm2 at 600 to 800 mV/cell.

The operated voltage depends on following factors:

Temperature, pressure , gas composition, usage of the reactant gases, current density, possible impurities inside the input currents and cell's running life.[49 50]

The performance(efficiency) of a fuel cell is defined as percentage of electrical power generated according to hydrogen power input, At the same time as cell performance will increase with higher working temperatures and pressures.[49 50]

The ideal efficient performance of fuel cell is described by using its Nernst capability represented as cell voltage expressed via the Nernst equation. The latter gives a relation between the ideal potential (E^0) for the cellular reaction and the appropriate i.e. equilibrium potential (E) at different temperatures and partial pressures of reactants and products.[49 50]

Once an appropriate potential at ideal situations is understood, the correct voltage may be decided at different Temperatures and pressures using the equations .

The correct standard potential Of a H_2/O_2 fuel cell (e0) is 1.23 v with liquid water product and 1.18v water with gaseous product.

The ideal potential is proportional to the change in the standard Gibbs free energy .

Useful work (electric energy) is obtained from a fuel cell when an affordable current is drawn, however the Actual cell capability is reduced from its equilibrium potential because of irreversible losses originating normally[49]From 3 resources

(1) activation polarization (Δv_{act}),

(2) ohmic polarization (Δv_{ohm}) and

(3) attention polarization (Δv_{conc}). [24,25]

These losses bring about a mobile voltage (v) for a gasoline cellular that is less than its ideal potential

$$E\ (v = E - \text{losses}).$$

The maximum electrical work available in a fuel cell working at constant temperature and pressure is Given by using the trade in Gibbs free energy of the electrochemical reaction[51]

$$W = \Delta G = -gEF$$

where g is the number of electrons participating in the reaction, F is Faraday's constant, and E is the ideal potential of the cell. If reactants and products are in the standard state (25 ºC or 298 K and 1 atm),[51]

$$\Delta G^o = -gE^0F$$

The ideal thermodynamic efficiency of a fuel cell, operating irreversibly, is then:

$$n = \Delta G/\Delta H$$

If all the energy from the hydrogen fuel, its' ''calorific value'', heating value, or enthalpy of formation, were transformed into electrical energy, then maximum E would be:

E = 1.48 V if using the higher heating value (HHV)

or

E = 1.25 V if using the lower heating value (LHV)

These are the voltages that would be obtained from a 100% efficient system, with reference to the HHV or LHV. The actual efficiency of the cell is then the actual voltage divided by these values:

$$\mathbf{N} = \frac{V}{1.25} \mathbf{100\%}$$

A fuel cell can be operated at different current densities, expressed as mA/cm2 or A/ft2. The corresponding cell voltage then determines the fuel cell efficiency. Decreasing the current density increases the cell voltage, thereby increasing the fuel cell efficiency. The trade-off is that as the current density decreases, the active cell area must increase to obtain the requisite amount of power.[51]

2.3.5.1ASSUMPTIONS

The following assumptions made for the present application

• Steady state conditions.

• Uniform temperature profile, since for the operation temperature region of phosphoric acid fuel cells, temperature is mainly uniform.

• Ideal gas behaviour.

• Laminar flow conditions, since the Re< 2000.

• The electrochemical procedures are considered to be described satisfactory from Faraday's first law.

• It is considered that the oxidant and the fuel gas never get in contact as they flow in different channels, and they are separated from the two solid electrodes which enclose the electrolyte solid matrix.

2.3.6 Evaluation of Performance of PAFC

Two conditions in evaluation of performance of PAFC are

A) Constant current density and variable feed rates.

B) Constant feed rates with variable current densities.

In the presentation of the processed outcomes, some exceptionally critical terms are used such as the utilization of fuel or oxidant gas, U_f and U_{ox}, the cell efficiency, and the power density. Usage alludes to the small portion of the total fuel or oxidant brought into a power module that reacts electrochemically. [49 50]

Cell efficiency refers to the maximum electrical energy that can be acquired from a fuel cell. At last, power density (PD) refers to the product between cell working voltage and current density.

This term is extremely valuable in the correlation of, various in size, energy units . The mathematic equations for all the above terms are given in Table[49 50]

Table 2.19 Equations for PAFC systems [49 50]

Equation	Nomenclature
$E = -\frac{\Delta G}{zF} = E^0 + \left(\frac{RT}{zF}\right)\ln\left[\frac{\alpha_{hydrogen}\alpha_{oxygen}^{0.5}}{\alpha_{water}}\right]$ $E = -\frac{\Delta G}{zF} = E^0 + \left(\frac{RT}{2F}\right)\ln\left[\frac{\left(\frac{P_{H_2}}{P^0}\right)\left(\frac{P_{O_2}}{P^0}\right)^{0.5}}{\left(\frac{P_{H_2O}}{P^0}\right)}\right]$	E^0: ideal standard cell potential (V) R: universal gas constant (J mol^{-1} K^{-1}) T: temperature (K) z: total transferred electrical charge F: Faraday constant (Cb mol^{-1}) $\alpha_{hydrogen}$: hydrogen activity α_{oxygen}: oxygen activity α_{water}: water activity P_{H_2}: hydrogen partial pressure (Pa) P_{O_2}: oxygen partial pressure (Pa) P_{H_2O}: water partial pressure (Pa) P^0: standard pressure (e.g. 10^5Pa) at which E^0 is defined

Equation	Nomenclature
$V_{stack} = \sum_{k=1}^{l} V_i$ $I_{stack} = I_i$ $P_{cell,i} = V_i I_i$ $P_{stack} = V_{stack} I_{stack}$, or $P_{stack} = \sum_{k=1}^{l} P_{cell,i}$	V_i: close circuit voltage (CCV) of each cell unit (V) I_i: current density for each cell unit (A m^{-2}) l: number of cell units consisting the fuel cell stack P_{cell}: power of fuel cell unit P_{stack}: power of the entire fuel cell stack (W)
$i = \frac{I}{A_{eff}}$ $PD = V_i$ $U_f = \frac{m_{H_2,react}}{m_{H_2,input}}$ $U_{ox} = \frac{m_{O_2,react}}{m_{O_2,input}}$ $n = U_f \frac{V}{1.25} 100\%$	i: current density (A m^{-2}) I: electrical current (A) A_{eff}: electrode effective area (m^2) V: cell voltage (V) PD: power density (W m^{-2}) U_f, U_{ox}: fuel and oxidant gas utilization $m_{H_2,react}$: mass of fuel reacted in cell $m_{H_2,input}$: mass of fuel input in cell $m_{O_2,react}$: mass of oxidant reacted in cell $m_{O_2,input}$: mass of oxidant input in cell n: fuel cell efficiency (%)

(i) Constant current density (1250 A m^{-2}) and various inlet feed rates

From equations in Table 2.19 ,The approximate utilization of oxygen is U_{ox} = 13% while the utilization of fuel varies (Table 2.20). The voltage curve as a function of distance in the z-direction is the same for all five runs .

The average cell voltage is 0.69 V, the power is 34.5 W and the power density 862.5 W/m2 In each run the power remains constant but there is a significant change in the fuel cell efficiency

(Table 2.20). It is obvious that as hydrogen utilization increases the efficiency of the fuel cell increases, too[49 50]

Table 2.20 Fuel and oxidant gas utilization and efficiency

Attempt	**U_f (%)**	**U_{ox} (%)**	**Estimated efficiency n(%)**
1	43.5	13	24
2	50.5	13	28
3	62.0	13	34
4	72.0	13	40
5	86.5	13	48

In Case of constant current density value (1250 A m^{-2}) and various inlet fuel rates.

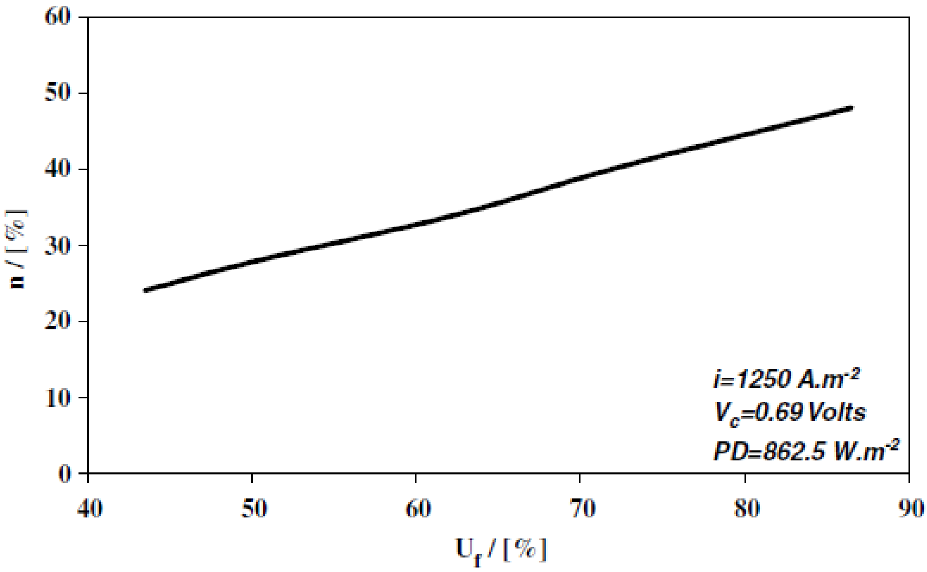


Fig. 2.15. Fuel cell efficiency as a function of fuel gas utilization. Case of constant current density value (1250 A/m^2) and various inlet fuel rates.

In Fig. 2.16, the cell voltage curve as a function of oxidant gas utilization is presented. it can be used as a very useful tool in an optimization study since when the oxidant gas utilization increases the working cost drops but also voltage and power drop, and the opposite happens when the oxidant utilization decreases.[24,25]

Table 2.21 Fuel and oxidant gas utilization predicted average cell voltage, power and power density

Attempt	**U_f (%)**	**U_{oxi}(%)**	**V_p(v)**	**P_{cell} (w)**	**Power Density (w/m^2)**
1	62	8	0.691	34.55	863.75
2	62	9	0.690	34.50	862.50
3	62	11	0.689	34.45	861.25
4	62	15	0.684	34.20	855.50
5	62	20	0.680	34.00	850.00
6	62	26	0.674	33.70	842.50
7	62	40	0.659	32.95	823.75
8	62	56	0.651	32.70	817.50

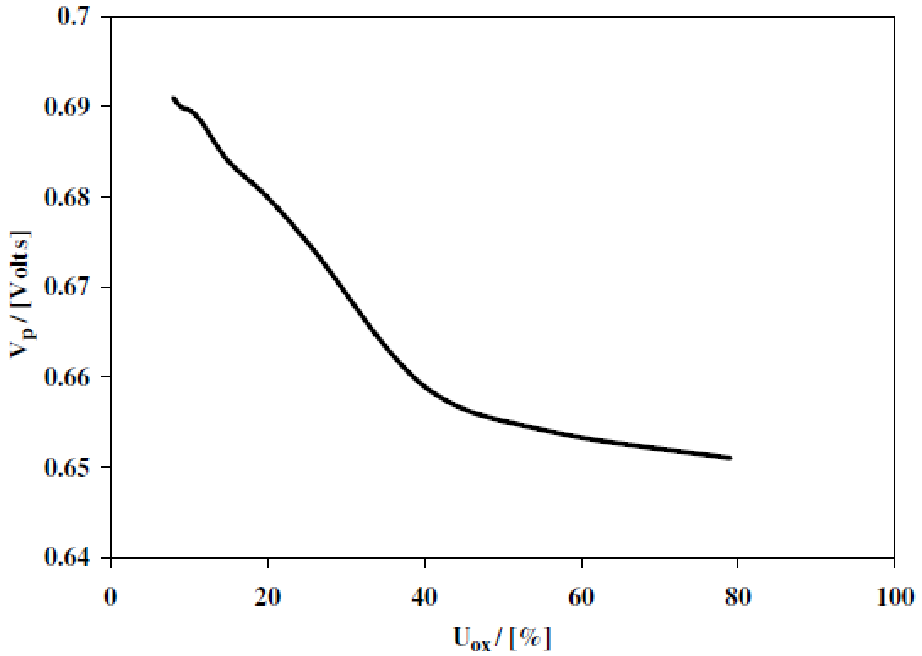


Fig. 2.16. Average cell voltage curve as a function of oxidant gas utilization. Case of constant current density value (1250 A m^{-2}) and various inlet oxidant gas rates.

(ii) Constant inlet feed rates and various current densities

In this case, the study focuses on various current density values assuming constant inlet fuel rate and inlet oxidant gas rate. which implies different consumption and production rates on each electrode surface because of the variation in current density value. For each run the inlet fuel gas volumetric rate is equal to 90 l/h and the inlet air volumetric rate is 500 l/h. Both volumetric rates are calculated under STP conditions (25 ºC and 1 atm). In Table 2.22 the current density and the fuel and oxidant gas utilization for the above runs are shown.[49 50]

Cell voltage curves show a similar form with the voltage curves presented in the previous cases. In Table 2.23 the current density, the average cell voltage, the power and power density for all the runs mentioned above is shown.

It came to the conclusion that the fuel cell efficiency increases as fuel gas utilization increases, as the voltage drop (because of increase in the oxidant gas utilization) does not take place in the same scale as the corresponding increment in fuel gas utilization.[49 50]

Another very important point that has to be defined is the parabolic form and the dropping trend of the cell voltage curves as a function of distance in z-direction on the electrode's surface. As it has been mentioned above, z-direction is the flow direction of the oxidant gas. Thus, as the oxidant gas reacts on the electrode's surface, there is a constant reduction of the incoming quantity from inlet to outlet. This results to an increase of the oxidant gas utilization in the z-direction. Moreover, in the z-direction there is a reduction in the oxygen's molar fraction and an increment in the water's one, due to the surface electrochemical reaction (consumption of air's oxygen, production of steam). [49 50]

Consequently, the partial pressure of oxygen falls whereas the partial pressure of water increases. From Nerst's law, the term in the logarithm decreases and so the open circuit voltage (OCV) decreases, which results to the final drop of the close circuit voltage.

Table 2.22 Current density, fuel and oxidant gas utilization

Attempt	**I (A/m^2)**	**U_f(%)**	**U_{oxi} (%)**
1	1000	19	8
2	1200	24	10
3	1400	27	11
4	1600	30	13
5	1800	34	15
6	2000	38	16
7	2500	48	20
8	3000	57	24

Table 2.23 Predicted average cell voltage, current density, power and power density

ATTEMPT	**I(A/m^2)**	**V_p(v)**	**P_{cell} (W)**	**PD(W/m^2)**
1	1000	0.71	28.4	710
2	1250	0.69	34.5	863
3	1400	0.68	38.1	952

4	1600	0.66	42.2	1056
5	1800	0.65	46.8	1170
6	2000	0.64	51.2	1280
7	2500	0.62	62.0	1550
8	3000	0.59	70.8	1770

Case of constant inlet feed rates and various current densities

Measurements from Ghouse. [52] were used for validation of the developed model. Ghouse et al. designed, fabricated, and assembled a 1 kW phosphoric acid fuel cell (PAFC) stack with an effective electrode area of 400 cm. The stack was operated at 180 ºC for 250 h without any degradation, using commercial H_2/CO_2 gas and air at 1 bar.

During the simulation, the current density and temperature were considered constant and the potential was calculated equal to 0.67 V per cell. Thus the potential for the total stack of 30 cells was 20.7 V. [52]

In this context, the produced power of 30 cells in series (with

active electrode area of 0.04 m2) is calculated:

P_{model} = V*I = 20.7 V = 1250 A/ m^2 * 0.04 m^2 = 1035 W

which is in very satisfactory agreement with the respective experimental value of [52]:

$P_{experimental}$ = V * I =20.5 V = 1250 A/ m^2 * 0.04 m^2 = 1020 W

Moreover, Fig. 2.17 presents the average cell voltage as a function of current density.

. Based on the above, it is concluded that the developed model can realistically predict the cell voltage given a constant current density, the power and power density both for a single cell and a stack of cells, as well as and the overall fuel cell efficiency.[52]

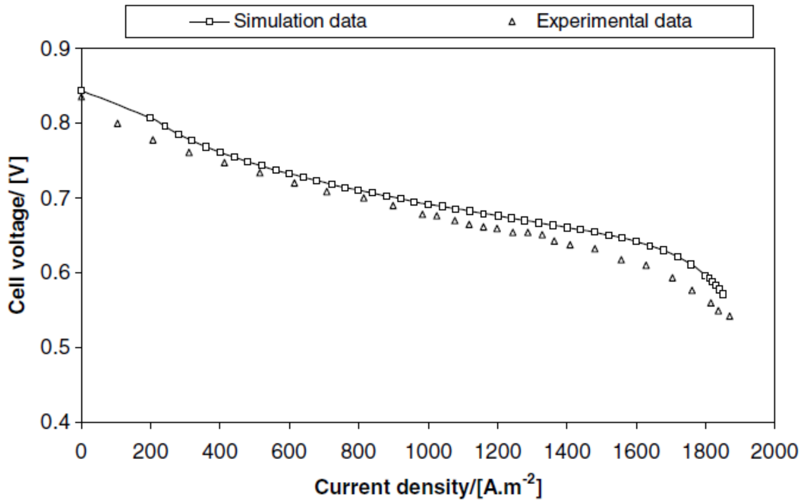


Fig. 2.17. Simulated and experimental data concerning the average cell voltage as a function of current density.

2.3.7 Applications

The energy crises of the 1970s inspired researchers at Los Alamos National Laboratory to start studying fuel cells. With an eye fixed toward developing electric vehicles, they designed a golf cart powered by a PAFC cell.

H-Power, Georgetown University, and the U.S. Department of Energy adopted a 50 kW Fuji Electric PAFC for transit buses and commenced running these buses in 1994. After 4 years, the U.S. Department of Transportation began tests on a bus powered by a 100 kW PAFC from International Fuel Cells Corporation (a joint venture of Toshiba and United Technologies). PAFC currently requires an extended warm-up period. However, so their usefulness for the private cars remains limited.[53]

PAFCs supplied stationary power for 10 years. A model PC25 power station from ONSI Corp. recently began providing supplemental power within the new Conde Nast Building at 4 Times Square in New York. During a subsequent blackout in New York, when this building remains lighted, it provides some powerful publicity for fuel cells.[53]

The Yonkers Waste Treatment Plant has been powered by a 200 kW ONSI unit since 1997. This plant reforms sewage methane as a fuel, and therefore the stacks have an estimated lifetime of five to six years (they cost about $100,000 to replace).

The military's interest in PAFCs led in 1993 to a program of buying these units for various bases where air quality is a problem. From 1993 to 1997, International Fuel Cells Corp. placed 15 PAFCs in commission through this program.

PAFC have been used for stationary power generators with output in the 100 kW to 400 kW range and are also finding application in large vehicles such as buses.[54]

The following are the technology and progress of phosphoric acid fuel cells with different applications [54]

1. Demonstration of phosphoric acid FC in homes based on natural gas. Development of prototype 12.5 kW referred to as "Power Cell 11 by Pratt & Whitney Aircraft Division.
2. The development of the 1-MW FC power plant model by Japanese Companies and the Moonlight Project.
3. A hydrophilic material, i.e., carbon paper was employed in the cell arrangements by Trocciola 1975
4. An impregnation technique was developed for the use of carbon in the arrangement by Petrow and Allen at the Prototech Company.
5. The PAFC Bus Program was introduced to demonstrate the feasibility of fuel cells in heavy-duty transportation systems

2.3.8 PAFC Bus System

The PAFC Bus Program was introduced to demonstrate the feasibility of fuel cells in heavy-duty transportation systems. PAFC-powered buses are being built to meet transit industry design and performance standards as part of U.S. Department of Energy (DOE) contract DE-AC02-87NV10649. Testbed bus- 1 (TBB-1) was designed in 1993 and integrated in March 1994. TBB-2 and TBB-3 are under construction and should be integrated in early 1995.[55]

i) Description

The PAFC bus system comprises of three principle subsystems: [55]

Fuel cell, Battery, electrical drive.

The significant parts in the Fuel cell subsystem are the Fuel cell stack, methanol steam reformer, auxiliaries, Fuel cell inner regulator, and up-chopper.

The battery subsystem incorporates the Surge battery modules, battery plate, and battery uphold.

The DC motor, controller, line Filter, and regenerative brake controls are the primary constituents considered in the electric drive subsystem.

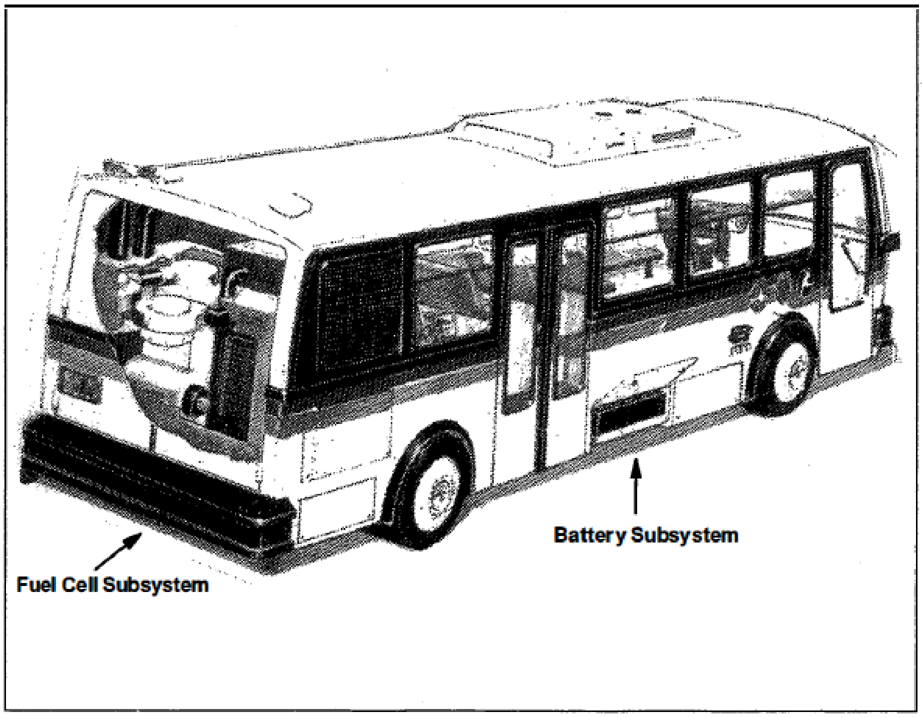


Figure 2.18 . PAFC bus illustration

ii) Configuration and **Operation**

The design of the PAFC transport Fuel cell unit subsystem incorporates a power section, fuel processor, and power conditioner. The power section area is a phosphoric acid fuel cell stack (as the essential fuel source) associated through an up-chopper to a Ni-Cd battery. [55]

The battery gives the crucial moment reaction to heavy load demands. the fuel processor, methanol is changed over to Hz and C02 in the steam-reforming and moving cycle. power conditioning is needed for the fuel cell and battery in view of their diverse nominal voltages.

The voltages additionally vary at various rates under load or during charging and regenerative slowing down. The up-chopper supports the vital voltage-coordinating ability between the power device and the battery to keep away from an undercharged or cheated state. [55]

Blowers, fans, and solenoid drivers likewise require power conditioning since they utilize both AC and DC power[HPC 1993]

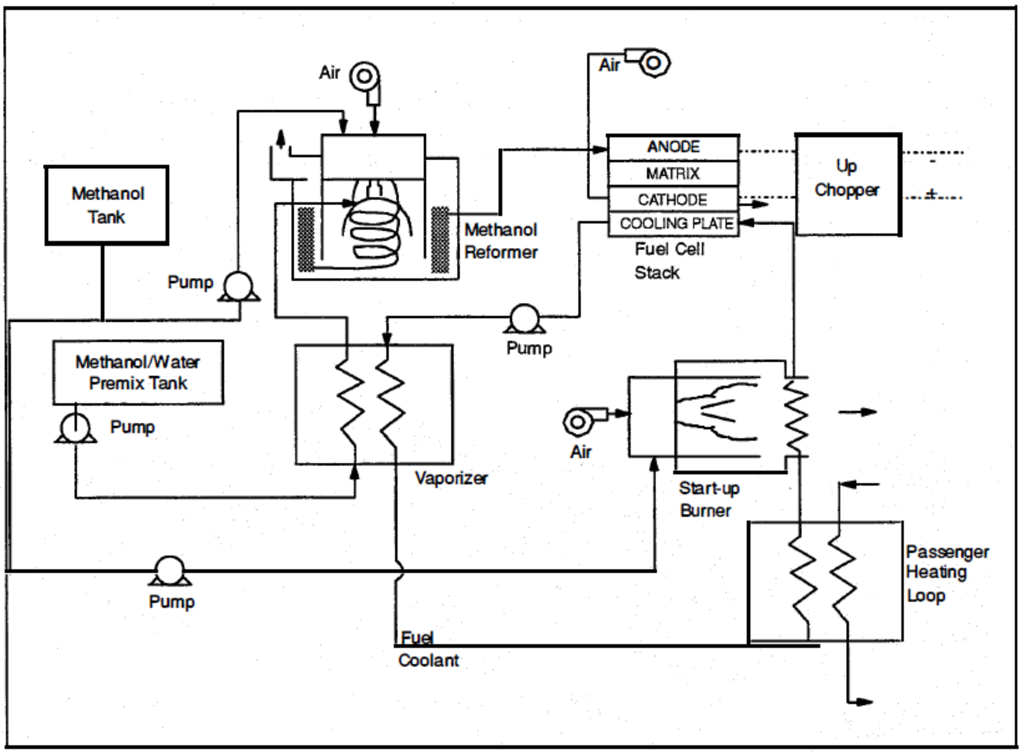


Figure 2.19. Circuit of fuel-cell operation of PAFC Bus

During initiation, the mineral oil, which is utilized as the temperature-control medium in the cooling system, is warmed by the burner to raise the temperature of the fuel cell stack to its working temperature. At the point when the temperature of the oil has reached at the stack's working temperature, ignition of the reformer burner takes place. The premix enters to the methanol-reformer through the vaporizer. superheater coils are used to warm up The disintegrated premix and conveyed to the catalyst beds in the reformer, where it is reformed and moved to H_2 and $C0_2$. [55]

The hydrogen streams to the anode of the stack and undergoes reaction with the oxygen in the air. Then it is provided to the cathode in the catalytic matrix to create electrical energy.

iii) Fuel-Cell Stack

Fuel cells are ordinarily joined by a bipolar electrical course of action. In bipolar stacks, the plane of the cell cathode is in contact with the anode of the bordering cell through an electronically conductive plate. Enough electrolytes should be accessible to limit gas leaks among cathodes and to keep up proper cell activity. A reservoir ability is to make up for electrolyte evaporative losses over the life of the fuel cell unit is generally joined inside the stack or at the anode and cathode[56].

The fuel-cell stack for the PAFC bus was designed with a non-pressurized, liquid-cooled, bipolar stack configuration.

The stack power density is 95 W/kg

The subsystem power density is 32 W/kg.

The stack will be connected to 220-V AC shop power while the bus is in the garage to keep the fuel-cell stack warm (45°C or 1 13"F).[55]

This will prevent possible damage to the stack from thermal shock and will reduce start-up time

Table 2.24. Stack Configuration of Fuel Cell	
Power (to chopper	DC 50 kW
Design current density	240 mA/cm2
Rated current	480 A
Cell design voltage	0.66 V DC
Rated voltage	115 V DC
Number of cells	175
Size	70 cm (W) x 70 cm (D) x 145 cm
Weight	583 kg
Hot standby temperature	130° C
Operating temperature range	160° to 190° C
Electrical efficiency	52.8%
Voltage degradation	1.5% over 10,000-hr rated life
Stack efficiency	41%
Thermal management	Liquid cooling
Operation pressure	Atmospheric

Source: HPC 1993.

iv) Methanol Reformer

The steam-reforming process for the PAFC bus takes place after a premix of methanol and deionized water has been vaporized:[30]

$CH_3OH+H_2O \longrightarrow CH_3OH+H_2O$ ΔH= +81.51 KJ (1)

Steam reforming the pre-vaporized methanol and water requires two steps. First, the methanol is dissociated:

$CH_3OH \longrightarrow CO+ 2H_2$ ΔH = +90.64 KJ (2)

A higher percentage of the methanol can be converted when the temperature is above 200°C . an appropriate catalyst will also increase the reaction rates.

Following the dissociation, the CO is oxidized by steam :

$CO+H_2O \longrightarrow H_2+CO_2$ ΔH = -41.16 KJ (3)

The reforming and moving of methanol can be consolidated inside a similar unit. Every activity happens at an optimal temperature. Methanol separation happens at or above 400°C. The oxidation of CO by steam happens at about 200°C. An appropriate plan can be created with discrete zones to give the temperatures needed to each stage. [57]

Heat transfer to the reaction zone of the reformer is a significant design element. The overall reaction in steam reforming is endothermic and requires external input. Therefore, most reformer configurations fuse heat exchanger plan components. Reformer size and dynamic execution are for the most part determined by heat transfer boundaries.

Table 2.25. Reformer Configuration

Type	**Catalytic steam reformer**
Catalyst	Copper oxide/zinc oxide
Methanol conversion	>99%
Steam: carbon ratio	3 :2 (molar
Hydrogen flow rate	47 m^3/hour
Hot standby temperature	250°C
Reformed gas temperature	260°C

Size	700 mm (D) x 1 ,000 mm (H)
Weight	220 kg

Source: HPC 1993.

v) System Controller Subsystem

The SCS provides real-time control and data logging capabilities necessary for effective energy management, fault logging, and emergency shutdown. Energy management functions are implemented by the SCS, Fuel-Cell Internal Controller (FCIC) and Motor Controller (MC). The FCIC and MC control their own components with input to and from the SCS[55]

vi) Fuel-Cell Auxiliaries

The blowers, fans, and solenoid drivers require both AC and DC power to accomplish the operating characteristics indicated by Fuji Electric Company. The auxiliaries give the necessary power and incorporate DC/DC converters/variable voltage/variable frequency inverters, driver units, and valve drivers with economizers. The assessed power requirement for the auxiliaries is 5.2 kW.

The fuel cell stack can be damaged whenever permitted to run under no-load conditions. An inside dummy load is included for the coolant circulation to provide a load during crises when the stack is disconnected from the rest[55]

vii) Fuel-Cell Internal Controller (FCIC)

The FCIC controls. the fuel-cell subsystem start-up, operation, and shutdown. When the system controller, fire suppression subsystem, or FCIC detects a fault, the FCIC automatically shuts down the fuel-cell subsystem. The FCIC also acts as an interface for the SCS signals that are sent to modulate the fuel-cell stack output and up-chopper voltage.

The up-chopper coordinates the battery and power device voltage. The FCIC controls the step up ratio of the up chopper. A surge protector inside the up-chopper limits an excessive amount of current from going through the fuel cell stack. The stack will be disconnected automatically from the system and the power output will be redirected to the dummy load at the point when the stack power should be separated. The up-chopper can detach the fuel cell stack through an arrangement of DC/AC and AC/DC converters and transformers which forestall stack current inversion.[55]

Table 2.26 Up-Chopper Configuration

Type	Isolated step-up PWM chopper
Chopper operating frequency	20 kHz
Control	Microprocessor -based
Communications	Serial to battery tray
Maximum output current	294 A
Nominal voltage	115 V in, 189-280 V out
Efficiency	> 95%
Output power	47.5 kW
Dimensions	48 cm x 60 cm x 143 cm
Weight	68 kg

Source: H P C 1993.

viii) Traction Motor

A DC shunt motor supplies traction for the PAFC bus. The motor features improved high-current brush assemblies with a three-brush cage design and a modified armature design. The improved cage design provides the current rating and increases the durability of the motor.[55]

Table 2.27. Motor Configuration

Manufacturer	General Electric
Model	CD-407
Armature circuit resistance	0.0290
Shunt field	4x4.45 = 17.8
Maxim um torque	1057 N-m at 600A, 200A, 975 RPM
Maximum continuous power rating	74 kW
Base speed	1000 RPM at 21 6 V

Maximum speed	3800 RPM
Volume	0.13 m3
Weight	622 kg
Efficiency	85% to 90%, average

ix) Motor Controller

The MC provides a peak power of 120 kW to the motor. An extreme traction power of 100 kW to be required was assessed. Tills configuration gives an adequate safety margin. The motor runs in reverse with a present safe most extreme speed.

At forward speeds surpassing zero, the MC prevents the bus from switching into the turnaround. the MC obtains signals from the SCS to supply a given measure of regenerative energy to the battery on specific occasions.

Table 2.28 configuration of Motor controller

Voltage	21 6 V DC nominal
Current	600 A DC
Efficiency	98% average
Chopper frequency	800 Hz
Volume	0.1 m3
Weight	193 kg

Table 2.29 Battery Module

Type	Nickel-Cadmium
Manufacture	SAFT
Battery model number	STM 5-200
Number of cells	.180

Nominal battery subsystem voltage	210 V DC
Battery cooling	Forced-air cooling provided by thermostatically controlled fans, ambient air to 40°C
Minimum life	2 years
Weight	1007 kg

x) Safety

The PAFC appears to be as safe and comfortable as the diesel powered bus as a result of its safety features. Cadmium and nickel are contained within the batteries, so they accommodate low risk to human during in-use life of the bus. The temperature of the PAFC bus exhaust is equivalent to the conventional diesel bus exhaust and the exhaust quits from the top of the bus. The high-power batteries may be a hazard during maintenance or a collision. The risk from these constituents was minimized through design specifications incorporated into the PAFC bus.[55]

2.3.9 Advantages Of PAFCs

PAFCs delighted in three significant advantages. The first of these is their capacity to run on effectively accessible fuels. This is the reason that phosphoric acid fuel cells were the primary fuel cell units to turn out to be commercially viable and why they stay the most mainstream for distant establishments and back-up power generation.

The second significant benefit is the production scale of electricity. 200 kW units are very normal and the significant manufacturer, United Technologies Corp., Has introduced more than 75 MW of capacity. PAFCs can be able to provide power on a scale that is valuable for modern and business applications.

PAFCs are high-temperature fuel cell units, running at about 250-300° C. While their generated electric efficiency goes from 37 to 42%, their general productivity can arrive at 80% when they are joined for heat and power applications.

2.3.10 Drawbacks Of PAFCs

In spite of the way that PAFCs are the most mainstream fixed power devices, they actually endure as they depend upon hydrocarbon powers. This implies greenhouse gases are generated and the potential for catalyst harming is of concern. The issue of catalyst harming has been overcome in these specific fuel cells by delivering electrodes made of carbon paper covered with a finely scattered platinum catalyst. While this focus on carbon monoxide poisoning, it additionally makes these fuel cells exceptionally costly to produce.

The greenhouse gas discharge made by using petroleum derivatives has just been partly solved. The gases can't be totally wiped out, yet they can be captured and prevent them from escaping into the atmosphere.

2.3.11 Comparison Between PAFC With Other Key Fuel Cells

Table 2.30 Comparison between different fuel cells

FC TYPE	ALKALINE (AFC)	PROTON EXCHANGE (LPEM & HTPEM)	PHOSPHORIC ACID (PAFC)
Anode	Platinum or Carbon	Platinum	Platinum
Electrolyte	Potassium Hydroxide (KOH)	Polymer Membrane	Phosphoric Acid (H_3PO_4)
Electrolyte Type	Liquid	Solid	Liquid
Fuel	• Hydrogen • Ammonia	• Hydrogen	• Hydrogen • Methanol
Temperature	• 60-70 ºC	• 80-100 ºC(Ltpmefc) • 200 ºC (Htpemfc)	• 150-200 ºC
Efficiency	60-70%	30-40%	40-50%
Power	0.5–200 kW	0.12-5 kW	100 - 400 kW
Start Up Time	< 1 minute	< 1 minute	Not applicable
Uses	• Backup generators (long-duration UPS) • Primary power generators	Automobiles	• Buildings • Hotels • Hospitals • Utilities

	• Off-grid telecom		• Buses
Advantages	• Quick startup • Temperature resistant • Low-cost ammonia liquid fuel	• Quick startup • Small • Light-weight	• Stable • Maturity
Disadvantages	• Liquid catalyst adds weight • Relatively large	• Sensitivity to humidity or dryness • Sensitivity to salinity • Sensitivity to low temperatures	• Phosphoric acid vapor • Less powerful

Efficiency of PAFC is ~ 35%–50%, which is higher than PEMFC, but lower than MCFC and SOFC. When it works with Combined heat and power (CHP), heat and power are applied simultaneously, so the efficiency grows dramatically and reaches to about 80%.

2.4 Solid Oxide Fuel Cells(SOFC)

2.4.1 Introduction

Solid oxide fuel cells (SOFCs) offer a clean and low pollution Fuel cell technology to generate electricity electrochemically at high efficiencies. SOFC provide major advantages over traditional energy conversion systems including reliability, modularity, adaptability, high efficiency and very low levels of NOx and SOx emissions. Quiet and vibration free operation of SOFC eliminates noise associated with conventional power generation systems.[58]

About six years ago, SOFCs were being developed primarily in the temperature range of 900 to 1000ºC; High temperature SOFCs provide high quality exhaust heat for cogeneration in addition to the capability of internally reforming hydrocarbon fuels (e.g., natural gas) and when pressurized, can be integrated with a gas turbine to further increase the overall efficiency of the power system.

Reduction of the SOFC operating temperature by 200ºC or more allows, is less-demanding on the seals and the balance of plant components, simplifies thermal management, helps in rapid start up and cool down, and results in less degradation of cell and stack components. Because of these advantages, activity in the development of SOFCs capable of operating in the temperature range of 650 to 800ºC has increased spectacularly in the last few years. However, at lower temperatures, electrolyte conductivity and electrode kinetics decrease significantly to overcome these limitations, alternative cell materials and designs are being broadly investigated. [59]

An SOFC consists of two porous electrodes separated by a dense-ion oxide conducting electrolyte. The operating principle of such a cell is illustrated in Fig.2.20. Oxygen which is supplied at the cathode (air electrode) reacts with incoming electrons from the external circuit to form oxide ions, which transferred to the anode (fuel electrode)through the oxide ion conducting electrolyte.

At the anode, oxide ions combine with H_2 in the fuel to form H_2O (and/or CO_2), liberating electrons. Electrons (electricity) flow from the anode by means of the external circuit to the cathode. The materials for the cell components are selected based on suitable electrical conducting properties. Adequate chemical and structural stability at high temperatures encountered during cell operation as well as during cell fabrication. Minimal reactivity, interdiffusion and matching thermal expansion among different components.[60]

2.4.2 Operating principle of an SOFC

A SOFC comprises of two electrodes and a gas-tight ceramic electrolyte. The figure portrays the working of a SOFC. The Dense electrolyte turns into an ionic conductor at high temperatures. Deterioration and decrease of oxygen concentration happen at the cathode by electrons and the subsequent oxygen particles are transferred through the electrolyte. At the anode, the oxygen particles respond with the inlet fuel generating oxidation products, heat, and electrons. The electrons are liberated through an external circuit empowering electricity generation, while the heat is vented from the cell with the oxidation items and different gases.[73]

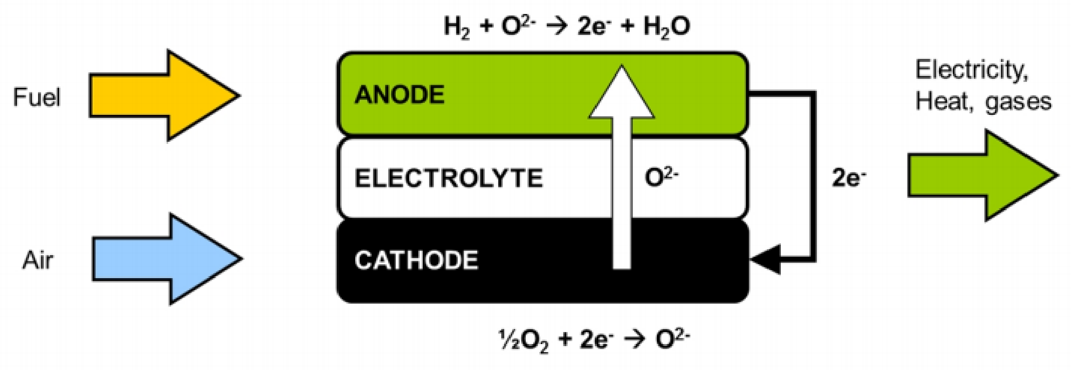


Fig 2.20 Operation of SOFC

The half-cell reactions occurring at anode and cathode, and the total reaction in an SOFC operated with hydrogen, are given in Eqs. (1),(2), (3), respectively.

$$\mathbf{H_2 + O_2^- \longrightarrow H_2O + 2e^-} \qquad (1)$$

$$\mathbf{\tfrac{1}{2}\,O2 + 2e^- \longrightarrow O_2^-} \qquad (2)$$

$$\mathbf{H2 + \tfrac{1}{2}\,O2 \longrightarrow H_2O + 2e^- \qquad \Delta G(800^o c) = -189\ kjmol^{-1}} \qquad (3)$$

2.4.2.1 Current-voltage behaviour

The thermodynamic potential difference between the anode and cathode results in a voltage difference over the SOFC. The reversible cell voltage for the system in Eqs. (1)–(3) can be calculated by using the Nernst equation Eq. (4) [73]

$$E_0 = -\frac{\Delta G}{2F} + \frac{RT}{2F}\ ln\left(\frac{pH2\ \sqrt{pO2}}{pH2O}\right) \qquad ...(4)$$

Where E_0 is the reversible voltage of an SOFC,

ΔG is the Gibbs free energy of the total fuel cell reaction Eq. (3),

F is the Faraday constant, R is the ideal gas constant, T is the temperature,

pH_2 and $pO_2$are the partial pressures of the reactants and pH_2O is the partial pressure of the product.

The voltage of a fuel cell reduces because of non-ideal losses. The losses are denoted by an overpotential that is required or a polarization that emerges, separately, when current is drawn from the cell. The misfortunes are ordered as activation, ohmic and mass-transfer losses. Figure 2 portrays the combined impact of the losses on the fuel cell unit voltage and the dominating loss mechanism concerning the extent of the current.[62]

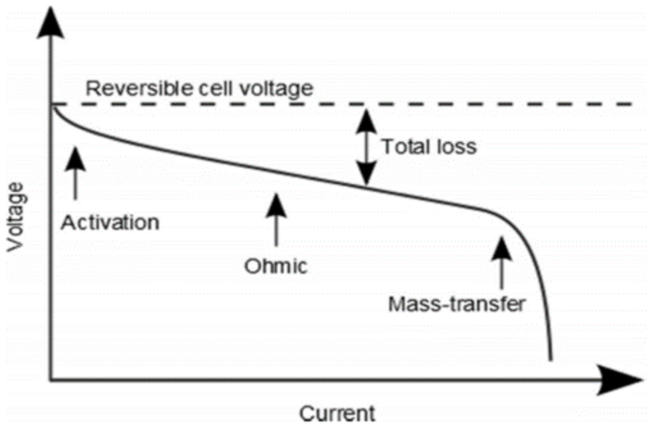


Fig 2.21 Current voltage characteristics and loses

Activation losses are prevailing at low current and are related to electrode reaction kinetics. Ohmic losses display a direct relationship between the current and the electrical resistance of the different components of the fuel cell. Finally, the mass-transfer losses happen at high current because of the limited moment of reactants to (or products from) the reaction sites at the electrodes. An SOFC is often operated in the region of mass-transfer losses, because of risks related to fuel starvation and the ensuing danger of harming the anode, as examined in more detail in the following areas.[73]

2.4.3 SOFC systems

Figure illustrates a general design for a stationary, natural gas fuelled SOFC system with its basic components. The system components can be divided on the basis of their functionality into different subsystems, which are briefly described in the following.

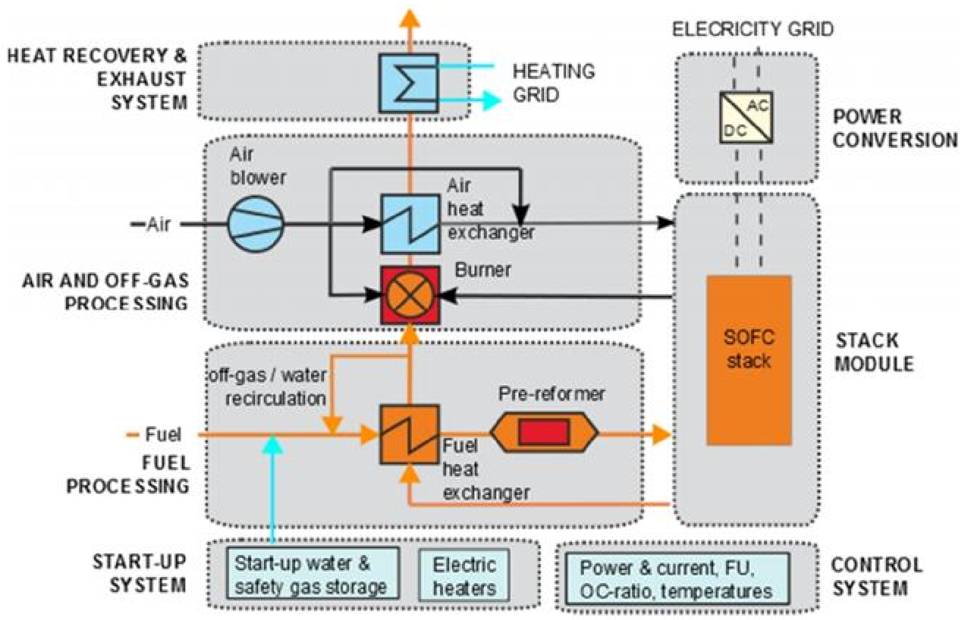


Fig 2.22 Block Diagram of Solid Oxide Fuel cell components

2.4.4 Solid oxide fuel cell stack

It depicts the basic structure of a planar SOFC stack design. Anode supported SOFCs have a thick nickel-ceramic anode electrode acting as a mechanical support for the cell. Metallic interconnect plates are employed to deliver the gases to the electrodes and to connect the cells electrically in series , the gas-tightness of the stack is an important characteristic which can affect the design and operation of the entire system. Gastight seals are used at the interfaces between the cells and interconnect plates in order to prevent mixing and oxidation of inlet fuel and air .Typically, a compressive force is needed over a planar stack to achieve good electrical contacts as well as sufficient gas-tightness between the different parts of the stack assembly.[73]

The normal operating voltage of a single SOFC is less than 1 V, typically in the range of 0.7–0.9 V in the system environment. Therefore, to realize higher and more practical voltage levels, the cells are connected electrically in series and assembled together into stacks

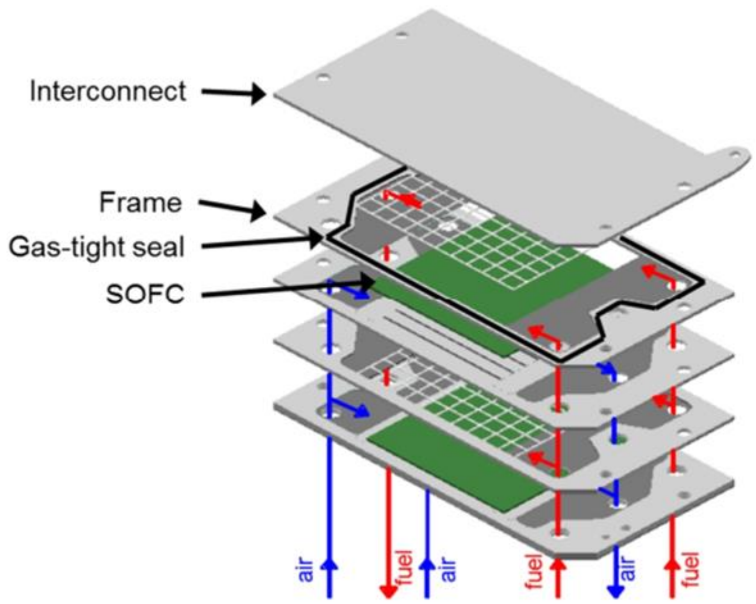


Fig 2.23 SOFC Fuel cell stack

The common stack design that are developed and Came into use for SOFCs are

<u>Segmented-cell-in-series design</u>: the segmented cells connected in series to the electrical and gas flow. The cells are either arranged as a thin banded structure on a porous support (porous substrate configuration) or fitted one into the other to form a tubular self-supporting structure. [63]

<u>Tubular design</u>: in this design, the cell is configured as a tube and a stack consists of a bundle of single cell tubes. In the most common tubular design, the tube is made of cathode material (cathode-supported) closed at one end. Electrolyte and anode layers are formed on the outside of the tube.[63]

Monolithic design: the cell components formed into a corrugated structure of either gas flow or crossflow configurations. The cell is commonly based on electrolyte support.

Planar design: in this design, the single cell which are connected in electrical series is configured as flat plates. Common plate shapes are rectangular (square) or circular.[63]

the models can be categorized based on their SOFC type rather than modeling approach.

For instance,

- ♣ Fuel cell type :
  - Planar
  - Tubular
  - Monolithic (MSOFC)
  - Integrated Planar (IP-SOFC)
- ♣ Cell and stack design (anode-, cathode-, electrolyte-supported and co-, cross-, and counter-flow types)
- ♣ Temperature level:
  - Low temperature (LT-SOFC, 500–650℃)
  - Intermediate temperature (IT-SOFC, 650–800℃)
  - High temperature (HT-SOFC, 800–1000˚C)
- ♣ Fuel reforming type
  - External steam reforming
  - Internal steam reforming
  - Partial oxidation (POX)

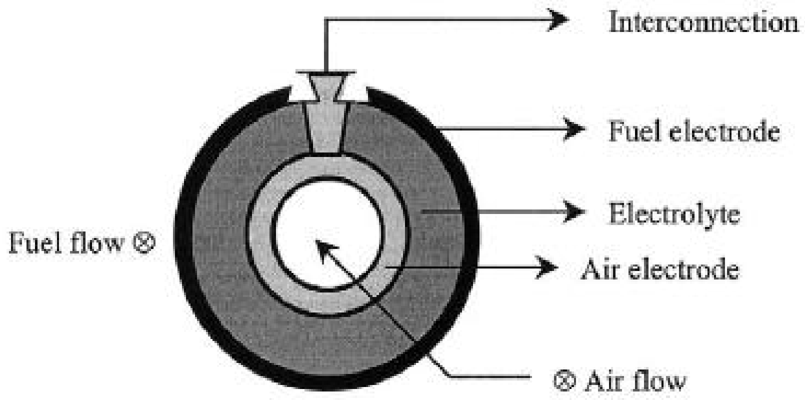


Fig 2.24 Typical tubular SOFC configuration

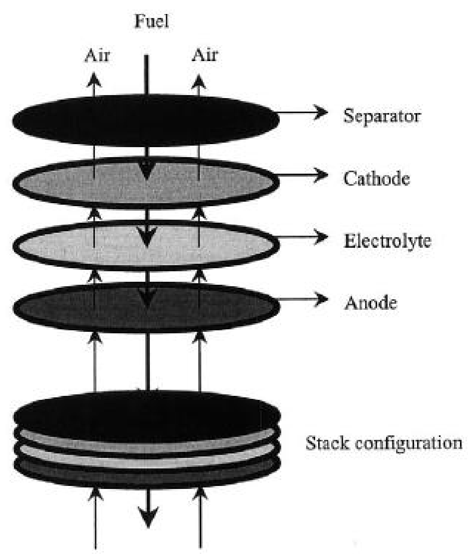


Fig 2.25 radial planar SOFC configuration

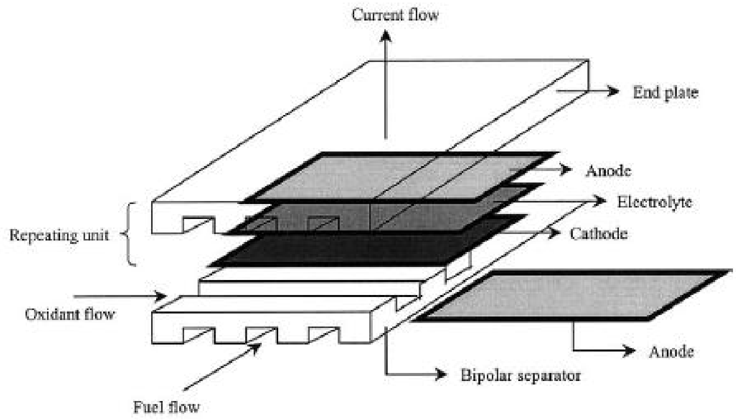


Fig 2.26 planar flat-plate SOFC configuration

2.4.5 SOFC component requirements

Each component of the SOFC performs several functions and meet certain requirements such as [65]:

- Proper stability (chemical, phase, morphological, and dimensional)
- Proper conductivity
- Chemical compatibility with other components
- Similar thermal expansion to avoid cracking during the cell operation
- Dense electrolyte to prevent gas mixing
- Porous anode and cathode to allow gas transport to the reaction sites.
- High strength and toughness properties
- Fabricability
- Amenable to particular fabrication conditions
- Compatibility at higher temperatures at which the ceramic structures are fabricated
- Low cost

2.4.6 Materials for cell components

The following SOFC components materials, over long periods, has been put forth by a number of SOFC manufacturers such as the Global Thermoelectric company, Westinghouse Electric Corporation, Siemens (now called Siemens Westinghouse Power Corporation) and Fuji Electric as the Stable materials.[67]

a) Electrolyte

Present technology employs different ceramic materials for the active SOFC components.

Although a variety of oxide combinations has been used for solid non-porous electrolytes, the most common has been the stabilised zirconia with conductivity based on oxygen ions ($O_2\_$), especially yttria-stabilised zirconia (Y_2O_3—stabilised ZrO_2 or YSZ, $(ZrO_2)_{0.92}(Y2O_3)_{0.08}$ for example) in which a tiny amounts of the element yttrium, a silvery-grey metal, is added to the zirconia during manufacture. This choice is mainly due to availability and cost (70% of the world's supply of zirconia comes from Australia).[67]

YSZ exhibits purely oxygen ionic conduction (with no electronic conduction). The crystalline array of ZrO2 has two oxide ions to every zirconium ion The most commonly used stabilising dopants are CaO, MgO, Y2O3, Sc2O3 and certain rare earth oxides such as Nd2O3, Sm_2O_3, Yb_2O_3.[67]

b) Anode

Metals can be used as SOFC anode materials because of the reducing conditions of the fuel gas. Moreover, these metals must be non-oxidised since the composition of the fuel changes during the operation of the cell. SOFC anodes are fabricated from composite powder mixtures of electrolyte material (YSZ, GDC, or SDC) and nickel oxide NiO (the nickel oxide subsequently being reduced to nickel metal prior to operation) [67]

NiO/YSZ anode material is suited for applications with YSZ electrolyte material.

NiO/SDC and NiO/GDC anode materials are best used with ceria-based electrolyte materials.[67]

c) Cathode

Because of the high operating temperature of the SOFC, only noble metals or electronic conducting oxide can be used a s cathode materials.

The most prevalent applications for these materials are as cathode materials for solid oxide fuel cells and as electrode materials for oxygen generation systems. Perovskite-type lanthanum strontium manganite, LaSrMnO3 (LSM) and lanthanum calcium manganite, LaCaMnO3 (LCM) offer excellent thermal expansion match with zirconia electrolytes and provide good performance at operating temperatures above 800°C. For applications requiring lower temperature operation (600–800°C), [67]

Similar to the anode, the cathode is a porous structure that must permit rapid mass transport of reactant and product gases.

d) Fuel

SOFCs require only a single partial oxidation reformer to pre-process their fuel, which can be gasoline, diesel, natural gas, etc. The nature of the emissions from the fuel cell will vary correspondingly with the fuel mix. Using hydrocarbons, for which a supply infrastructure is currently available, offers a variety of advantages over using hydrogen. First of all, hydrocarbons are much easier to transport and to store because they are in a stable state which requires no processing before use. They are also more efficient at producing energy. Methane for example yields eight electrons per molecule whereas hydrogen only yields two electrons energy. This advantage could be magnified with the use of more complex hydrocarbons, such as pentane.[67]

e) Operating temperature

The SOFC can be designed for efficient operation within a temperature range, from as high as 1000 ºC to as low as 500 ºC [69].

The 1000 ºC operating temperature is generally selected for cells with thickness(>25 Am) YSZ electrolytes, especially electrolyte-supported cells, to limit ohmic losses.

Lower operating temperatures (<800 ºC) are possible with thin YSZ electrolytes[70] or highly conducting electrolytes such as doped LaGaO3 [71].

Recently, it has been shown that not only operation at temperatures 800 ºC is. feasible but also high electrochemical performance can be achieved for reduced temperature SOFCs

2.4.7 Reforming of hydrocarbon fuels

The high operating temperature of the SOFC permits direct operation on hydrocarbon fuels by either electrochemical oxidation or reforming within the fuel cell.[72] The direct electrochemical oxidation reaction of hydrocarbons at the SOFC anode can be described as follows (example: CH4):

$$CH_4 + 4O_2^- \longrightarrow CO_2 + 2H_2O + 8e^- \quad \ldots(1)$$

The key issue in the direct oxidation of hydrocarbons at the Ni/YSZ anode is carbon deposition.

Internal reforming involves conversion of hydrocarbons to hydrogen (and carbon monoxide) followed by electrochemical reactions:[72]

$CH_4 + H_2O \longrightarrow 3H_2 + CO$ …(2)

$CH_4 + 2H_2O \longrightarrow 4H_2 + CO_2$ ….(3)

$H2 + O2^- \longrightarrow H2O + 2e^-$ ......(4)

$CO + O2^- \longrightarrow CO2 + 2e^-$ ....(5)

Direct electrochemical oxidation and internal reformation are attractive because of the possibility of operating the SOFC on hydrocarbon fuels without an external reformer. Reforming reactions are endothermic and therefore, internal reforming has been considered as a potential approach for stack cooling/thermal management[72]

2.4.8 Efficiency and output power

The electrical output power and the efficiency of the SOFC system depend mainly on the electrochemical performance of the stack, but also on the internal, parasitic, power consumption of the BoP components, such as blowers, and the losses related to power conversion from DC to AC.[73] The output power of an SOFC system is determined by Equation

$$P_{ac} = P_{dc,sofc}\, \eta_{pcu} - P_{blowers,aux}$$

P_{ac} is the output power of the SOFC system,

$P_{dc,sofc}$ is the output power of the SOFC stack

η_{pcu} the total efficiency of the power conversion unit and

$P_{blowers,aux}$ the parasitic power consumption of blowers and auxiliary equipment of the system.

The net electric AC efficiency is determined by the system's AC electric output power and the reaction enthalpy of the inlet fuel flow.

$$\eta_{AC} = \frac{P_{AC}}{\dot{n}_{fuel}\,\Delta H_{fuel}}$$

The electrochemical performance of the SOFC stack has the most significant impact on the achievable electrical efficiency of a complete system. Low area specific resistance (ASR) is required from the stack in order to achieve a sufficiently high power density, enabling compact stack size and high operating voltage, beneficial for the electrical efficiency of the system.[73]

The relationship between the DC electrical efficiency of the stack, the stack operating voltage and the fuel utilization rate is given by[16]

$$\eta_{DC} = \frac{z\,F\,U_{sofc}}{\Delta H_{fuel}\,N_{cells}}FU$$

η_{DC} is the DC electric efficiency of the stack, z is the number of electrons that participate in the reaction, F is the Faraday constant.

U_{sofc} is the SOFC voltage, ΔH_{fuel} is the lower heating value of the inlet fuel, N_{cells} is the number of cells in the stack and FU is the fuel utilization.

The system's net electrical efficiency relates to stack DC efficiency according to

$$\eta_{AC} = \eta_{DC}\,\eta_{PCU} - \frac{P_{blowers,aux}}{\dot{n}_{fuel}\,\Delta H_{fuel}}$$

2.4.9 Intermediate Temperature Solid Oxide Fuel Cells

Intermediate temperature solid oxide fuel cells (ITSOFCs) become a major competitor not only for stationary power generation, but also for tractionary applications, e.g. for electrical (hybrid) vehicles. These ITSOFCs are based on ceria-salt composite ceramic materials. These new ceria-based composite ceramic materials have shown a super ionic conductivity (0.1- 1.0 S cm^{-1}) in the Intermediate Temperature region (400-600ºC). Using them as the electrolytes the ITSOFCs are operated between 300 and 1500 mA cm^{-2} (200-700 mW cm^{-2}) continuously between 400 and 600ºC. The efficiency is , ITSOFCs fed directly with hydrocarbon containing gas-type and liquid-type fuels have shown an enormous potential for application in electrical vehicles.[74]

Temperature management and Quick start for SOFC powered electrical vehicles are more critical compared to those run by batteries and PEFCs.

Present Days , there is Research is going on about how to combine the present batteries or super capacitors with fuel cells to drive electrical vehicles, thus, providing a quick start up.

On the other hand, based on recent achievements with respect to the automotive applications the ITSOFCs proposed here require operating temperatures around 400-500ºC. For the raised operational temperature, i.e. 200ºC, the PEMFCs and DMFCs (direct methanol)are always subject to further development in order to overcome the carbon monoxide (CO) poison and methanol cross-over, as well as to enhance the operating efficiency.[74]

The future trend would result in a very close operating temperature range for PEFC and SOFC powered electrical vehicles. It may also be realised that during the vehicle parking period the temperature (400- 500ºC) of the ITSOFCs would be easily maintained by electricity heating from the super capacitor self-discharge or battery discharge to compensate the heat loss from the thermal insulation of the fuel cells.[74]

i) Fuel cell construction

ITSOFCs were constructed utilizing the composite anode supported technique. A composite anode was made by a mixture of electrolyte (40 vol.%), anode, e.g. GDC(commercial Gd0.1Ce0.9O1.95 (GDC) powder), NiO composite, (40 vol.%) and carbon/graphite (20 vol.%) powders.
The cathode was prepared as the composite form in a similar way to that of the composite anode in replacement of NiO.[74]

To avoid cracking and separation of the fuel cell components (anode, electrolyte and cathode) during heating, complete fuel cell assemblies were heat-treated using a program-controlled furnace to carefully adjust the temperature rise and holding time, e.g. for 30 min at 600ºC.

Anode (fuel chamber)/electrolyte/cathode (oxidant chamber), the cell size normally being 13 mm in diameter and 1.0-2.0 mm thick. The fuel was a hydrogen, hydrocarbon gas-type (methane mixed with hydrogen) or liquid-type (e.g. methanol and ethanol) and the oxidant was air. The gas flows were controlled between 10 and 50 ml/min under 1 atm pressure. All gases were directly fed into the fuel cell chambers without preheating.

The liquid fuels, e.g. methanol and ethanol, were fed by the syringe pump through the tubular evaporator (about 180ºC), and then became gas-type to the fuel cell device in operation[74]

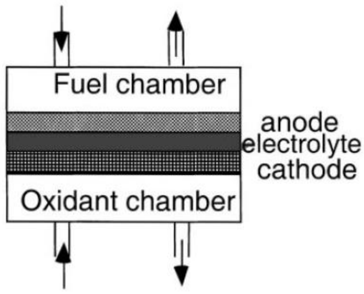


Fig 2.27 ITSOFC Arrangement

ii) Electrolyte properties and fuel cell performances

Ionic conductivity value which is in the range of 0.1-1.0 $Scm^{-1}$is 10^4 times higher than that of the zirconia-based electrolytes for HT SOFCs (above 800ºC) and 10-100 times higher than that of the conventional ion-doped ceria at the same temperatures. These new materials have also overcome the chemical stability problem for the conventional ceria-based electrolytes. These highly conducting new composite ceramic materials create a great potential for commercialising ITSOFCs. The success in continuous Research & Development of these new materials and novel ITSOFCs will lead to new fuel cell areas, correspondingly changing the strategy of R & D for SOFCs and accelerating the SOFC commercialisation.[74]

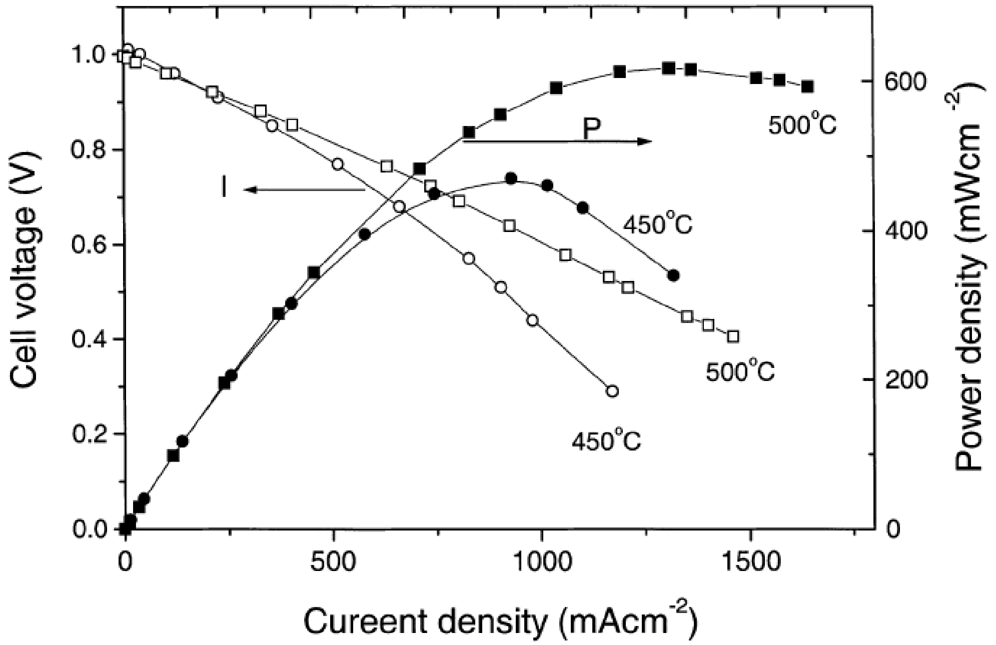


Fig 2.28 Typical I-V characteristics for the ceria-salt composite ceramic electrolyte SOFCs at different temperatures. Fuel: H2 plus 10% CH4; oxidant: air; pressure: 1 atm; flow: 30-50 ml/min.

Fig.2.28 shows typical current and power density versus voltage, i.e. I-V-P characteristics, at different temperatures the cell reaches a max. power density of around 500 and 600 mW cm^{-2} at 450 and 500°C, respectively.

iii) Properties of ITSOFCs

The ITSOFCs using these new composite ceramic electrolytes were operated between 300 and 1500 mA cm^{-2} (200-700 mW cm^{-2}) continuously between 400 and 600°C.Table 1 lists some typical ITSOFC performances at various temperatures in presence of the hydrogen fuel.

The highest power density of 718 mW cm^{-2} (1200 mA cm^{-2}) at 6008C has been reached so far. Under the speeded-up testing conditions, i.e. the operation with the heavy loads, the fuel cells were operated

constantly for several 10 h with the power density output around 600 mW cm^{-2} corresponding to the current density output, around 1000 mA cm^{-2}at 600°C,[75]

Table 2.31 The performance at various temperatures obtained from the composite ceramic ITSOFCs

Temperature (ºC)	**Power Density (mW cm^{-2})**
420	380
450	460
500	590
530	620
560	650
580	680
600	718

Fuel: H2; oxidant: air; pressure: 1 atm; flow: 10-50 ml/min.

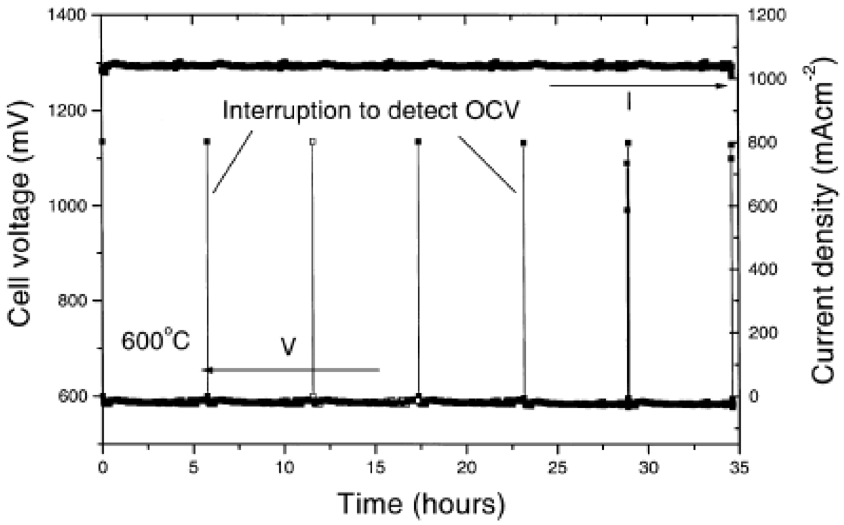


Fig 2.27 Discharging performance of a typical ITSOFC using the ceria-salt ceramic composite electrolyte operated at 600ºC. Fuel: H2; oxidant: air; pressure: 1 atm; flow: 30-50 ml/min.

ITSOFCs the fuel cell devices showed around the OCV 0.95 V for the 2 M methanol, 0.91 V for the 1 M ethanol and 0.78 V for the 1 M acetone at 6008C. Directly using the liquid fuels, the ITSOFCs were operated under 300-450 mA cm^{-2} (180-280 mW cm^{-2}) at 600oC with a peak power density around 330 and 300 mW cm^{-2} for the methanol and ethanol fuel cells, respectively.[75]

The CuO additives in the electrodes can significantly promote the electrode reaction for methanol and ethanol and improve the DMSOFCs (direct methanol SOFCs) and DESOFCs (direct ethanol SOFCs) performances. Further study on this subject is under progress.

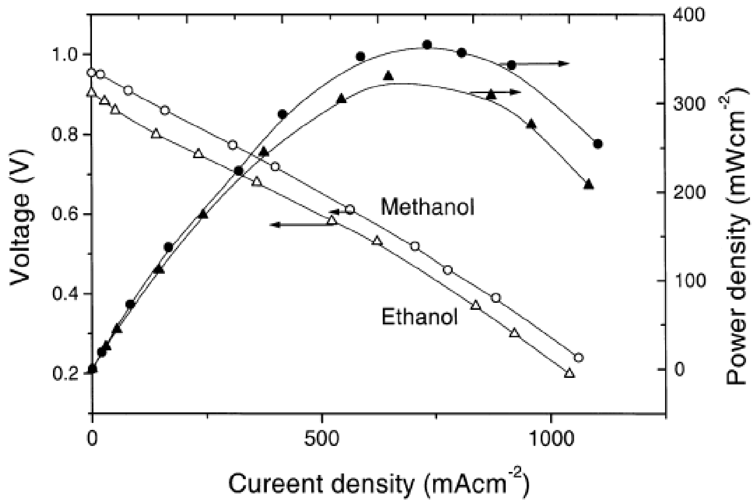


Fig 2.28 Typical ITSOFCs using the ceria-salt ceramic composite electrolyte and methanol and ethanol fuels operated at 600°C. Fuels: 2 M methanol, and 1 M ethanol; oxidant: air; pressure: 1.5 atm of the methanol or ethanol back pressure, and 1 atm for the oxidant (air).

since methanol is highly corrosive and more volatile than ethanol; furthermore the methanol vapour is also highly toxic. With no doubt the IT operation provides benefit, for the liquid fuelled fuel cells, especially in terms of lower catalyst cost and better electrode reaction efficiency.[75]

2.4.10 State-of-the-art SOFC

The dominant SOFC developers aim at stationary applications. Such ceramic solutions are indeed heavy, sluggish, expensive and fragile and must be operated at high temperatures. But different SOFCs are presently developed for mobile applications. results come from different laboratories illustrate the potentials of advanced SOFC technology: planar, hybrid (metal-ceramic), bipolar designs with thin (5 to 10\in) supported ceramic electrolytes and operating temperatures between 650°C and 800°C. Such light weight, compact SOFCs are under development for automotive applications[76]

Table 2.32 Projected trends of development of SOFC for transportation

Features	**Projections**
Operating temperature	(550°C) 600°C to 800°C
Start-up (ambient to operating temp.)	less than 2 minutes
Stack power per volume	2 kW / L
Stack power per mass	2 kW / kg
2 kW / kg	unleaded gasoline, ethanol, Methanol
Reforming	integrated internal
Cooling	air, heat rejection by exhaust
Duty lifetime	5,000 hours

The advantages of SOFC can be modular, but they are distributed to extinguish the need for transmission lines. They can be useful in achieving the Higher system efficiency, power density and at the low costs they compete with gas turbines for distributed applications.

Moreover, the operating temperatures are substantially elevated and thereby performance issues are not related to kinetics, but to ohmic losses due to charge transport across components and component interfaces[77]

The benefits of the solid oxide fuel cell as follows [67]

1. Reduction of oil consumption, cutting of oil imports, and increase the amount of the available electricity supply.
2. Achieves operating times in excess of 90% and power available 99%
3. Low operating and maintenance cost, the efficiency of the SOFC system will drastically reduce the energy bill.
4. Generates power continuously unlike backup generators, diesel engines or Uninterrupted Power Supply.

2.4.11 Advantages for ITSOFCs compared with PEFCs for electrical vehicles

The new advanced ITSOFCs have unique advantages of operation with hydrocarbon gas-type and liquid-type fuels without the need of using noble catalysts. These achievements have shown a great interest and economical potential in developing new generation fuel cell technology for the electrical vehicles. The ITSOFCs are surely a new candidate and capable competitor for the electrical vehicle in comparison to the PEFCs[74]

TSOFCs may be superior to PEFCs in the following respects:[74]

1. High temperature SOFC (400-600ºC compared with PEFCs at the temperature 80-150ºC) operation allowing to get higher electrochemical efficiency.
2. ITSOFCs have no CO poison problem at all. The carbon monoxide is actually the fuel operated for the ITSOFCs.
3. There is no need for noble Pt catalyst in ITSOFCs. The usage of Pt catalyst has the demerit for future PEFC electrical vehicle industrialisation due to very limited Pt resource in the world, in addition to expensive cost as well. On the contrast, the ITSOFCs are based on materials which have abundant and inexpensive natural resources.
4. There is no need for reformer as carbon containing fuels can be directly fed into the ITSOFCs allowing direct reforming mechanism to occur in the electrode chamber. On the other side, the reformer is a size dependent reactor, is hardly compatible with a module type fuel cell construction.
5. The ITSOFCs can be directly operated with many fuels, such as various hydrocarbon fuels, natural gas and liquid fuels, e.g. methanol and ethanol, while the PEFCs are limited seriously by the fuel.
6. The manufacturing cost and final product price for the ITSOFC would be much cheaper than that of the PEFC, since low cost metals and ceramics are used for the bipolar plates and cell components.

The deposits of the carbon can be effectively avoided in the IT region, as compared to the conventional SOFCs with high temperatures (above 800ºC) operation, which easily causes carbon deposition for using the hydrocarbon fuels, such as methane etc. Therefore, for the on board technology with the carbon containing liquid fuels, such as methanol and ethanol, intermediate temperature operation and ITSOFC technology are preferable.[74]

2.4.12 Limitations

For high temperature, decreases the cell lifetime and increases the cost of materials, since expensive high temperature alloys are used to house the cell, and expensive ceramics are used for the interconnections, increasing the cost of the fuel cell substantially.

Lower operating temperature has been recognised worldwide as the key point for low-cost SOFCs. The reduction in the temperature will therefore allow the use of cheaper interconnecting and structural components, such as stainless steel. [78]

The 600–1000°C operating temperature of the SOFC requires a significant start up time. The cell performance is very sensitive to operating temperature. A 10% drop in temperature results in 12% drop in cell performance, due to the increase in internal resistance to the flow of oxygen ions[78]

2.4.13 Applications

SOFC technology are developed for a broad spectrum of power generation applications. SOFC systems that have been considered ranges from portable devices(e.g., 500-W battery chargers), small power systems (e.g. automobile auxiliary power units) to distributed generation power plants (e.g., 100–500 kW systems). [81]

SOFCs can also be integrated with a gas turbine to form Huge (Hundred kW to multi-MW) pressurized hybrid systems. The SOFC is the only type of fuel cell that has the potential for such a wide range of applications. Some examples of SOFC power system concepts are discussed below

1. 20-W portable system: The system concept is shown in Fig.2.29 The system is a thermally integrated unit that includes an SOFC operating on jet fuels (JP-8). This system weighs about 0.6 kg (without fuel) in a volume of 3.3 X 4.5 X 7.9 in. (8.5 X 11.5 X 20 cm) and is designed to produce 20 W at 12 VDC

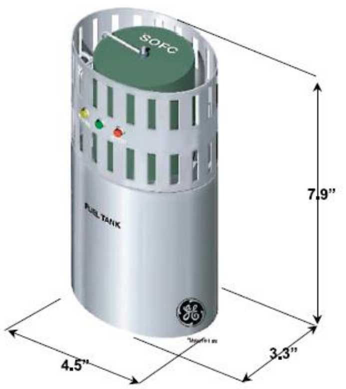


Fig 2.29 20-W portable system

2. 500-W portable system: Fig.2.30 shows as an example the design of a portable 500-W battery charging system operating on logistic fuels (JP-8) for military applications [54]. The system produces 28 V and is estimated to weigh 7 kg in a volume of 17 by 11 by 9 in. (43 by 28 by 23 cm).

Fig 2.30 500-W portable system:

3. kW power system: an example of a 5-kW power system concept for stationary applications is shown in Fig.2.31 [55]. The system consists of all the required components for a self-contained unit, including SOFC stack, fuel processing subsystem, fuel and oxidant delivery subsystems, thermal management subsystem, and various control and regulating devices. A 5-kW system concept has also been developed for automobile auxiliary power units (APUs) . Stationary kW size systems have been Demonstrated[81]

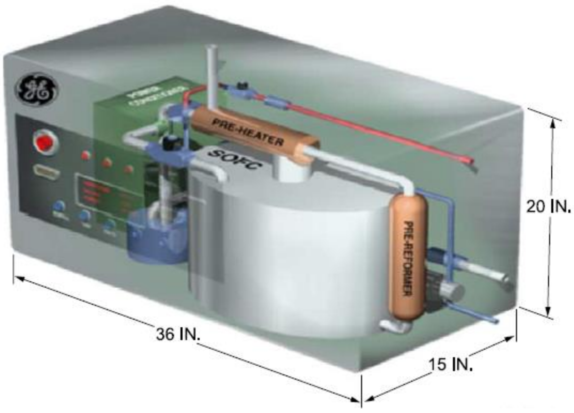


Fig 2.31 100–250 kW combined heat and power (CHP) SOFC system:

4. 100–250 kW combined heat and power (CHP) SOFC system: several CHP systems (100 to 250 kW) has been built and operated. For example, a 100-kW unit operated for more than 20,000 h at 110 kW net AC and 46% electrical efficiency[82]
5. Multi-MW SOFC/gas turbine (GT) hybrid system. SOFCs can be integrated with gas turbines to form highly efficient multi-MW hybrid systems (up to 70% system efficiency). In this hybrid arrangement, the residual fuel from the fuel cell is burned by the gas turbine to produce further electricity[82]

2.4.14 Comparison of SOFC with PEMFC

PEFC fuel cells gained wide acceptance for use in hydrogen-powered busses and cars. There is no doubt that this cell is better suited for hydrogen than any other type of fuel cell. The impressive success of Ballard and associated car manufacturers is convincing by itself and will promote diverse applications of fuel cells in transportation for traction and onboard power.

But the limited range of operation of hydrogen powered vehicles, whether equipped with fuel cells or internal combustion engines cannot be neglected. The economic storage of hydrogen or other gaseous fuels at cryogenic temperatures in the liquid or adsorbed state, or at ambient temperatures but high pressures are a still unsolved problem

Table 2.33 Comparison of PEMFC and SOFC

FC type	**PEMFC**	**SOFC**
ANODE	Platinum	Ceramic
ELECTROLYTE	Polymer membrane	Yttria-Stabilized Zirconia (YSZ)
TYPE	solid	Solid
FUEL	hydrogen	Natural gas • Methanol • Ethanol • Biogas

TEMPERATURE	• 80-100 ºC(Ltpmefc) • 200 ºC (Htpemfc)	• Low temperature (LT-SOFC, 500–650℃) • Intermediate temperature (IT-SOFC, 650–800℃) • High temperature (HT-SOFC, 800–1000˚C)
EFFICIENCY	50-60%	60%
POWER	0.12-5 kW	0.01 – 2000 kW
START UP TIME	< 1 minute	60 minutes
PROS	• Quick startup • Small • Light-weight	• Fuel variety
CONS	• Sensitivity to humidity or dryness • Sensitivity to salinity • Sensitivity to low temperatures	• Long startup time • Intense heat
USES	Automobiles	• Corporate power plants

2.5. Direct Methanol Fuel Cells(DMFC)

2.5.1 Introduction

The Direct Methanol Fuel Cell (DMFC) has been considered as the ideal fuel cell since it produces power by the conversion of the methanol fuel at the fuel cell anode. In the case of the conventional hydrogen-fuelled cells, especially for transportation applications, depends on reformer framework to change over methanol or other hydrocarbon powers to hydrogen.[83]

In any case, the commercialization of the DMFC has been hindered by its poor performance compared with hydrogen lair systems, the significant impediment being the anode performance which requires exceptionally proficient methanol oxidation catalysts. The new use of proton exchange membrane electrolyte materials has widened the operational temperature of DMFCs beyond those achievable with conventional fluid electrolytes and this has prompted major enhancements in performance over the last five years.

2.5.2 DMFC Components

The electrodes i.e., anode and cathode are in intimate contact with the membrane faces. The electrodes usually comprise of three layers: catalytic layer, diffusion layer, and support(backing) layer. The catalytic layer is composed of a mixture of catalyst and ionomer and characterized by a mixed electronic-ionic conductivity.

The catalysts are based on carbon supported or unsupported Pt, Ru and Pt materials at the anode and cathode, respectively. The membrane and the ionomer consist of a perfluorosulfonic acid polymer. The diffusion layer is usually a combination of carbon and polytetrafluoroethylene (Teflon) with hydrophobic properties necessary to transport oxygen molecules to the catalytic sites at the cathode or to support the escape of CO_2 from the anode.[84]

The catalytic layer contains also a Nafion network, particles of Nafion, in order to help the removal and the transportation of the hydrogen protons H^+. Fuel cells are using the bipolar plates, for providing the fuel and to collect the current. The electrons are taken by the plates, from the electrode and so, the external circuit is closed between the two plates.[85]

2.5.3 Working Principle Of The DMFC

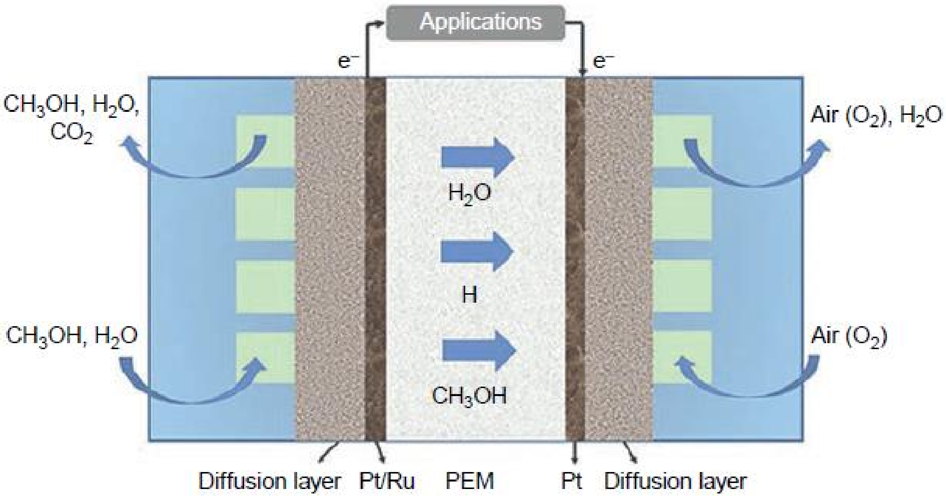


Fig. 2.32 Operation of Direct Methanol fuel cell

Proton electrolyte based DMFCs are fed directly with a Methanol/Water mixture at the anode. Methanol is directly oxidized to carbon dioxide which also results in the possible formation of compounds such as Formaldehyde, formic acid or the other organic molecules. Formation of such organic molecules limits the usage of the fuel.[84]

A scheme of the overall reaction process occurring in a DMFC.

$CH_3OH + H_2O \longrightarrow CO_2 + 6H^+ + 6e^-$ (anode)

$3/2O_2 + 6H^+ + 6e^- \longrightarrow 3H_2O$ (cathode)

$CH_3OH + 3/2O_2 \longrightarrow CO_2 + 2H_2O$ (total)

For an alkaline electrolyte,

$CH3OH + 6OH^- \longrightarrow CO_2 + 5H_2O + 6e^-$ (anode)

$3/2O2 + 3H2O + 6e^- \longrightarrow 6OH^-$ (cathode)

$CH3OH + 3/2O \longrightarrow CO2 + 2H2O$ (total)

The thermodynamic efficiency of the process is given by the ratio between the maximum value of electrical work (ΔG^O) that can be obtained, and the total available energy for the process, that is, the enthalpy (ΔH^O).[84]

Under standard conditions:

$$\eta_{rev} = \frac{\Delta GO}{\Delta HO}$$

with

$$\Delta G^O = \Delta H^O - (T \, X \, \Delta S^O)$$

And

$$\Delta G^O = -nF \, x \, \Delta E_{REV}$$

ΔE_{REV} is the electromotive force. At 25ºC, 1 atm and with pure oxygen feed, the reversible potential for methanol oxidation is 1.18V. It does not vary significantly in the operating range 20–130ºC and 1–3 bar abs. pressure.[84]

In real conditions, the Direct methanol fuel cell, generate an electric potential of 0,6V, less than the hydrogen fuel cell.

2.5.4 Performance, Efficiency and Energy Density

i) Polarization Curves and Performance

The open circuit voltage of a polymer electrolyte DMFC is significantly lower than the thermodynamic or reversible potential for the overall process. This is mainly due to methanol crossover that causes a mixed potential at the cathode and to the irreversible adsorption of intermediate species at electrode potentials close to the reversible potential.[84]

the total potential of the cell, can be determined like the difference.

$$E_{cell} = E_{cathode} - E_{anode}$$

Moreover, anode, cathode and cell potentials can be measured simultaneously by a dynamic hydrogen electrode. The methanol adsorption on the cathode fundamentally impacts the region of activation control with a reduction in oxygen. Indeed, at high cathode potentials, oxygen decrease is moderate, and oxidation of methanol pervaded through the membrane is improved by the raised potential.[84]

The two opposite reactions compete with each other and no spontaneous current is registered above 0.9 V. At high currents (from Figure 2.33), both anodic and cathodic polarization curves show the onset of mass transport constraints due to the removal of CO_2 from the anode and the effect of flooding at the cathode.

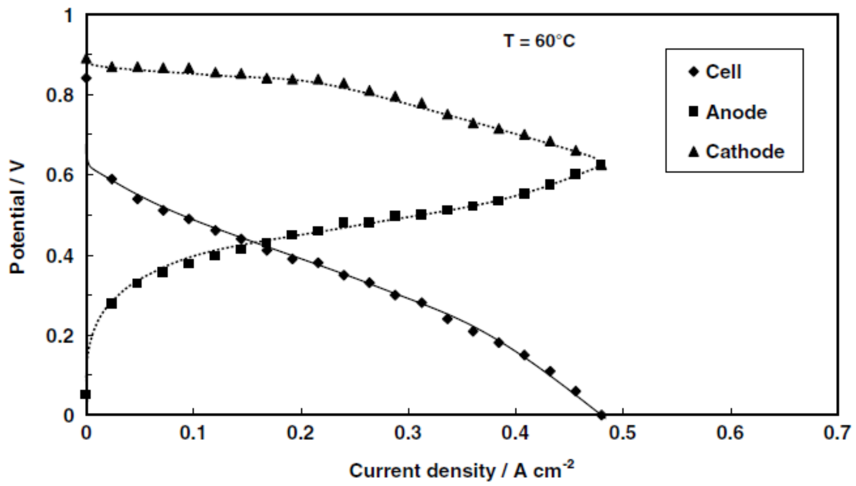


Figure 2.33 Single cell and half-cell electrode polarizations for a DMFC operating at 60ºC, ambient pressure, with 1M methanol at the anode and air feed at the cathode.

ii) Methanol Crossover

In case of DMFC, diffusion of fuel takes place through the Nafion layer. Because of the hydroxyl grouping and its hydrophilic properties, methanol in contact with the ion exchange sites and is hauled by hydronium particles in addition to diffusion as a result of the concentration gradient between anode and cathode. Methanol that crosses reacts directly with oxygen at the cathode. [87]

Electrons are brought from the anode to the cathode alongside methanol results in interior short circuiting consequently results in current loss. Moreover, the cathode catalyst, which is the pure form of platinum, is fouled by methanol oxidations intermediates like the anode.

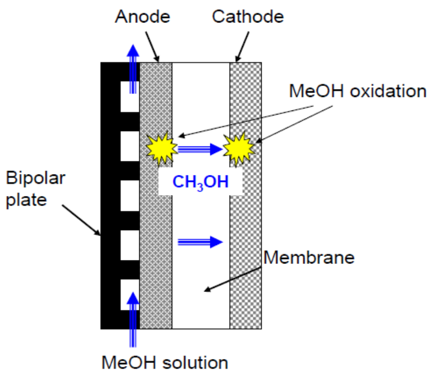


Fig. 2.34 Methanol cross over phenomena

A significant issue is to limit the crossover. the following techniques could do that.

- The first one is to do a trade-off in regard to the methanol concentration in water and to reduce the concentration, to acquire a convenient polarisation curve (potential and current density).
- The second is to equilibrate the pressure, between the anode and the cathode.
- The third is to control the temperature of the cell as a result of the high-temperature increases in the methanol crossover.

iii) Fuel Utilization

In a polarization Curve, beside the terminal voltage and the power density, it is also useful to report variations of the ohmic resistance and the crossover current (equivalent current density) as functions of the electrical current density.

Generally, internal resistance does not significantly vary in the current density range of a DMFC, whereas the equivalent current density is important for the methanol fuel cell because it determines fuel use and influences the overall performance.[84]

The crossover rate of methanol can be determined by the so-called CO2 sensor method. In the presence of a Pt based catalyst, almost all the methanol that is permeated to the cathode is oxidized to CO2 at high electrochemical potentials.

the equivalent current density is calculated according to the following equation:

$$\mathbf{I_{crossover} = moI_{MeOH\ crossover} .\ 6.\ F}$$

Where moI $_{MeOH\ crossover}$ rate of methanol permeation to the cathode per unit of time and geometric electrode area(moles/min.cm^2)

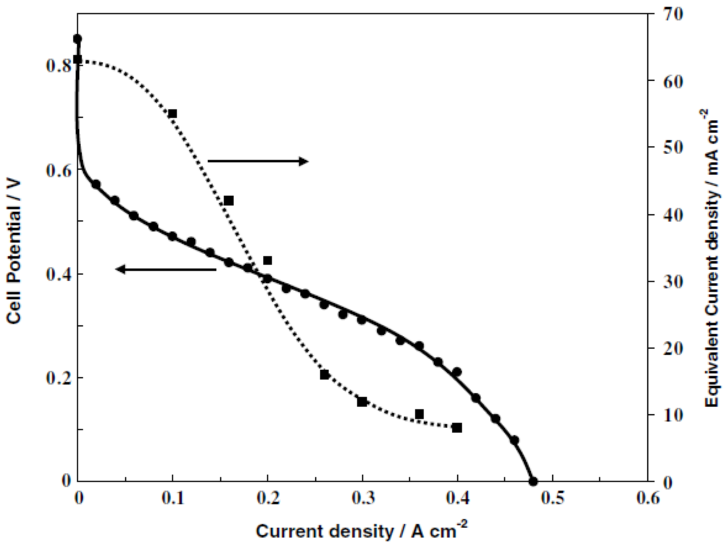


Figure 2.35 Cell potential and equivalent current density (due to methanol crossover) as a function of electrical current density for a DMFC operating at 60ºC.

iv) Cathode Operating Conditions

The negative effects of methanol poisoning at the cathode can be neutralized by an increase of oxygen partial pressure. The Temkin adsorption isotherm is often used to model the adsorption of oxygen at the cathode in PEMFCs[86]

Accordingly, an increase of oxygen partial pressure significantly influences the coverage of adsorbed oxygen species. This process is in competition with the adsorption of methanol permeated through the membrane, on the cathode surface.

It appears that the increase of air stoichiometry especially favours the physical removal from the cathode of the liquid mixture of water/methanol that permeates through the membrane or is formed by the reaction (water) avoiding the electrode flooding. [84]

The flooding of the cathode is more significant in a protonic electrolyte DMFC than in a PEMFC due to the supply of plenty of liquid water together with methanol to the anode that permeates to the cathode through the hydrophilic membrane.

2.5.5 Electrode structure

i) Catalyst

The Catalytic layer is made by diffusion layer or directly membrane is applied with the catalytic powder.

ii) Anode catalyst

adsorbed hydroxyl group is required in rate-determining steps of methanol oxidation. This gathering comes from water separation on the catalyst surface which happens only at high electrode potential (0.6V) on Pt. which makes methanol oxidation troublesome on a pure form Pt catalyst.

The chemisorption process of methanol is significantly favored on Pt sites.[86] Consequently, the steps concerned by the hydroxyl groups can only occur on adjacent Pt and Ru sites. This should be taken in count during the catalyst preparation. An optimized contact area between both catalysts is desired.

iii) Cathode catalyst:

Pure platinum is almost universally used as a cathode catalyst. The catalytic powders used for DMFC are either metal black or supported catalyst on carbon particles at various loadings. Both of them are widely used.[86]

2.5.6 Cell Efficiency

The efficiency of the Direct methanol fuel cell is influenced by the concentration of the methanol, the temperature and the pressure.

For a given current density, the voltage efficiency is defined as the ratio between the terminal cell voltage and the reversible potential for the process at the same temperature and pressure.[84]

$$\eta_v = \Delta V / \Delta E_{rev}$$

Due to crossover, the current delivered by the DMFC device is lesser than that calculated on the basis of overall methanol consumption. The ratio between the measured electrical current (I) and that calculated from the Faraday law on the basis of the total methanol consumption (I total) is defined as fuel efficiency[84]

$$\eta_f = \frac{I}{Itotal}$$

Fuel efficiency is defined as the ratio between measured electrical current (I) and that calculated from the Faraday law on the basis of the Total methanol consumption (I_{total}).

For a Passive DMFC, the overall efficiency can thus be expressed as

$$\eta = \eta_v \cdot \eta_f \cdot \eta_{rev}$$

2.5.7 Influence of the temperature

Operating Temperatures of DMFC are in the Range of 50-120^{O}C.

The heat produced in the fuel cell, is caused by the electrochemical process and reduced reaction from cathode results due to the crossover of the methanol.[85]

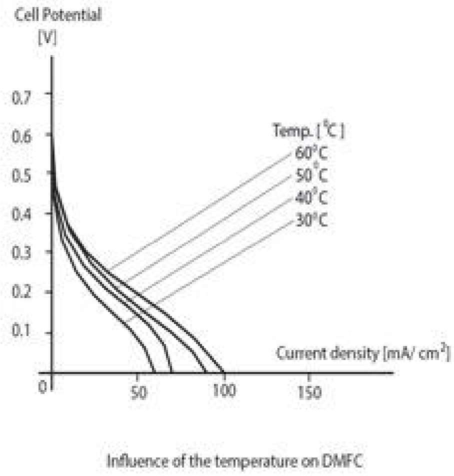


Fig.2.36 Potential and current density at different temperatures

2.5.8 Energy Density

The energy density of the fuel plays a significant role in several applications, including transportation and portable power sources. It is also a relevant factor for stationary generation it determines which is the appropriate infrastructure for fuel distribution.[88]

The energy density of a fuel is defined with respect to the weight (kWh/kg) or volume (kWh/l)

$$W_e = (-\Delta G / 3600\ M)$$

where M is the molecular weight (g/moles)

The energy density of pure methanol is also much higher than Li-Ion batteries but lower than conventional liquid fuels used in transportation, such as gasoline and diesel.

When considering the range, the driving distance, of a fuel cell car compared with an internal combustion engine or the operating time of a methanol portable power source compared with a Li-battery, besides the energy density, the overall efficiency of the process should also be considered.[84]

2.5.9 DMFC System Development

Targets for DMFC system development

1.DMFC overall efficiency ≥ 30 %

2.Durability: 25 % power loss @ 10,000 h

3.Water autonomous operation up to 35°C ambient temperature

4.Cost competitiveness.

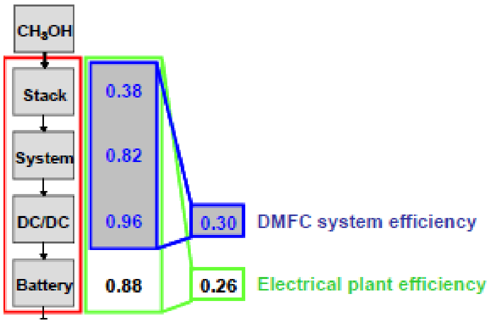


Fig.2.37 DMFC systems efficiency pattern vs Electrical plant efficiency

2.6.0 Challenges of Crossover on DMFC Performance and Efficiency

One of the most challenging problems affects the performance of DMFCs is Methanol crossover through the polymer membrane. The overall efficiency is obtained by both cell voltage and fuel efficiency for the consumption of methanol.

The crossover of methanol is influenced by

1. Membrane characteristics

2. Temperature, as well as by the operating current density

Generally, a raise in the temperature causes an increment in the diffusion coefficient of the methanol. The crossover includes both methanol permeability due to a concentration gradient and molecular transport caused by electrolyte-osmotic drag in the presence of a proton-conducting electrolyte.

For the DMFCs equipped with alkaline electrolytes, the electrolyte-osmotic drag is directed towards the anode. So, it does not contribute to the crossover. Methanol permeability, caused by the concentration gradient at the anode electrolyte interface, depends on the operating current density.

In a polarization curve, when the rate of reactant supply is lower than the rate of its electrochemical consumption, the onset of diffusional limitations occurs.

if the anode is sufficiently active to oxidize methanol electrochemically to CO_2 at a rate comparable to or higher than the rate of the methanol supply, the methanol concentration gradient between anode and cathode interfaces could be reduced significantly.

2.6.1 Applications of DMFC

The applications of the Direct Methanol Fuel Cells are mainly

1)The portable energy devices, like power for Battery chargers, for equipments and for different instrumentation.

2)The power supply has a long duration between refueling, more than 100 hours

3) In the field of automobile hybrid electric vehicles

4) Material handling systems

a) Transport Applications

Now a days DMFCS look much more ready for application in the field of electro traction system. The systems are operated successfully at temperature close or over the $100^{O}C$, which helps in the development of active catalysts and ionomeric membranes.

Particularly, the overall efficiency of the recent DMFC devices is superior to the reformer H2air fuel cells.

DMFC devices may be employed in a fuel cell vehicle if they fulfill specific requirements in terms of power density, durability, cost and system efficiency. Accordingly, more active catalysts need to be developed together with high temperature and crossover membranes.[84]

Practically all worldwide activities on fuel cell/battery hybrid vehicles (, Ford, Toyota, General Motors/Opel, Honda, Volkswagen, Fiat Chrysler) are essentially on PEMFC or PEMFC/battery hybrid vehicles.[84]

IRD Fuel Cell A/S (Denmark) has developed DMFCs primarily for transportation applications (0.7 kW) .The stack was built with separate water and fuel circuits and the bipolar flow plates are made of a special graphite/carbon polymer material. The MEAs had an active cell area of 154 cm^2. The air pressure was 1.5 bar at the cathode. A nominal cell voltage of 0.5 V was observed for IRDs stack at a current density at 0.2A/cm^2 and electric power was generated at 15W per cell. More recently, IRD has developed a 3kW DMFC stack.[91]

Siemens AG in Germany, in conjunction with IRF A/S in Denmark and Johnson Matthey Technology Center in the United Kingdom developed a DMFC stack with an electrode area of 550cm2 under the auspices of the European Union Joule Program. The projected cell performance was a potential of 0.5 V at a current density of 100mA/cm2 with air pressure at 1.5 atm and the desirable stoichiometric flow rate.[7] A 3-cell stack was demonstrated operating at a temperature of 110^{O} C and a pressure of 1.5 atm using 0.75M methanol; this stack exhibited a performance level of 175 mA/cm^2 at 0.5 V per cell, and at 200 mA/cm^2 the cell potential was 0.48 V. A 0.85kW air-fed stack composed of 16 cells and operating at 105^{O}C was demonstrated successively with a maximum power density of 100Mw/cm2.[92]

Los Alamos National Laboratory (LANL) is also actively pursuing the design and development of DMFC cell stacks for electric vehicle applications. According to the latest available information, a five-cell short stack with an active electrode area of 45 cm2 per cell has been demonstrated. The cells operated at 100 OC, an air pressure of 3 atm and a methanol concentration of 0.75 M. The maximum power of this stack was 50W, which corresponds to a power density of 1kW/l. At about 80% of the peak power, the efficiency of the cell stack with respect to the consumption of methanol was 37%.[84]

Due to following issues like

1) The efficiency losses in fuel processing it into hydrogen.
2) Significant weight of the fuel processing system
3) Substantial progress made in DMFC Technology with respect to efficiency, specific power and power density, there has been increasing interest in promoting the DMFCs in recent years. a 3 kW DMFC in a one-passenger vehicle prototype was demonstrated by Daimler-Chrysler/Ballard.

Table shows the DMFC prototypes for stationary, APU and automotive applications

Single Cell/Stack Developer	Power/Cell Power density	Temperature (°C)	Oxidant	Methanol Concentration (M)	Anode Catalyst	Membrane Electrolyte	Cathode catalyst	Number of cells/ Surface area (cm^2)
Ballard Power Systems, Inc.	3 kW	100	Air	1	Pt/Ru	Nafion	Pt	—
IRD Fuel Cell A/s	100 $mW cm^{-2}$	90–100	1.5 atm air	—	Pt/Ru	Nafion	Pt	4/154 cm^2 bipolar
Thales, CNR-ITAE, Nuvera FCs	140 $mW cm^{-2}$	110	3 atm air	1	Pt/Ru	Nafion	Pt	5/225 cm^2 bipolar
Siemens Ag	250 $mW cm^{-2}$/ 90 $mW cm^{-2}$	110/80	3 atm O_2 (1.5 atm air)	0.5 (0.5)	Pt/Ru	Nafion 117	Pt-black	3 cm^2 per cell
Los Alomos National Labs	1 kW/l	100	3 atm air	0.75	Pt/Ru	Nafion 117	Pt	30/45 cm^2 bipolar
Thales, CRF-Fiat, CNR-ITAE, Solvay (DREAMCAR Project)	5 kW/160 $mW cm^{-2}$	130	3 atm air	1–2	85% PtRu/C	Hyflon	60%Pt/C	100/300 cm^2 bipolar

2.6.2 Advantages of DMFC

DMFC technology offers a solution for transportation applications in transition towards a zero emission feature. Methanol is an attractive fuel because it is a liquid under atmospheric conditions and its energy density is about half of that of gasoline.[90]

Using methanol as a fuel evades one of the major hurdles causing in PEMFC technology, that is the development of an inexpensive and safe hydrogen infrastructure to replace the gasoline/diesel fuel distribution network.[91]

2.6.3 Disadvantages of DMFC

Despite of the advantages of DMFC in the field of transportation, there are the obstacles that include

i)The high cost of the material used in the fabrication of the Dmfcs.

ii)High cost of the platinum electrode catalysts.

iii)Crossover of the methanol through the electrolyte membrane from anode to the cathode.

iv)Low efficiency and power density performances with respect to PEMFC.

DMFC is not the fuel cell suitable for automotive application due to its working condition at the moment

Apart from these limitations a number of organisations (especially from Last ten years)have become actively engaged in the development of DMFC for automotive applications.

DMFC provides light weight, battery charging that made suitable for the Electric vehicles which are the vehicles of the future and proved Hybrid system for range extender of milage. As we know, when fuel cell connected to rechargeable battery, it constantly monitors charge state of the battery. Once this value drops below a predetermined point , the fuel cell automatically starts recharging the battery and returns to standby mode. This results in the optimum power generation stage for Electric Vehicles.

2.6.4 Extending EV Range with Direct Methanol Fuel Cells

DMFC is a solution for now a days for the problems raised for electric vehicles (EVs) with an onboard charge station. Although the power of the fuel cell is limited to directly power the motor, it is completely sufficient to recharge smaller EVs overnight or when they are parked for shorter periods. This creates an efficient bridge between public or private grid-charge stations and allows drivers to plan their routes more freely. An EV equipped with a fuel cell is not bound to the electricity grid anymore.[92]

Fig 2.38 Start Lab EV powered by SFC's EFOY fuel cell

The hybrid system includes a DMFC fuel cell, fuel cell cartridge and electric vehicle batteries. The fuel cell operates almost silently with virtually no exhaust, it is immune to extreme weather and the convenient fuel cartridges feature extremely high energy density, providing vehicle owners with a lightweight, efficient, and onboard power sour[92]

2.6.5 Overcoming battery limitations

- **Limited reach with batteries**

Small EVs weighing less than 500 kg, with one to two seats and a maximum speed of 45 to 65 km/h, are usually equipped with batteries with a capacity of three to five kWh and a system voltage of 48V or 72V. At an energy demand of four to seven kWh per 100 km these vehicles have a reach of approximately 50 km. This, of course, varies considerably depending on the driving style, the traffic situation, and the terrain to be covered, with the result that in city traffic the reach usually is limited to 30 to 40 km.[92]

- **Reach extension with fuel cells**

The DMFC solves this problem of grid dependency. Hydrogen fuel cells are not a valid alternative, as their infrastructure is even more limited than that of publicly available power sockets. With the EFOY direct methanol fuel cell, however, EV operators have a commercially available solution that has successfully proven its reliability and functionality in many off-grid applications.

- A major advantage of the DMFC is the extremely high energy density this technology offers compared to batteries. A fuel cartridge weighing only 22 kg contains a capacity of 31 kWh. Batteries providing an equivalent amount of power would weigh 1,000 kg. With 31 kWh, a lightweight EV can cover more than 500 kilometres.[92]

The energy density of batteries ranges from 30 Wh/kg of simple lead batteries to 110 Wh/kg for currently available lithium batteries. The energy density of DMFCs with 1,400 Wh/kg is much higher. In its liquid form methanol has a theoretical energy content of 5.500 W/kg. The DMFC transforms the methanol into power with an electric efficiency ratio of 25 percent.[92]

: Table 2.34 Comparing Power Solutions

Storage technology	**Solution**	**Energy density**
Battery	Lead Battery	35 Wh/kg
Battery	NiMh	70 Wh/kg
Battery	Lithium	110 Wh/kg
Hydrogen, PEM Fuel Cell	200 bar steel bottle, electric efficiency ratio 40%	160 Wh/kg
Hydrogen, PEM Fuel Cell	350 bar steel bottle, fibre reinforced electric efficiency ratio 40%	400 Wh/kg
Methanol, DMFC	Plastic cartridge, liquid fuel electric efficiency ratio 25%	1,400 Wh/kg

2.6.6 Operating mode of fuel cell vehicle

When Fuel cell connected to rechargeable battery, it constantly monitors charge state of the battery. Once this value drops below a predetermined point , the fuel cell automatically starts recharging the battery and returns to standby mode. This eliminates unfavourable operation modes like partial load operation and, in return, increases the total efficiency ratio. This high total efficiency ratio enabled by the hybridization of fuel cell and battery significantly exceeds combustion engines on short distances.

In serial hybrid operation the DMFC offers a decisive added value for electric vehicles below the size of a car. It solves the problem of dependency on the grid and lack of available public power sockets and thus enables an EV to be independent of any power outlet for weeks on end.[92]

Table 2.35 Comparison of advantages and disadvantages of DMFC and PEMFC

	DIRECT METHANOL FUEL CELLS	**POLYMER ELECTROLYTE MEMBRANE FUEL CELLS**
ADVANTAGES	1.No need for reformer (catalyst separates H2 from liquid methanol) 2. Low temperature 3.High energy density-longer use-time, extended range 4.Quick Refueling 5.No high-pressure tanks	1. Solid electrolyte reduces corrosion & electrolyte management problems 2. Low temperature 3. Quick startup

DISAVANATAGES	1)the high cost of the material used in the fabrication of the Dmfcs. 2)High cost of the platinum electrode catalysts. 3)crossover of the methanol through the electrolyte membrane from anode to the cathode. 4)low efficiency and power density performances with respect to PE	1. Expensive catalysts 2. Sensitive to fuel impurities 3. Low temperature waste heat
APPLICATIONS	1)Portable energy devices, like power for Battery chargers, for the equipments, for the different instrumentation. 2)power supply has a long duration between refueling, more than 100 hours 3) In the field of automobile hybrid electric vehicles for extending range 4) Material handling systems	1. Portable power 2. Distributed generation 3. Automobile sector 4. Special vehicles

Table 2.36 Properties DMFC VS PEMFC

TYPE OF FC	**DMFC**	**PEMFC**
Operating Temperature	60-130 ºC	80-100 ºC
Fuel	CH_3OH	Pure H_2

Charge carrier	H+	H+
electrolyte	Solid polymer membrane	Solid polymer Nafion
Startup time (h)	<0.1	<0.1
Efficiency (%)	20-40	40-60
advantages	1) High energy density-longer use-time, extended range 2) Quick Refuelling 3) No high pressure tanks	• Quick startup • Small • Light-weight

Table 2.37 Performance comparison between DMFC & PEMFC

PROPERTY	**DMFC**	**PEMFC**
power density	200 mW/cm^2	458.8 mW/cm^2
Cell potential	0.5v	0.75v
Energy density	6kwh/kg	39.7 kwh/kg
power	0.2-2KW	0.12-5 KW
Efficiency	Less than 40%	35-50%
cost	2000$/KW	600-1000$/KW

Overview Of Fuel Cell Technologies

Fuel cells provide Zero harmful emissions without compromise the efficiency of the Vehicle's propulsion system. Considering the advantages of the smooth operation modularity and the low maintenance and due to the absence of the moving parts, available fuel cells become an alternative for current combustion engines.

Form the above scenarios, PEMFC technology can be ideally suited for Transportation and vehicular applications due to its power density, light weight, high energy conversion efficiency and low operating temperature. PEMFCs are the most popular fuel cells in the light Fuel cell electric Vehicles As for DMFC, even it is less advanced compared to PEMFC technology and affected by problems of reduced power density caused by methanol crossover and poisoning of the catalysts. Because of the Size of the reformer and gas-cleaning unit a DMFC would be desirable for the mobile systems. There are a lot of car manufacturers which are increasingly progressing for the commercialisation of L-FCEV (e.g., General Motors, Toyota, Mazda, Volvo, Honda, Hyundai, Nissan).Heavy-duty Fuel cell electric vehicles (H-FCEVs) Include buses, Heavy-duty trucks, locomotives, vans and other large load vehicles which use fuel cells for electric propulsion. from our above detailed analysis of PEMFC and on PAFC, they are most commonly used types for fuel cell stacks for heavy duty, taking advantage of regenerative breaking and high dynamic response.

PEMFCs are the one with the largest range of possible markets with numerous advantages and can employed in different fields. There are some issues to be solved before PEMFC including current high cost of the unit, need to improve durability and performance.

Table 2.38 Grand comparison of All Fuelcell Technologies which have scope in Automobile industry

FC TYPE	Alkaline Fuel cell (AFC)	Proton Exchange membrane(PEMFC)	Phosphoric Acid (PAFC)	Solid Oxide Fuel Cell (SOFC)	Direct Methanol Fuel Cells(DMFC)
Anode	Platinum or Carbon	Platinum	Platinum	Ceramic	Platinum
Electrolyte	Potassium Hydroxide(KOH)	Polymer membrane	Phosphoric Acid (H_3PO_4)	Yttria-Stabilized Zirconia (YSZ)	Solid polymer Nafion
Electrolyte type	Liquid	Solid	Liquid	Solid	Liquid
Fuel	Hydrogen	Hydrogen	• Hydrogen • Methanol	Natural gas • Methanol • Ethanol • Biogas	CH_3OH
Temperature	60-70 ºC	• 80-100 ºC • 200 ºC	• 150-200 ºC	• Low temperature (LT-SOFC, 500–650 ℃) • Intermediate temperature (IT-	60-130 ºC

				SOFC, 650–800℃) • High temperature (HT-SOFC, 800–1000° C)	
Efficiency	60-70 %	30-50%	40-50%	60%	20-40%
Power	0.5-200kW	0.12-5 KW	100 - 400 kW	0.01 – 2000 kW	0.2-2KW
Startup time	< 1minute	<1 minute	Not applicable	60 minutes	< 1 minute
Merits	• Quick startup • Temperature resistant • Low-cost ammonia liquid fuel	• Quick startup • Small • Light-weight	• Buildings • Hotels • Hospitals • Utilities • Buses	• Fuel variety	• No need for reformer (catalyst separates H2 from liquid methanol) • Low temperature • High energy density-longer use-time, extended range • Quick Refueling • No high-pressure tanks
Demerits	• Liquid crystal adds weight • Relatively large	• Sensitive to humidity or dryness • Sensitivity to salinity • Sensitivity to low temperatures	• Stable • Maturity	• Long startup time • Intense heat	• The high cost of the material used in the fabrication of the Dmfcs. • High cost of the platinum electrode catalysts. • Crossover of the methanol through the electrolyte
Uses	• Backup generator (Long-duration UPS) • Primary Power generators • OFF-grid telecom	• All automobile vehicles like Cars, Buses, Trucks etc. • Portable power • Distributed generation	• Phosphoric acid vapor • • Less powerful	• Corporate power plants	• Portable energy devices, like power for Battery chargers, for the equipments, for the different instrumentation. • Power supply has a long duration between refueling, more than 100 hours • In the field of automobile hybrid electric vehicles for extending range

3. Vehicles Powered by Fuel cells

3.1 Plug-in Fuel Cell Vehicles

3.1.1 Introduction

Plug-in Fuel cell vehicles gave an opportunity to collate the advantages and mitigate the drawbacks of Both Electrical vehicles and Fuel Cell vehicles. PFCVs can offer a competitive alternative to conventional PHEVs with the additional advantages of being 100% Gasoline independent and having zero tailpipe emissions.

a) Description

A Plug-in fuel cell vehicle (PFCV) is an advanced technological electric vehicle concept with guarantee to assist with accomplishing key environmental and energy strategic objectives. As well as being a zero emission vehicle, the plug-in fuel cell vehicle combines the merits of hydrogen fuel cell vehicles with those of grid-charged Battery Electric Vehicles (BEVs). It overcomes the range limitation and long refueling time of BEVs, considered by many to be the continuing barriers to their widespread acceptance. Contrast to fuel cell vehicles, the plug-in fuel cell vehicle offers the client lower fuel costs and home refueling with electricity from the grid. PFCVs offer the advantage of increased operating fuel cell efficiency while working with the market acknowledgment of FCVs in a period of hydrogen infrastructure availability is diminished.[93]

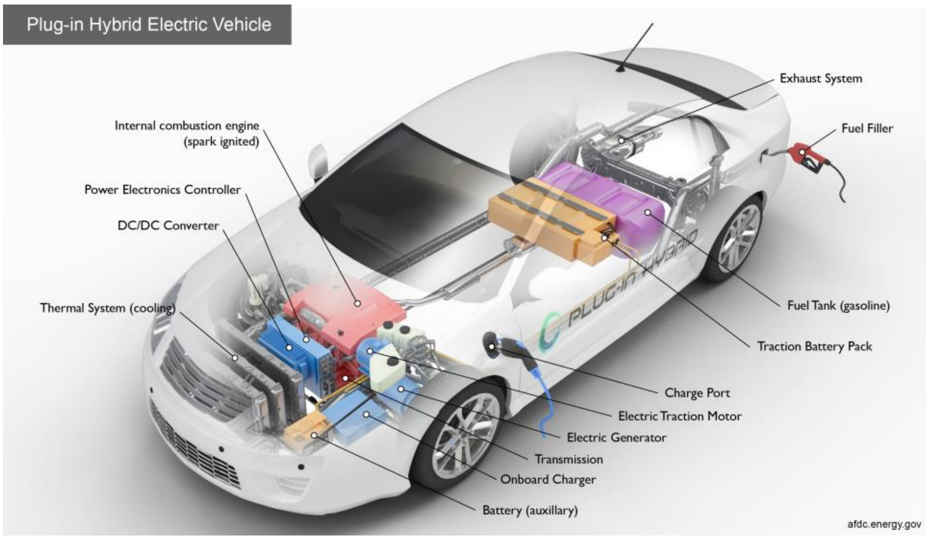


Fig 3.1 Conventional Plug-in Hybrid Electric Vehicle

b) Key Components of a Plug-In Hybrid Fuel Cell Electric Car[94]

- Battery (auxiliary): The auxiliary battery provides necessary electricity to start the car before the traction battery is engaged and powers other vehicle accessories.
- Battery pack: This battery stores energy generated from regenerative braking and provides subsidiary power to the electric traction motor.
- DC/DC converter: This device converts higher-voltage DC power from the traction battery pack to the lower-voltage DC power needed to run vehicle accessories and recharge the auxiliary battery.
- Electric traction motor (FCEV): Using power from the fuel cell and the traction battery pack, this motor drives the vehicle's wheels. Some vehicles use motor generators that perform both the drive and regeneration functions.
- Fuel cell stack: An assembly of individual membrane electrodes that use hydrogen and oxygen to produce electricity.
- Fuel filler: A nozzle from a fuel dispenser attached to the receptacle on the vehicle to fill the tank.
- Fuel tank (hydrogen): Stores hydrogen gas onboard the vehicle until it's needed by the fuel cell.
- Onboard charger: Takes the incoming AC electricity supplied via the charge port and converts it to DC power for charging the traction battery.
- Traction battery pack: Stores electricity for use by the electric traction motor.
- Power electronics controller (FCEV):This unit manages the flow of electrical energy delivered by the fuel cell and the traction battery, controlling the speed of the electric traction motor and the torque it produces.
- Thermal system (cooling) - (FCEV): This system maintains a proper operating temperature range of the fuel cell, electric motor, power electronics, and other components.
- Transmission: The transmission transfers mechanical power from the engine and/or electric traction motor to drive the wheels.

c) Architecture

The PFHCV model incorporates a Polymer Electrolyte Membrane fuel cell(PEMFC) with electric vehicle components to simulate zero emissions vehicles.

The Plug-in Hybrid hydrogen fuel cell model differs from the ICE parallel vehicle models because it is an electric drive vehicle and with incorporated fuel cell . This model utilizes the same motor and battery presented in the previous section, with identical scaling.[93]

The fuel cell is modeled through a static system polarization curve with a maximum efficiency of 60% at 0.1A/cm2 and maximum power at 0.7A/cm2 [95]

The DC-DC converter is modeled with an efficiency of 90%. In the BEV, the fuel cell and DC/DC converter are disconnected from the PFCV system, allowing for battery-only operation.

The fuel cell can be turned on through two mechanisms:

1) A power request which occurs when the battery is not capable of satisfy the power demand, or

2) An energy demand which happens when the battery state of charge must be increased. When the fuel cell is on, its power demand is calculated by adding vehicle power demand and the battery SOC correction factor demand.[94]

The vehicle models were simulated on a combination of drive cycles which include the Supplemental FTP (US06 divided into city and highway segments), Urban Dynamometer Driving Schedule (FU505), and Highway Fuel Economy Driving Schedule (HWFET)[94]

d) Design space

Experiments were performed on the PHEV, PFCV and BEV design spaces. Vehicle designs are characterized by three design variables :

- Total Vehicle Power (Kw),
- Battery Energy Capacity (Kwh) And
- Degree of Hybridization.

For a parallel architecture vehicle, similar to the modeled PHEVs, the total tractive power is the sum of the electrical and mechanical drivetrain powers.

For electric drive vehicles, like the PFCV model, the total tractive power is the electric motor power rating. A vehicle with Degree of Hybridization(DOH) of one represents an electric vehicle while a DOH of zero represents a conventional vehicle.[93]

Degree of Hybridization can be evaluated by

$$DOH = \frac{POWER\ total\ - POWER\ fuel\ capacitor}{POWER\ total} \qquad ....(1)$$

From these design variables and sizing rules all drivetrain component sizes are defined.

Table 3.1: Ranges of design variables investigated for each of the vehicle architectures simulated.

Property	**PFCV**	**BEV**	**PHEV**
Battery energy(kwh)	5-30	15-45	5-30
Degree of hybridization	0.2-0.9	1	0.2-0.9
Vehicle power(kw)	80-180	80-180	80-180

e) Analysis

Analysis metrics focus on the economic, environmental and consumer assessment on the factors like Performance, Fueling cost and greenhouse gas emissions.

f) Fueling costs.

Hydrogen long-term costs are estimated from DOE targets the long-term scenario assumes that the costs of gasoline, electricity and hydrogen evolve over a period of approximately 10 years.[96]

Gasoline fuel prices increase under the impact of resource competition. electricity prices remain stable due to embedded capacity and the continues availability of off-peak power for battery charging;[93]

Table 3.2: fueling cost analysis conversion metrics

	Gasoline ($/kWh)	**Electricity ($/kWh)**	**Hydrogen ($/kWh)**
Near term (2012)	0.093	0.113	0.266
Long term (2020)	0.107	0.111	0.089

g) Green House Gas emissions

Calculating the WTW GHG emissions from the PFCEVs requires the emissions from BEVs and FCEVs to represent the two driving modes of the PFCEV. The fraction of miles that are driven in each of these two modes is also required. The fraction of miles driven using the battery is designated as the “utility factor”. [97]

Reducing GHG emissions is one of the main reasons for alternative vehicles. Upstream Hydrogen GHG emissions assume 100% natural gas (NG) reformed hydrogen. Downstream GHGs are evaluated from the carbon content of the fuel.[93]

For the CA study, BEVs gives the lowest WTW GHG emissions across all design variables. PFCVs offer slight improvements over BEVs and PHEVs. WTW GHG based vehicle designs as hydrogen is supported by CO2 intensive electricity generation. Increased use of hydrogen is preferable over electricity for low DOH and low energy capacity PFCVs.[93]

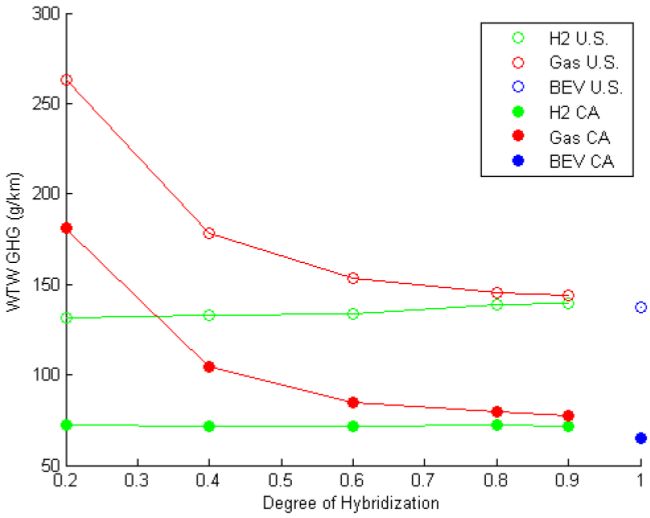


Fig 3.2 Pareto-optimal vehicles for U.S. and CA GHG emissions, by degree of hybridization.

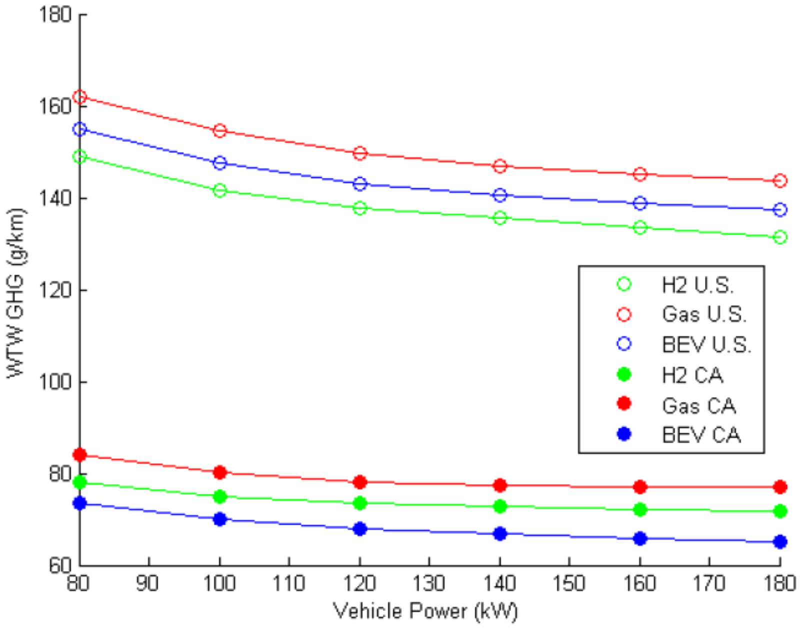


Fig 3. 3 Pareto-optimal vehicles for U.S. and CA GHG emissions, by total vehicle power.

3.1.2 Performance of PFCEV

Performance of each vehicle is evaluated using a power to weight ratio (P/W). Vehicles with high power to weight ratio will have high performance while low performance vehicles have a low ratio.[93]

3.1.3 Plug-in fuel cell vehicle: FASTSim model

The National Renewable Energy Laboratory's FASTSim vehicle simulator was used to Design and evaluate the performance and fuel economy of the PFCEV.[98]
The configuration of the Chevrolet Volt in FASTSim was first modified to resemble a PFCEV. Sequentially, the fuel converter efficiency profile was modified to match the current FCEVs, with a maximum efficiency of 62%.[99]
The Chevrolet Volt was used as the reference for the PFCEV in FASTSim since this research addresses a mid-sized sedan targeted at the general passenger vehicle market.

a) Performance and process analysis calculations

To calculate the electricity and hydrogen that would be used by PFCEVs. Some of the individual trips were modified to account for the Battery Electric Range(BER) of the PFCEV.
Assuming that level 2 electric vehicle chargers are widely available in the next decade, vehicles making multiple trips in a row will deplete their BER and start to use hydrogen until they recharge at home or at work. Based on a charge time for level 2 charging provided by Tesla, a charging time of 81 minutes was specified for the 40-mile BER.[98]
To calculate and compare the fuel used by FCEVs and BEVs, a similar analysis was used. The same trips from the 2009 NHTS data were used, but this time hydrogen was used for all FCEV trips and electricity was used for all BEV trips. Average efficiencies for BEVs and FCEVs were gathered from prior research and actual vehicle testing[99]

Table 3.3 Specifications of Plug-in fuel cell vehicle.

Battery storage (kWh)	**Hydrogen storage (kg)**	**Battery power (kW)**	**Fuel cell power (kW)**	**Electric motor power (kW)**	**Vehicle mass (kg)**
13	4	112	75	112	1665

For both BEVs and FCEVs, the electricity and hydrogen use, respectively, were calculated using the total number of CA passenger vehicle miles and the average efficiency of BEVs and FCEVs. Taking the emissions from BEVs using the California electric grid and the emissions from FCEVs using 33% renewable hydrogen and weighing the emissions by the fraction of miles that are driven using the battery and the fuel cell, the total WTW GHG emissions of PFCEVs. FASTSim provided information on the fuel use and efficiency of the PFCEV[5]

Table 3.4. PFCEV performance results from FASTSim

Charge sustaining efficiency (MPGGE)	**Charge depleting efficiency (kWh/mi)**	**Average electric efficiency (kWh/mi)**	**Charge depleting range (mi)**	**Total range (mi)**	**0-60 mph time (s)**
82	0.322	0.203	42.3	341	6.1

Fuel use results obtained by using FASTSim and NHTS data are displayed in Table 4. These were calculated by using the efficiency results from FASTSim and applying them to the vehicle trip data from NHTS[97]

Table 3.5 Fuel use for advanced alternative vehicle type

	Electricity use (MWh/yr)	**Hydrogen use (kg/yr)**
BEV	$7.9 \times 1O^{7}$	0
FCEV	0	4.1×10^{9}
PFCEV	5.6×10^{7}	6.8×10^{8}

Table 3.6 Mass of PFCEV Calculation[100-103]

Part added	**Part removed**	**Mass change(kg)**
Volt		1715
	ICE	-136
Fuel cell stack		57
Fuel cell balance of plant		57
New battery		92.4
	Old battery	-198.1
Compressed hydrogen tank		87.5
	Gasoline tank	-10
	Total mass	1664.7

Mass of fuel cell balance of plant is estimated as the same as the mass of the fuel cell stack itself. Mass of the PHEV transmission is assumed equal to the increased mass of electronic controllers for the PFCEV, and therefore these are both neglected in the above calculation.

3.1.4 Working example of PLUG-IN FUEL CELL Vehicle

Fig 3.4 Mercedes GLC FCV

The Mercedes-Benz GLC F-CELL is a plug-in hybrid that can run on electricity +pure hydrogen. The sport utility vehicle(SUV) is an all-electric vehicle suitable for daily use which does not emit CO2 emissions during operation.[104]

Provisional combined hydrogen consumption: 0.34 kg/100 km, combined CO2 emissions: 0 g/km combined electrical consumption: 13.7 kWh/100 km.

Fig 3.5 Engine of Mercedes GLC FCV

Four operating modes

- HYBRID: the vehicle draws power from both energy sources. Power peaks are handled by the battery, while the fuel cell runs in the optimum efficiency range.
- F-CELL: the state of charge of the high-voltage battery is kept constant by the energy from the fuel cell. Only hydrogen is consumed. This mode is ideal for steady cruising over long distances.
- BATTERY: the GLC F-CELL runs all-electrically and is powered by the high-voltage battery. The fuel cell system is not in operation. This is the ideal mode for short distances.
- CHARGE: charging the high-voltage battery has priority, for example in order to recharge the battery for the maximum overall range prior to refueling with hydrogen or to create power reserves.[104]

Energy source

World first one in which a fuel-cell-operated electric car uses a lithium-ion battery as an additional energy source that can be externally charged by means of plug-in Hybrid technology. the two energy sources drive the electric motor while offering local zero emissions driving pleasure. The long range, short refueling time, an output of 155 kW.[104]

The lithium-ion battery in the GLC F-CELL has a capacity of 13.5 kWh and serves as an additional energy source for the electric motor. Offers maximum efficiency and comfort, with the fuel-cell/battery system. if the full capacity is used, the charging time from 10 up to 100% is around 1.5 hours[104]

3.2 Fuel cell Hybrid Electric Vehicles

The Fuel Cell System in the car consists of four main subsystems, namely: the fuel supply, the air supply, a cooling system and the fuel cell stack. During operation, the fuel cell produces water and heat as well as electricity. Water is an important product and is used to humidify one, or both, of the gas streams to the cell. The electrolyte membrane must be humidified to a controlled extent to ensure its optimum functioning. Too much humidity would cause water to condense and block the reactant flows, whereas too little humidity would result in the membrane drying out and the proton conductivity becoming inadequate. Fuel cell performance is also likely to be degraded should water at critical locations within the system freeze during operation. Prevention of such an occurrence is challenging because the amount of heat lost to the ambient environment i.e. −30 °C can exceed the amount of heat that is produced when operating at low loads.[104.a]

Fuel Cell Hybrids offer three principal advantages, as follows

(i) The fuel cell system itself produces no carbon dioxide or other harmful emissions such as nitrogen oxides, carbon monoxide or particulate matter
(ii) The fuel cell system offers the potential for around 30% higher energy efficiency. The energy content of 1 US gallon of gasoline (2.76 kg) and 1 kg of hydrogen are similar at 120 MJ, but an FCV achieves around double the km (miles) per kg hydrogen compared with the km (miles) per gallon of gasoline achieved by a standard internal-combustion engine. On the other hand, pressurized gas cylinders occupy a far greater volume than a gasoline tank and it is this volume factor that is likely to determine how much hydrogen can be carried and, consequently, the vehicle range
(iii) The Hydrogen fuel that is consumed can be produced from a variety of renewable sources, including carbon-free methods such as the electrolysis of water.[104.a]

The hybrid fuel cell vehicle also offers three advantages in comparison with BEVs, as follows:
(i) Vehicle fully charged (with hydrogen) has a greater driving range than BEVs with existing battery technology.
(ii) Refueling is very much faster and thereby enables brief maintenance stops during long journeys compared with battery recharging, which may take hours[104.a]
(iii) In cold weather, the fuel cell can be warmed up more rapidly than can a battery and thus can produce full power in a shorter period of time.
Many major automobile manufacturers have active FCV programmes but, till date most have produced only small numbers of vehicles.

Commercially available fuel cell cars for sale and leasing are

- 2008–2015 : Honda FCX clarity
- 2015–2020 : Toyota Mirai
- 2016–2021 : Honda Clarity Fuel cell
- 2018 : Hyundai Nexo
- 2020 : Toyota Mirai II

Let’s discuss in detail the some of these vehicles which are successfully emerged in the Automobile market

3.2.1 Hyundai Nexo

The South Korean automaker Hyundai launched the Nexo in 2018, 20 years after its first fuel-cell concept car. a fuel-cell-powered CUV with a 500-mile (800-km) range.
Hyundai developed a series of Fuel cell prototypes from the Santa Fe FCV in 200 to first generation TUCSON in 2007. Hyundai launched the Nexo in South Korea in March 2018 with a first-year sales target of 200-300 units. In 2019, it hopes to sell about 3,000 units following the launch of the vehicle in Europe and the U.S.
In 2013 Hyundai launched the Hyundai ix35, a hybrid fuel cell electric vehicle (VEHCC) that had its design adapted to that of its combustion version. This model was produced until 2017, until in 2018 Hyundai launched the Nexo as its successor. The Nexo was not an adaptation of a previous vehicle design, but the result of an innovative project.
Nexo is available for sale and lease in California (USA), some countries in Europe, Japan and South Korea. Due to the high cost of acquisition and high cost of hydrogen, the US government offers a $ 7,500 incentive to purchase Nexus and the California government offers $ 5,000. Hyundai offers $ 13,000 to purchase fuel or 3 years of free fuel.

Fig 3.6 Hyundai Nexo

Table 3.7 Specifications of Hyundai Nexo

Electric Driving Motor	**Type**	**Permanent Magnet Synchronous Motor**
	Max. Output (kW)	113
	Max. Torque (Nm)	395
Reduction Gear	Gear Ratio	7.981
Inverter	Input Voltage (V)	240~450V
Bidirectional High Voltage DC-TO-DC Converter	Input Voltage (V)	160~275.2V
Output Voltage (V)	250~450V	
Low Voltage DC-To-DC Converter	Input Voltage (V)	250~450V
Output Voltage (V)	12.8~13.9V	
Hydrogen Fuel Tank	Capacity (L)	156.6
Stack	Max. Output (kW)	95
	Output Voltage (V)	250~450V
Battery	Type	Li-ion polymer
	Rated Voltage (V)	240
	Capacity (Ah) / Energy (kwh)	6.5 / 1.56
	Weight (kg)	51.2

1) Vehicle Components Location

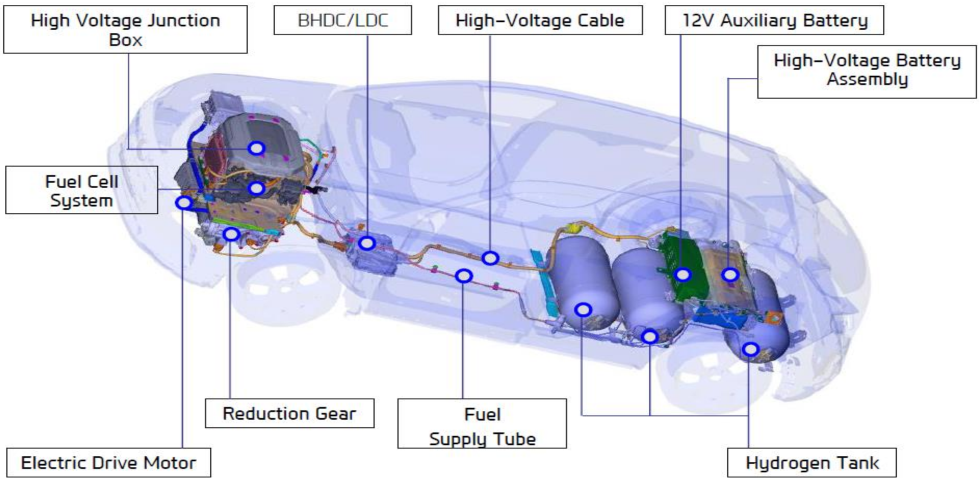


Fig 3.6 Components of Hyundai Nexo

1. Battery

The Hyundai Nexo uses a Lithium Ion battery bank, with 40 kW of Power, 1.56 kWh of Energy and Voltage of 240 V.

Table 3.8 summarizes the actual values previously described and estimated values of the battery:

Type	Lithium Ion
Voltage (V)	240
Voltage per cell (V)	3.75
Cells	64
Capacity [Ah]	6.5
Mass [kg]	33
Energy [kWh]	1.56
Cell energy density [Wh / cell]	24.4
Power [kW]	40.0
Cell power density [W / cell]	625

2. Fuel Cell and Tank System

The Fuel cell system is composed of

1. Fuel cell which generates electric energy through an electro-chemical reaction between the hydrogen and oxygen,
2. Hydrogen supply system which provides the hydrogen (fuel),
3. Heat control system which controls the heat and
4. Air supply system which provides oxygen. The electricity generated by the fuel cell system powers the high-voltage battery and the electric motor and makes the vehicle move.

Nexo uses a polymeric electrolyte membrane fuel cell(PEMFC) with 95 kW of power, the fuel cell system is manufactured by Hyundai itself, has a mass of 89 kg and a maximum efficiency of 60%. The time for the fuel cell to reach maximum power, 5s.[107]

Table 3.9 summarizes the actual and estimated values of the fuel cell and tank system

Type	PEMFC
Power [kW]	95
Time to reach maximum power [s]	5
Mass of the fuel cell system[kg]	89
Maximum Efficiency	60%
Tank capacity [L]	156.6
Tank Capacity [kg]	6.3
Mass of the tank [kg]	112
Hydrogen mass [kg]	6.3
Pressure [MPa]	70
Hydrogen density [g / L]	40.2

3. Fuel cell stack

Hydrogen electric vehicles, not like regular internal combustion engine vehicles, utilize high voltage electrical energy generated as a power source in the fuel cell stack. Because of high voltage electricity, the vehicle requires cautious handling which results in great voltage hazard. [107]

The following items are safety guidelines of the high voltage in the fuel cell stack of NEXO.
1) A metal chassis and electro-conductive enclosure is situated in the fuel cell stack to forestall an electrical shock because of the direct or indirect contact of users.
2) Live parts and high voltage buses, generating over 400V DC in the fuel cell stack, are intended to maintain a reliable insulation resistance with an electro-conductive enclosure. When the insulation resistance is lower than a predefined value, the user is informed , and the output current of fuel cell stack is limited.[107]

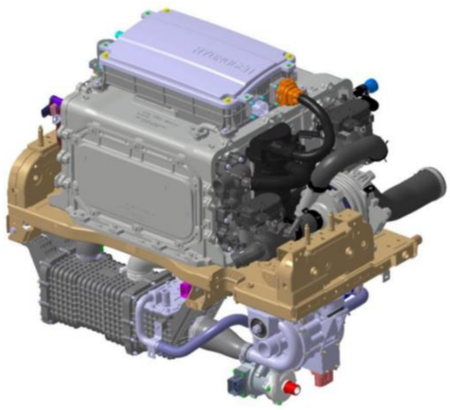


Fig 3.7 Fuel cell stack

4. High Voltage battery system

This system supplies the energy which is applied during vehicle acceleration. The system is additionally used to store the energy produced during regeneration braking.
The high voltage system is located in trunk region and is protected with a steel case. The system comprises of 64 cells. Each cell is sealed with an aluminium case to protect against an electrolyte spillage. [107]
an over-current protection and ceramic coating isolation layer are used for safety. Non-flammable electrolyte material is used to prevent explosions or fire in an emergency case such as a car accident. High voltage cables (orange colour) connect the battery system to the DC converter.

There is a high voltage regulator used to control the high voltage line. In addition, a high voltage fuse and a safety plug are used to separate the electrical sources in the system for safety.[107]

i) 12V Auxiliary Battery

The 12V Lithium-ion polymer auxiliary battery is situated in front of the high-voltage battery in the trunk. This battery supplies power to all the standard electric devices such as the audio. Also, the battery supplies power to the control unit which controls the flow of the supply of hydrogen and high-voltage current .

ii) High-Voltage (HV) Battery

The Lithium-ion Polymer High Voltage battery contains a gel electrolyte and is made up of 64 cells with 3.75V each cell , wired in series for a nominal voltage of 240V with 6.5 Ah of capacity.

iii) Motor Control Unit

The inverter coverts the direct current of the high-voltage battery to alternative current and supplies it to the driving motor. Also, the inverter converts the alternative current of the regenerative braking to the direct current to recharge the high-voltage battery. The inverter is equipped with a Motor Control Unit (MCU) to control the motor torque.[107]

iv) Electric Drive Motor

Electric motor is mounted in fuel cell power module compartment with the gear reduction unit, the Electric Drive Motor is used for vehicle propulsion. During deceleration or braking, it acts as an alternator and charges the high-voltage battery by converting the vehicle's kinetic energy into electrical energy.[107]

v) Gear Reduction Unit

The Gear Reduction Unit increases motor torque and transfers it to the wheels, with a maximum torque output

2. Fuel cell and battery bank control strategy

The battery bank is used in Charge sustaining (CS) mode, with a maximum charge state (SOC_{max}) of 0.8 and a minimum charge state (SOC_{min}) of 0.4. The fuel cell is only used when a 50% efficiency for fuel economy is reached. Table 3.10 summarizes the control strategy adopted for the Hyundai Nexo.

Table 3.10 - Control strategy for the Hyundai Nexo

Operation mode	**Charge Sustaining**
SOCmax	0.8
SOCmin	0.4
Minimum efficiency for cell activation	50%

Table 3.11 The values of SOCmax and SOCmin were taken from the FASTSim database.

Name	**Value**	**Unit**
	Fuel cell	
Type	PEFC	-
Wattage	95	kW
	Battery	
Type	Lithium Ion	-
Wattage	40	kW
Capacity	1.56	kWh
Voltage	240	V
Stacking mass	89	kg
	Motor	
Type	Permanent magnet motor	-
Maximum power	120	kW
Maximum	395	Nm

torque		
Tank		
Fuel	Compressed gaseous hydrogen	-
Capacity	156.6	L
Pressure	700	Pub
Vehicle features		
Drag coefficient	0.329	-
Length	4670	mm
Width	1860	mm
Height	1630	mm
Length between the axis	2790	mm
Pasta	1873	kg
Traction	Forward	-
Streaming	Automatic	-
Front area	2.52	m^2
Tire radius	0.351	m
Performance		
Maximum speed	179	km / h
Acceleration 0-100 km / h	9.2	s
Acceleration 80-120 km/h	7.4	s
CO2 Emission	0	g / km

\

1 Commercial Value in the market

Hyundai Motor Company Prior to retail sales commencing, the NEXO had been met with wide public interest, with a total of 1,061 vehicles being ordered throughout the pre-order period between March 19-26, 2018. Just on the first day of pre-order availability, NEXO recorded order of 733 vehicles. [108]

“We are witnessing a historic day as fuel cell technology is being commercialized in large quantities. With this positive beginning, we will continue our efforts in overseas markets to support fostering the newly developing fuel cell vehicle market”, said Byung Kwon Rhim, Executive Vice President of Hyundai Motor Company in charge of Global Operations Division. [108]

Hyundai Motor also introduced new measures to encourage the further spread of fuel cell electric vehicles. Hyundai announced a 10-year, 160,000km warranty for fuel cell components to reassure customers of the durability and reliability of fuel cell electric vehicles sold in Korea.[109] Furthermore, Hyundai announced it has secured personnel and equipment to service NEXO vehicles in all its 22 service networks in Korea.

Hyundai claims the Nexo has an industry-leading 30-second cold-start capability.[110] Other improvements to its 2nd-gen system reduce refueling times, and a more efficient air-supply system improves performance at higher altitudes. Side benefits are the stack’s ability to filter particulate matter and fine dust – essentially cleaning the atmosphere as you drive – and potential future applications where a docked vehicle could provide both electricity and water to a home.[109]

3.2.2 Honda Fcx Clarity Fuel Cell Vehicle

History and Evolution of Honda's FCV Development

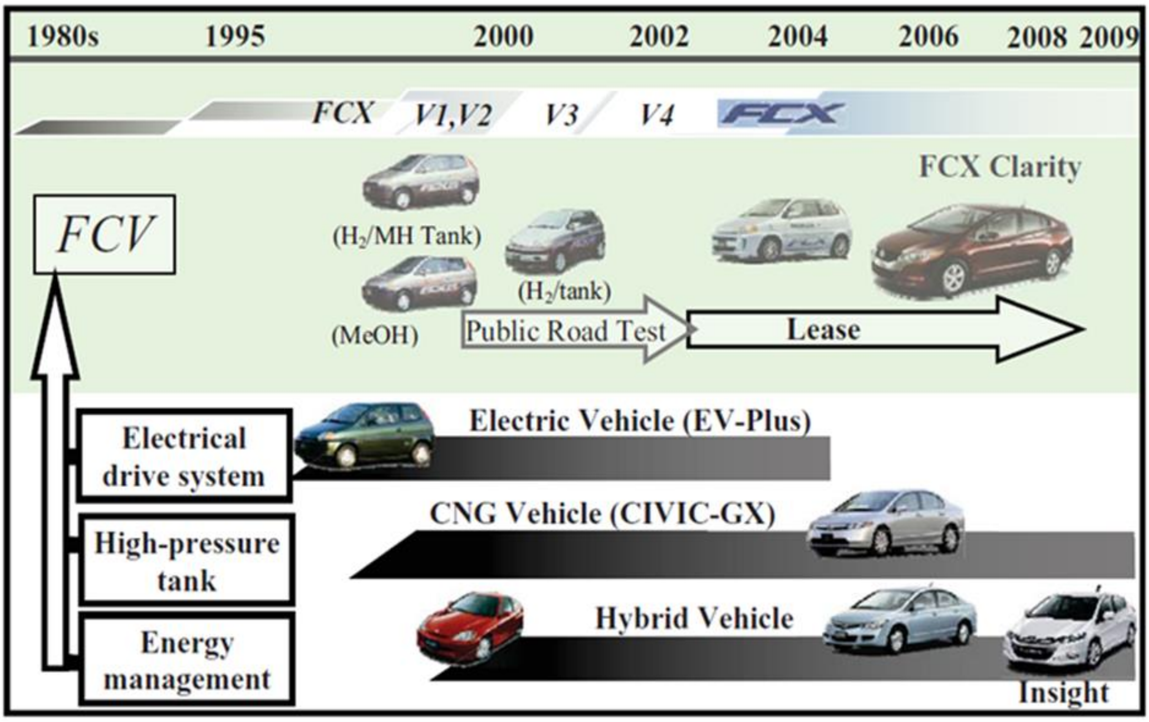


Figure.3.8 history of Honda FCX

Honda became the company which delivers the first fuel cell vehicles to its clients in USA and Japan. Its pursuing the Fuel cell technologies for R&D since the mid of the 1980s.

In 2002, Honda became the first company to deliver the fuel cells to the clients of Japan and united states. The Honda FCX clarity, Honda next generation fuel cell vehicle first cell vehicle was first leased to customers in july 2008.

Fig 3.9 Honda FCX clarity fuel cell

Table 3.12 Specifications of Honda FCX Clarity Fuel Cell Vehicle

	Name	**FCX Clarity**
VEHICLE	Overall length (mm)	4835
	Overall width(mm)	1845
	Overall height(mm)	1470
	Wheelbase(mm)	2800
	Vehicle weight(kg)	1625
	Number of occupants	4
PERFORMANCE	Max. Speed (km/h)	160
	Vehicle range(miles)	280

MOTOR	Type	AC Synchronous (Permanent magnet)
	Max. output (Kw)	100
	Max. torque (Nm)	256
FUEL CELL	Type	PEMFC
	Max. output(KW)	100
POWER ASSIST	Type	Li-ion battery
FUEL	Type	Compressed hydrogen gas
	Storage	High-pressure hydrogen tank
	Tank capacity (L)	171
	Max. pressure when full(MPA)	35
	Refueling time(min)	3-4

1. Powertrain System

Comprises of

1) Electric drive system
2) Fuel cell system
3) Lithium-ion battery
4) High pressure hydrogen supply system.

- The components which are dispersed throughout the vehicle are necessary to generate electricity. The maximum advantage of the layout comes through each components reduced size.

- Initially with the FC stack, each component which are reduced in size results in the achievement of the weight output density 2 times greater than previous model.
- High power is produced by the fuel cell stack.
- Power assist provided by the Li-ion battery.
- Motor torque is continuous.

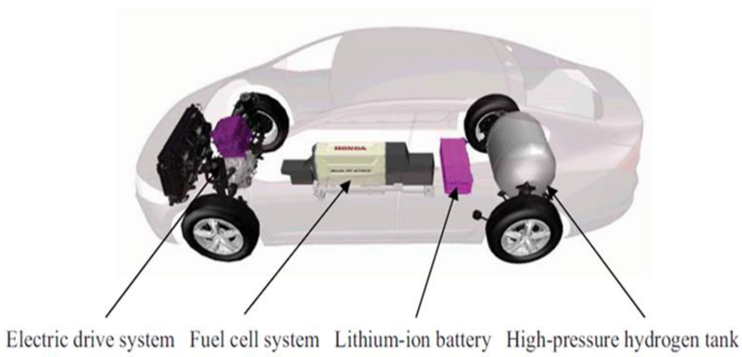


Figure 3.10 Powertrain layout of FCX Clarity

2. Electric drive system

- this includes drive motor, reduction box, and Power Drive Unit(PDU) which was developed in order to realize powerful acceleration and increased maximum speed.
- In addition, a coaxial configuration has been used for the drive motor and reduction box and the motor has been integrated with the PDU[112]

3. Fuel cell system

- The type of fuel cell stack used is in the form of V shaped flow structure in the new structure used in the V Flow FC stack, hydrogen and air flow vertically.
- This increases the ability of the system to drain the water produced during generation from the generating surfaces, resulting in the achievement of greater stability in power generation.
- The increased ability of the system to drain the water allowed the height of the flow channels to be decreased by 17%. This has reduced the weight and volume of the V Flow FC stack.[112]

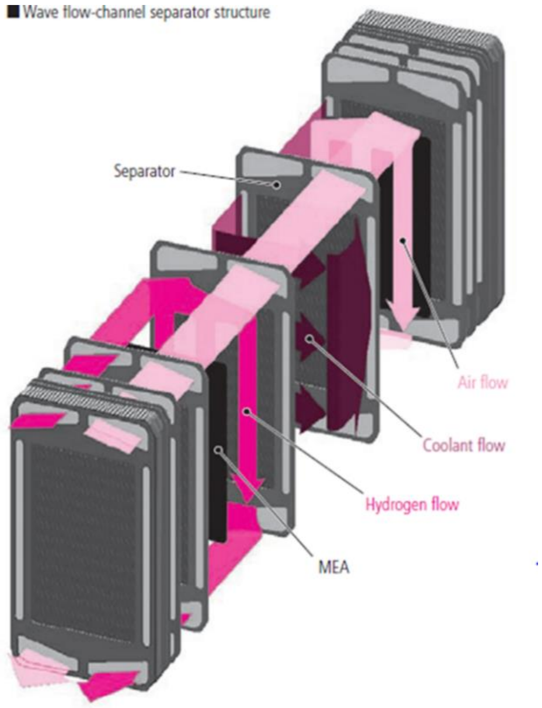


Figure.3.11 fuel cell system Of Honda FCX

4. Flow Of Hydrogen

The V Flow FC stack incorporated with coolant to the electrical generation layers. The coolant flows horizontally, across the vertical flow of the hydrogen and air.

Electrical generation layers achieve uniform cooling by this method contributed to reduction of amount of cooling layers needed for each cell.

the internal structure of the stack has made possible to replace the previous two-box configuration by a single box. As a result, the size and weight of the stack have been reduced significantly against the previous stack.[112]

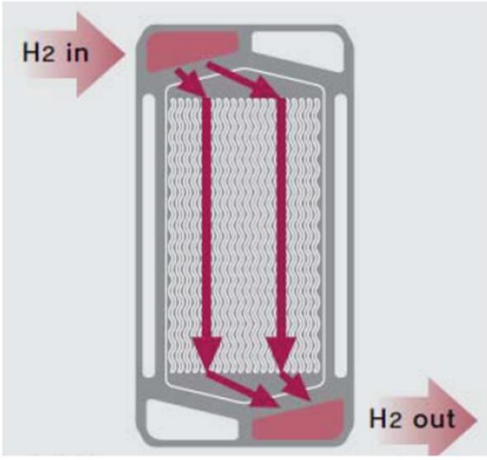


Figure. 3.12 Hydrogen flow

5. PERFORMANCE

- At a maximum power of 100 kW, the volume-power density of the new fuel cell stack is 50% higher and its weight-power density 67% higher than the previous stack.
- The conventional two-box Honda FC stack configuration has been concentrated into a one box configuration in the Clarity, enabling the components that connected the stacks to be eliminated. In addition, the use of a one-box configuration has enabled the hydrogen supply system, humidification system, and contactors to be integrated longitudinally, resulting in a 65% reduction in the area of the fuel cell system box against that of the previous model[112]

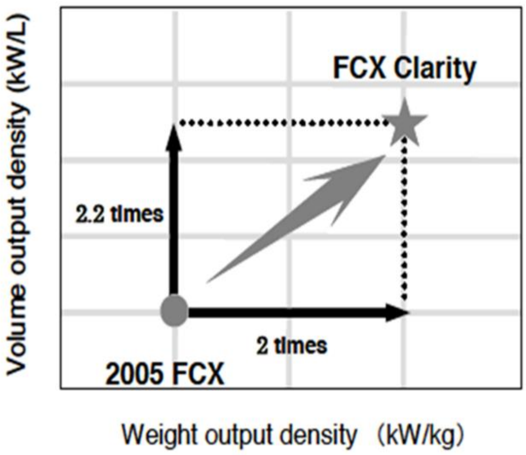


Figure 3.13 Volume /weight output density

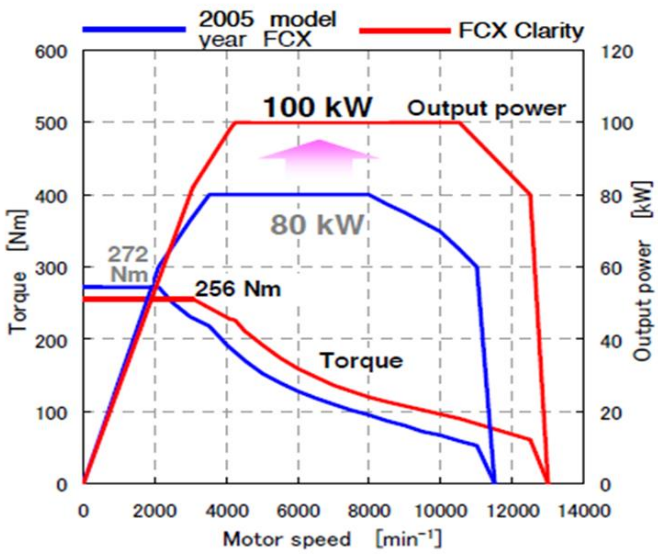


Figure 3.14 Output and torque characteristics

Table 3.13 Comparison of Old vs New FCX

	FCX clarity	Old FCX
Max. output	100 KW	80KW
Max. torque	256 Nm	272 Nm
Max. rpm	12500/min	11000/min
Max. efficiency	90%	90%

6. Battery system : Li-ion battery system

A Lithium-ion battery system is used as the assisting power source in order to improve performance and weight savings.
The use of a hydraulic-regenerative cooperative brake system that controls the allocation of regenerative and hydraulic braking has increased the Clarity's rate of recovery of energy regenerated during braking by 11% against the previous FCX, enabling recovery of 57% of total braking energy.[112]

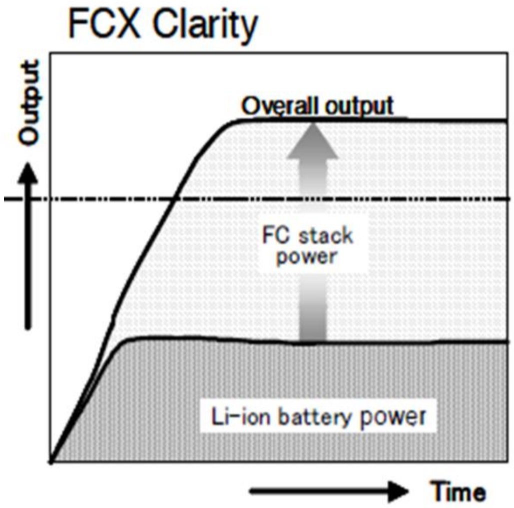


Figure 3.15 Battery performance

- The Li-ion battery system enables assistance to the output of the fuel cell stack at maximum power for an extended period. (Fig. 3.15).
- The use of a side-flow system to cool the batteries and employment of a one-box configuration for both the battery pack and ECU have resulted in a 40% weight and 50% volume reduction in the unit against the ultracapacitor employed in the previous FCX. As a result, it has been possible to fit the Lithium-ion battery system underneath the rear seats.[112]

7. Pressure hydrogen supply system

- One high-pressure hydrogen tank has been used in place of the previous two tanks in order to increase rear seat comfort .the filling and supply system, comprising a cut-off valve, regulator, pressure sensor, and other components, has been redesigned and condensed to be used as an in tank module. This has enabled the number of parts employed in the high-pressure hydrogen supply system to be reduced by 74%. As a result, the volume of the tank has been increased while its space efficiency has been increased by 24%.[112]

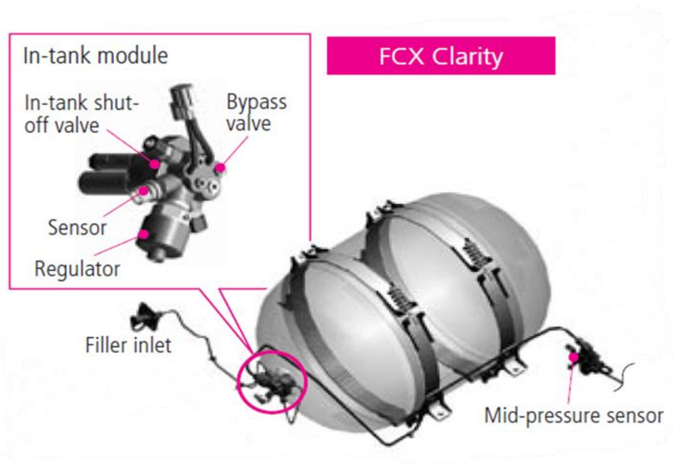


Figure.3.16 Hydrogen supply system.

8. Vehicle performance

Acceleration Performance

- The use of a Lithium-ion battery able to provide power assistance for an extended period in addition to the achievement of increased output from the fuel cell stacks has resulted in total power increase and has enabled the system to maintain a high level of power output for an extended period.[112]
- The newly designed drive motor is able to obtain maximum power output of 100 kW and can maintain this level of output up to high speeds, enabling a high level of drive power to be realized across the entire range of vehicle speeds, from directly after take-off to the high speed range.[112]
- One of the principle features of the electric motor is its ability to provide maximum torque from low speeds, resulting in rapid acceleration pickup. In addition, the motor's ability to supply continuous torque without shifting gears offers uninterrupted and smooth acceleration.
- Take-off acceleration time (0-60 mph, 9.7 sec) has been increased by 34% and passing acceleration time (50-70 mph, 5.9 sec) by 75%.[112]

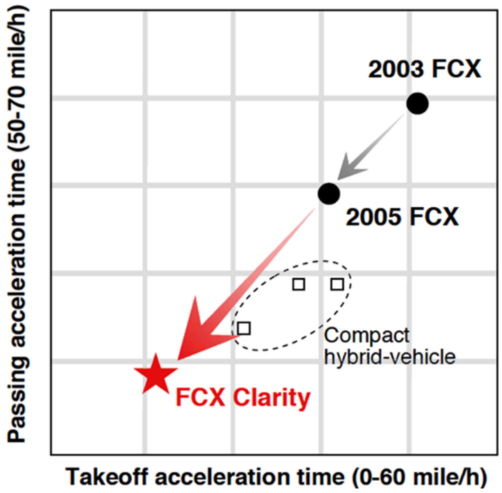


Figure 3.17 .Acceleration performance

9. **Efficiency and Fuel Economy**

Increase in the generating efficiency of FCX Clarity fuel cell system and increase in rate of recovery of regenerated energy achieved through the use of a Li-ion battery and hydraulic regenerative cooperative braking system has increased the rate of regenerative energy results in achievement of an energy efficiency of about 60%.[112]

This increased energy efficiency, the reduction of running resistance, and the achievement of weight savings have enhanced fuel consumption performance in the Clarity by 26% against the previous FCX.

The energy of 1 kg of hydrogen can be regarded as equivalent to the energy of 1 gallon of gasoline. The fuel economy of the FCX Clarity and an equivalently sized compact gasoline vehicle and compact hybrid vehicle was compared.[112]

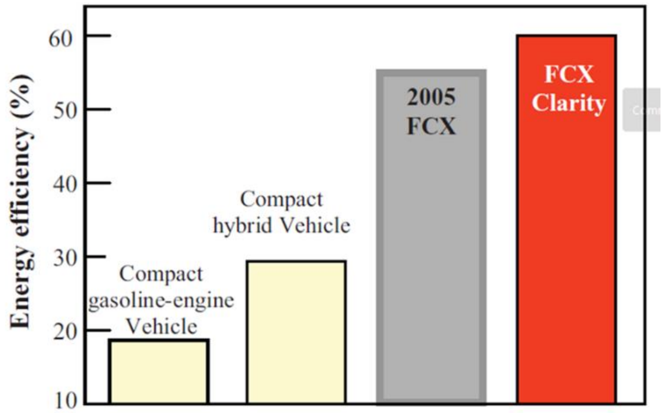


Fig 3.18 Vehicle energy efficiency

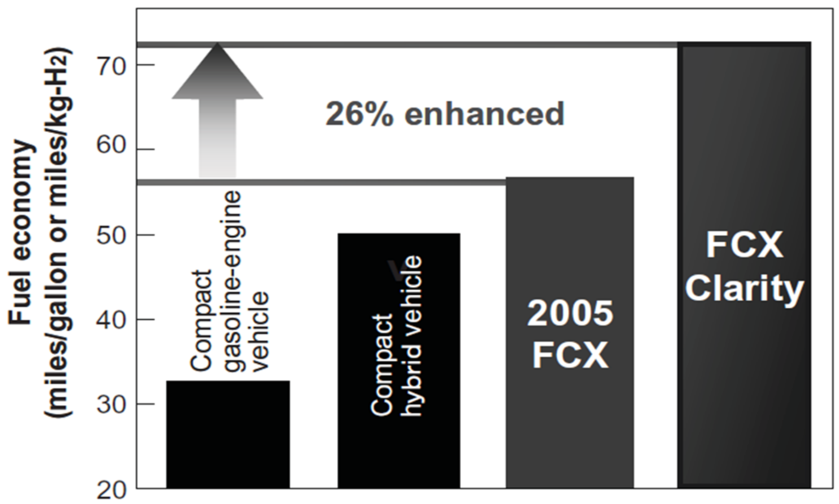


Fig 3.19 Vehicle fuel economy

10. **Vehicle Range and Refuel Time**

- The volume of the vehicle's hydrogen tank has been increased by 14L against the previous FCX, enabling the achievement of a 30% increase in vehicle range to 280 miles.
- The more recent advancement in battery performance achieved by the development of the Li-ion battery to be focused once again on the potential of electric vehicles.[112]

- The results showed that the vehicle's range would increase to approximately 160 miles. The charging time for the assumed electric vehicle is approximately 12 hours in the case of home charge and approximately 1.5 hours in the case of quick charging. Electric vehicles are suited to customers to whom these shortcomings do not make issues. On contrast, vehicle range and refuel time do not represent limitations in the case of the FCX Clarity.[112]
- It is able to refuel with approximately 4 kg of hydrogen in 4 minutes. The vehicle offers a level of convenience equivalent to that of a reciprocating engine vehicle.[112]

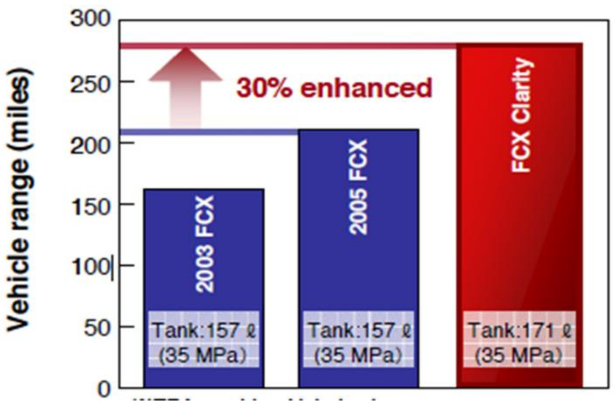


Fig 3.20 Vehicle range

Results

The following results have been achieved [112]

- Reducing the size and weight and increasing the efficiency of each component of the FCX Clarity fuel cell powertrain,
- A low-floor platform has been realized by means of positioning the fuel cell system in the Center tunnel.
- The reduction of the longitudinal length of the electric drive system, the reduction of the size of the fuel cell system and high-pressure hydrogen supply system, and the positioning of the Li-ion battery system under the rear seats have enabled the realization of a spacious full cabin.
- The Clarity has achieved enhanced acceleration performance against the previous model, with a 34% faster take-off acceleration time and 75% faster passing acceleration time.

3.2.3 Toyota Mirai FCV

1) Introduction

Toyota systems developed the first fuel cell system in 1992 and then number of progressive advancements have been integrated to overcome the prominent technical issues of range, durability etc.

Toyota first FCV Mirai was developed to encourage the commercial approach of the FCVs in the market and made available from 2014. The recent advancement and most augmented FCV was released in the 2017.

The MIRAI holds FCHV-advantages with excellent characteristics of zero emissions, enormous cruising range, cold start situation, and short refueling time, with additional enhancements towards calm operation and better acceleration. A power supply is added in case of an emergency. At present, overcoming the cost limitations to carry FCVs to commercial reality is the main objective.

Fig 3.21 Toyota Mirai FCV

2) Toyota Fuel cell system

Toyota Fuel Cell System (TFCS) is the world's first fuel cell system without an external humidifier.

The fuel cell stack control and the control system was refined so that the water formed at the bottom of the cathode was transported to the front of the upper cathode part via internal circulation through the anode.

The characteristic of the fuel cell system used in the tested vehicle is the 3 hydrogen injectors, that operates depending on the load on the system.[114]

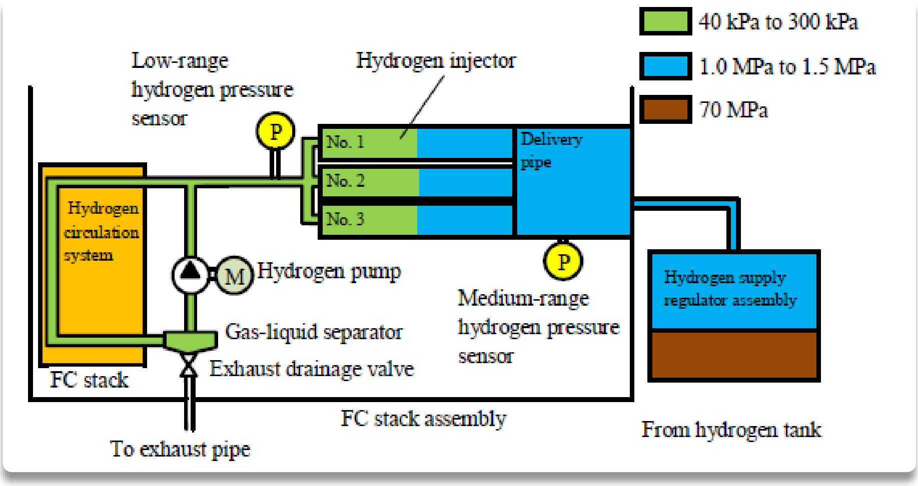
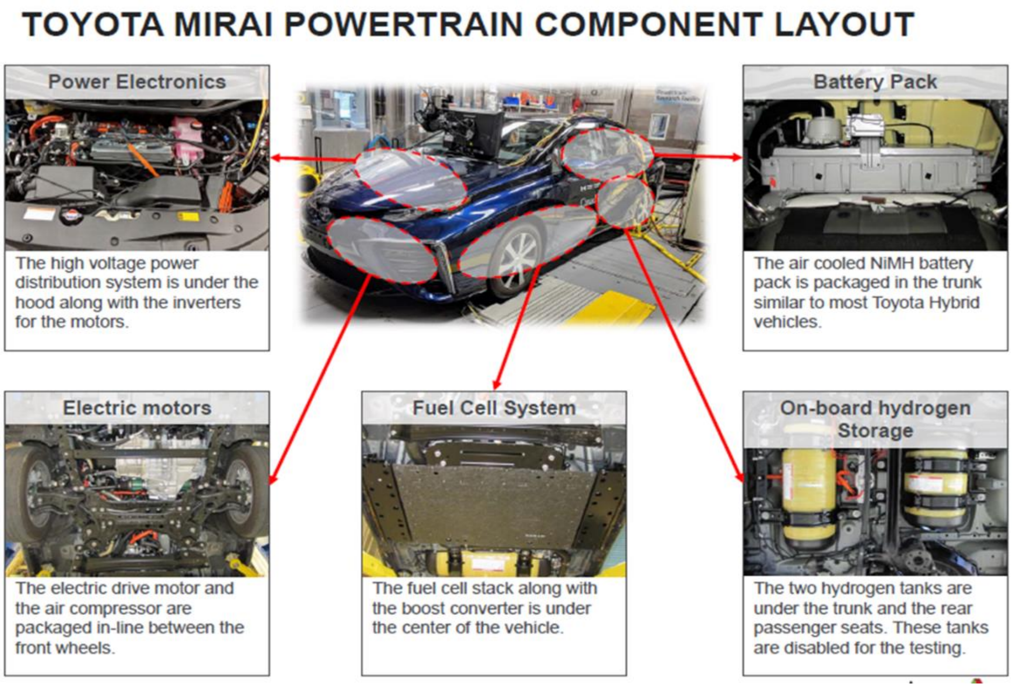


Fig.3.22 The fuel cell power supply system



*Technology Assessment of a Fuel Cell Vehicle: 2017 Toyota Mirai

3) **Power components of the Mirai**

i) **Power control unit**

A mechanism to optimally control both fuel cell stack output under various operational conditions and drive battery charging and discharging.

ii) **Electric Motor**

Motor driven by electricity generated by fuel cell stack and supplied by battery.

- Maximum output: 113 kW
- Maximum torque: 335 N-m

iii) **Battery**

A nickel-metal hydride battery which stores energy recovered from deceleration and assists fuel cell stack output during acceleration.[114]

iv) **Fuel cell stack**

Toyota's first mass-production fuel cell, featuring a compact size and world top level output density.

- Volume power density: 3.1 kW/L
- Maximum output: 114 kW.

4) **High-pressure hydrogen tank**

Tank storing hydrogen as fuel. The nominal working pressure is a high pressure level of70 MPa (700 bar). The compact, lightweight tanks feature world's top level tank storage density.[114]

5) **Fuel cell boost converter**

A compact, high-efficiency, high-capacity converter newly developed to boost fuel cell stack voltage to 650 V. A boost converter is used to obtain an output with a higher voltage than the input.[114]

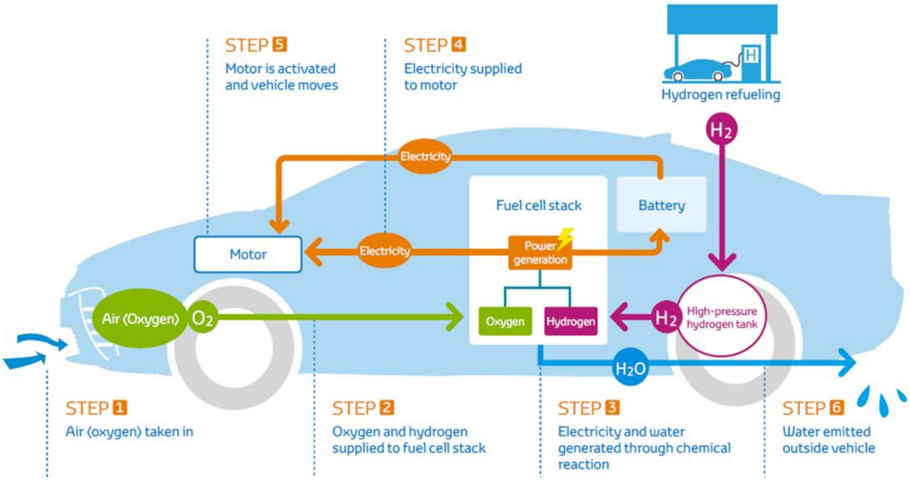


Fig 3.23 Operating Flow diagram

6) Configuration of FC system

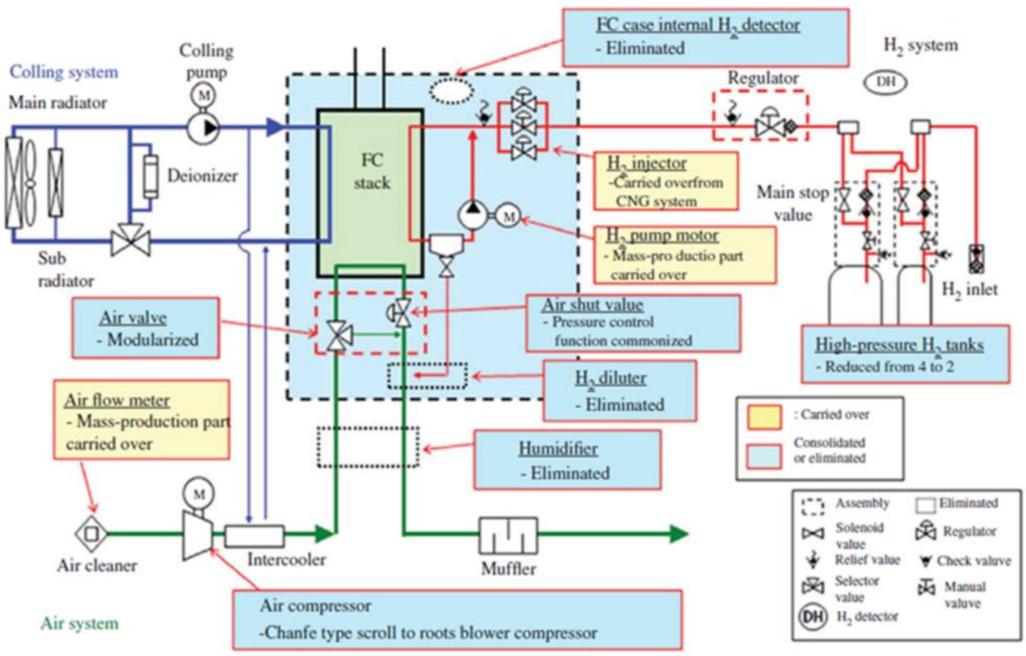


Fig 3.24 *Configuration of Toyota Mirai FC system*

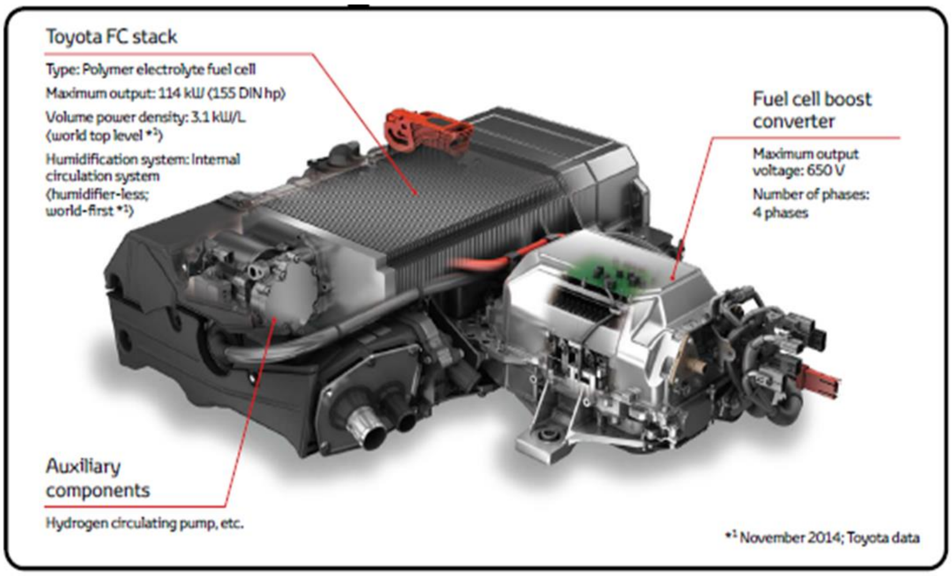
It composed of three subsystems

1. Hydrogen system which supplies hydrogen from the tank to FC system which supplies hydrogen from the tank to FC system which supplies hydrogen from the tank to FC system which supplies hydrogen from the tank to FC stack and recirculates the hydrogen discharge to increase fuel efficiency.[114]
2. Air system that supplies oxygen in the air to the stack.
3. The third one is the cooling system that radiates heat from electricity generation in FC. To further simplify and enhance the reliability of the FC system in Mirai, various modifications were made to the system [114]

7) Fuel cell stack assembly

Toyota fuel cell stack assembly consists of [115]

1. Fuel cell stack
2. Auxiliary components
3. Fuel cell boost converter



Fueling time varies with hydrogen fueling pressure and ambient temperature. *1 Toyota measurement under SAEJ2601 standards (ambient temperature: 20 °C; hydrogen tank pressure when fueled:

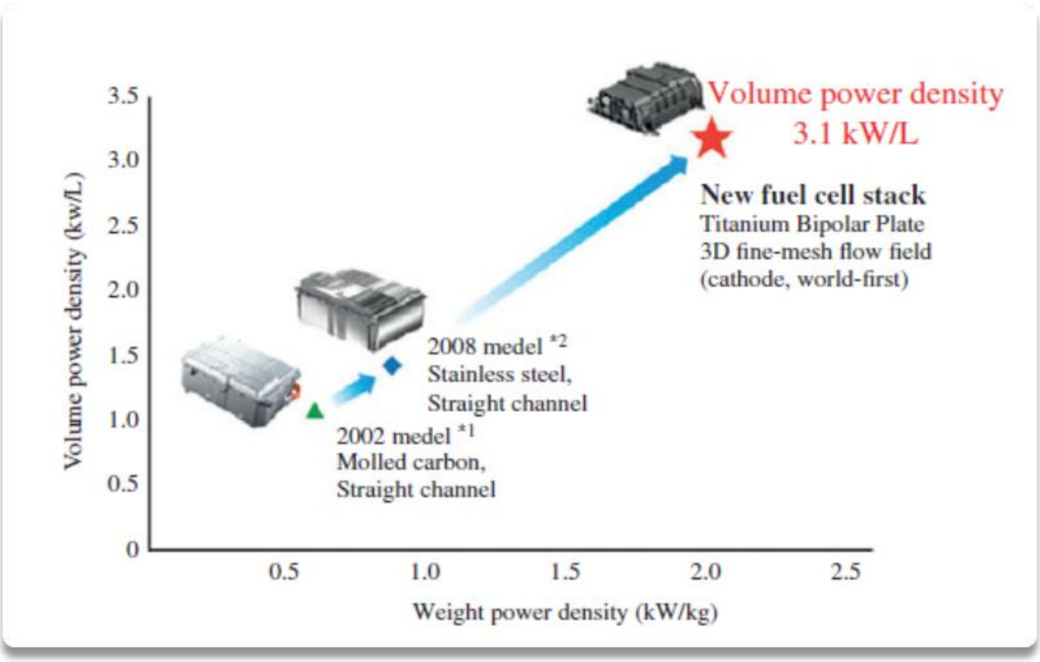
Fig 3.25 Toyota Mirai fuel cell stack

8) Power Density of The FC Stack

The new stack has a volume power density of 3.1 kW/L with increased output density (enhanced performance, more compact sized). The maximum power of the new FC stack was increased by 27% from 90 to 114 kW (36% increase a per cell) . [116]

At the same time, the volume of the cells was reduced by 24% as a result of the higher current density (increased by a factor or 2.4) and the use of thinner cells (thickness reduced by 20%) (Fig. 2.3.5). Furthermore, changing the separator material from stainless to titanium, which has a lower specific gravity, also reduces cell weight by 39%.[114]

Advancements in fuel cell technology have led to the creation of a smaller, lighter new fuel cell stack with enhanced performance. The new stack has a volume power density of 3.1 kW/L – among the world top level *2, and can now be mounted underneath the floor of a sedan



***1 Toyota measurement under SAEJ2601 standards (ambient temperature: 20 °C; hydrogen tank pressure when fueled: 10 MPa).**
***2 2002 model: Toyota FCHV Fueling time varies with hydrogen fueling pressure and ambient temperature.**

Fig. 3.26 Evolution of power density of the FC stack

9) Internal circulation system – Humidifier-less

Self-humidification by circulating water produced from power generation within the cells, eliminating the need for external humidification. This makes it possible to eliminate the humidifier making the system smaller and lighter.[117]

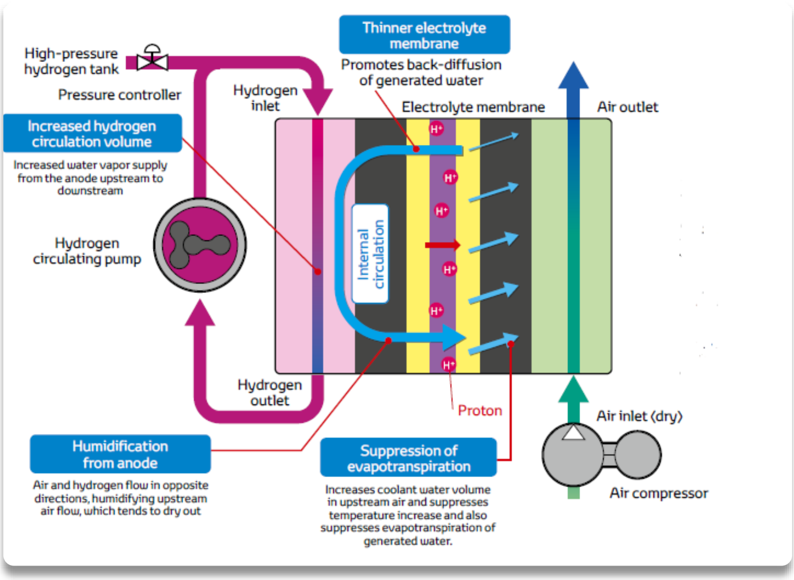


Fig. 3.27 internal circulation humidifier system

10) External circulating humidifier

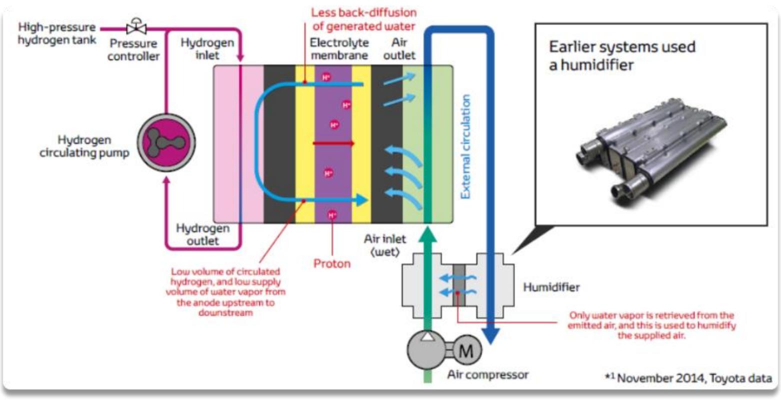


Fig 3.28 external circulation humidifier system

The system humidifies the supplied air (mainly oxygen) using a humidifier to maintain the proton conductivity of the electrolyte membrane.

11) Challenges to external Humidifier-free system.

The humidity of the electrolyte membrane must be controlled to ensure proton conductivity for stable power generation. Stable power output from the FC system is ensured by the innovative Fuelcell components and controls.[117]

In the FC system installed in Mirai, water generated in the FC stack is circulated internally, which allows high-temperature operation without an external humidifier.

External humidifier-free system was achieved by migrating water generated at the cathode to the anode and uniformly distributing the water onto the surface of the anode membrane electrode assembly[117]

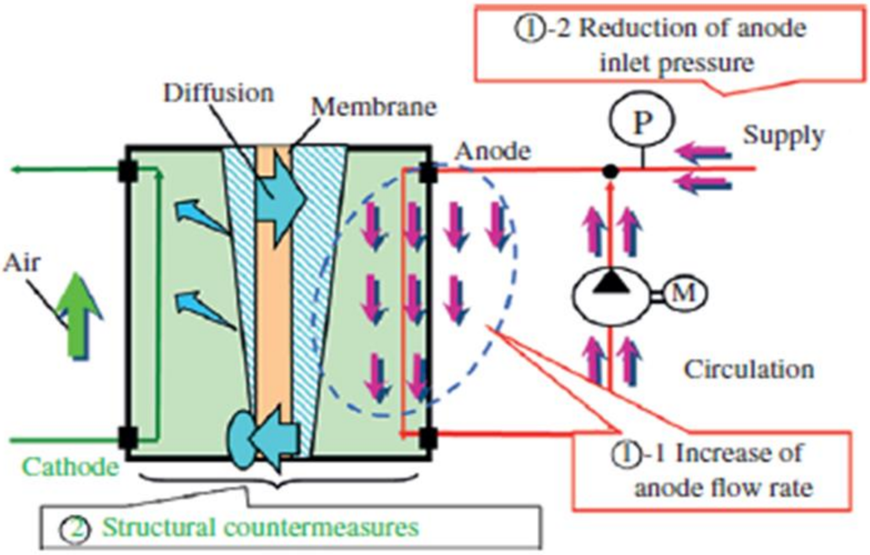


Fig 3.29. Water management by self-humidification

External humidifier free system was achieved by transferring water generated at the cathode to the anode and uniformly distributing the water onto the surface of the anode membrane electrode assembly. Impedance is used to perform precise control of the system in actual vehicle. In addition to this, the control is executed according to the inputs to the FC system such as temperature of the fuelcell stack and the vehicle operating conditions.[117]

In the actual FCV, precise control is performed in consideration of the driving conditions (FC temperature and the like) and the vehicle running state based on the impedance, which expresses the internal state of the FC.[117]

12) Fuel cell boost converter

By incorporating a high-capacity fuel cell boost converter, it was possible to increase the voltage of the motor, reduce the number of fuel cell stack cells, and reduce the size and weight of the system. Also innovations to the voltage-boost control and case structure provide exceptionally quiet operation.

In addition to the new system can be used with existing hybrid units, enhancing reliability and greatly reducing costs[117]

Fig 3.30 Fuel cell boost converter

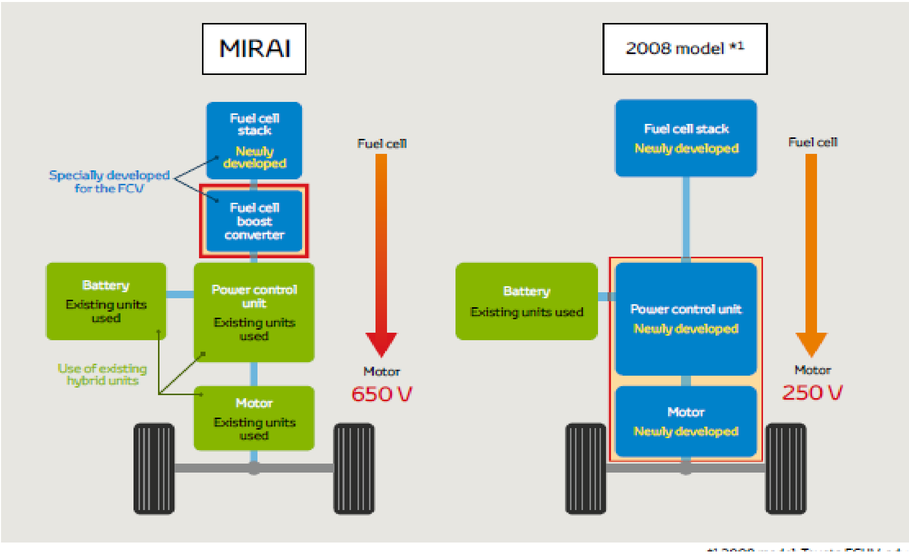


Fig. 3.31. *Comparison of fuel cell arrangement of 2008 and Mirai model*

13) High-pressure hydrogen tank

i. Structure of hydrogen tank

The high-pressure hydrogen tank is composed of two layers. One is the innermost layer made of a resin liner and plays a role of sealing the high pressure hydrogen gas.

The other layer surrounding the innermost layer is made of a strong carbon-fiber-reinforced plastic (CFRP), which is capable of withstanding high pressure. This is surrounded by a glass-fiber-reinforced plastic layer with high impact resistance. Aluminium bosses are provided at both ends of the resin liner for fitting valves.[117]

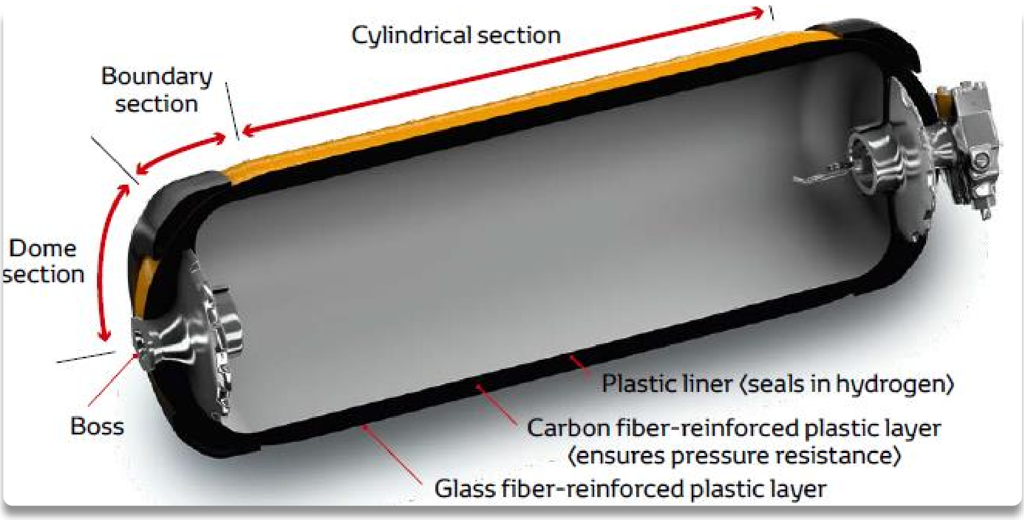


Fig 3.32. Structure of high-pressure hydrogen tank

ii) Tank storage density

Lighter weight achieved through innovations of carbon fiber reinforced plastic layer structure

Innovation of High-grade aviation carbon fiber material was used for the tank in the 2008 model of the FCV. Since carbon fiber accounts for more than half the cost of the high-pressure hydrogen tanks, the development of Mirai aimed to adopt carbon fiber materials of lower cost. [117]

Table 3.14 Specifications of high-pressure hydrogen tank

Nominal working pressure	70 MPa (700 bar)
Tank storage density	5.7 wt%
Tank internal volume	122.4 L (front tank: 60.0 L, rear tank: 62.4 L)
Hydrogen storage mass	Approx. 5.0 kg

iii. Innovation of lamination process

The normal basic lamination pattern on a high-pressure tank.

Carbon-fiber reinforced plastic recognised as a world leading H_2 storage material. Conventionally, a laminated high-pressure tank CFRP structure adopts a combination of the following three types of winding methods:

Hoop winding to strengthen the central area of the tank, helical winding to strengthen the dome area, and high-angle helical winding to reinforce the boundary regions. Actually, the high-angle helical winding would be wound over the central region.[117]

Particularly, the three changes were made to the lamination method.

(1) The shape of the liner was altered to flatten the boundary regions and allows lamination by hoop winding.

(2) The boundary regions strength was improved while forming the conventional liner shape by hoop winding.

(3) Hoop winding lamination was focussed on the inner layers.

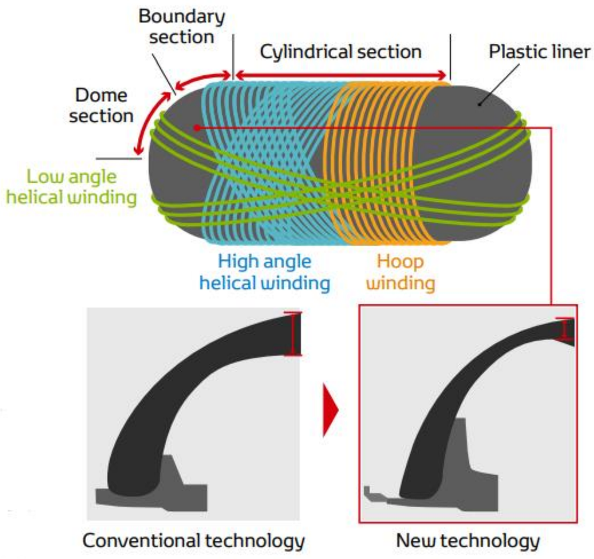


Fig 3.33 Lamination Process

iv. Hydrogen refueling

In response to new fueling standards *3 (the same in Japan, the US, and Europe), fueling time of approximately 3 minutes *4 has been achieved.

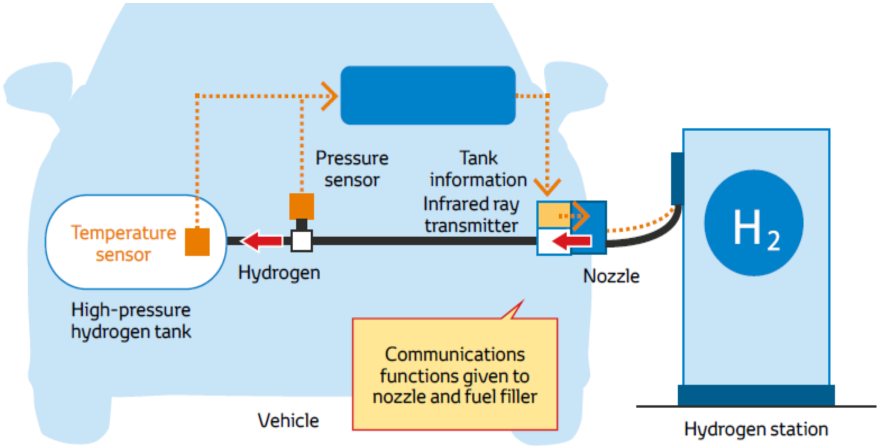


Fig 3.34. hydrogen refueling system of Mirai

*3 (Refuelling devices) ISO 17268: Gaseous Hydrogen Land Vehicle Refuelling Connection Devices

(Refuelling methods) SAE J2601: Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles

(Communications fueling) SAE J2799: 70 MPa Compressed Hydrogen Surface Vehicle Fueling Connection Device and Optional Vehicle to Station Communications

*4 Toyota measurement under SAEJ2601 standards (ambient temperature: 20 °C; hydrogen tank pressure when fueled: 10 MPa). Fueling time varies with hydrogen fueling pressure and ambient temperature

v. Fuel cell tests

The aim of the fuel cell tests for the vehicle was to analyze the operating conditions of the fuel cell in relation to its power supply

i) Starting the fuel cells,

ii) Standard operating conditions of a fuel cell

i. Fuel cell starting

The fuel cell analysis was conducted during the first test drive of the Toyota Mirai vehicle in Poland (the vehicle mileage was approximately 3,000 km at the time).[118]

The Toyota Mirai vehicle drive system analysis was performed in fuel cell start-up conditions. The first 20 seconds of operation is done then after the system start were analyzed.

The fuel cell start-up began from the state of being switched off completely (as seen by the level of minimum voltage in Fig.3.35). Within seconds (2–3 seconds), the value of the voltage generated by the cell stack was 315 V with a current of 32 A. The rated power (10 kW) is 10% of its maximum power. After a 10 second period, the current generated from the fuel cell increased (up to 40 A), which increased the power to about 13 kW.[118]

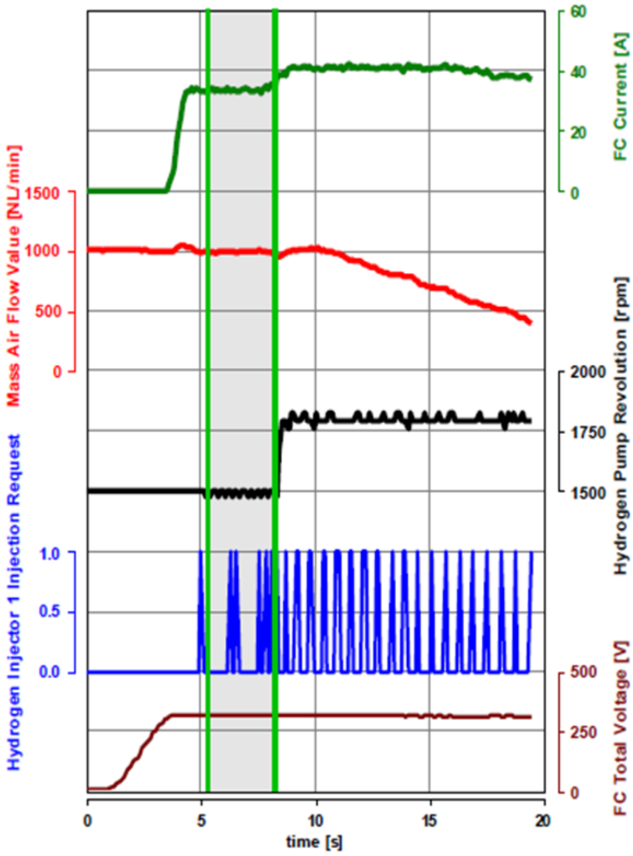


Fig 3.35 Changes in fuel cell operating parameters during start-up (vehicle stop)

ii. Fuel cell driving operating conditions

The Evaluation of drive operation began with an analysis of the test vehicle traffic conditions. Figure 3.36 shows the comparison of the conditions of the four Toyota Mirai routes. the maximum traveling speeds are comparable and reach 50 km/h. On these routes the time spent stationary is also close in value (equal to 50% of the total test time) – Fig. 3.36a. [118]

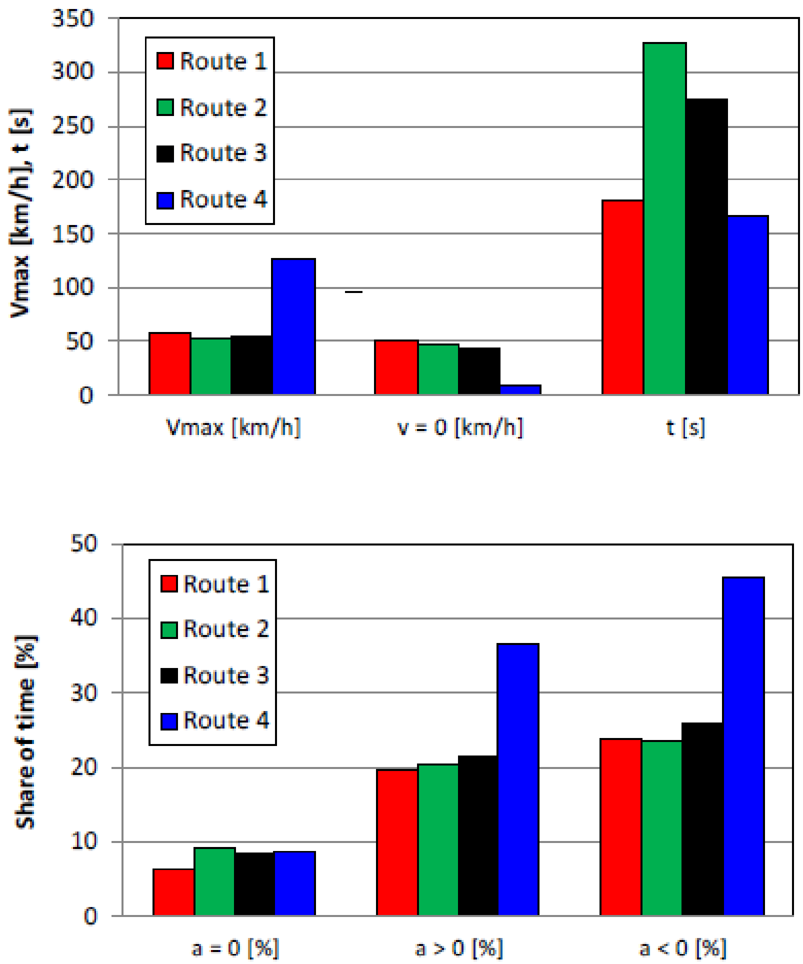


Fig 3.36 Road test results of the Toyota Mirai vehicle: a) the vehicle speed, b) the vehicle acceleration time density (excluding the vehicle being stationary)

Route 4 is characterized by an increased maximum vehicle speed. The test duration values are varied and range from 160 to 330 sec respectively.

The analysis of the time density of three driving phases, divided into: driving with-out acceleration (a = 0), acceleration (a > 0) and braking (a < 0) indicates that each drive had a similar driving parameters. In particular, routes 1–3 have a time density of up to 10% at constant speed and about 20% at acceleration and deceleration each.[118]

The fuel cell power analysis shown in Fig. 3.37 during vehicle acceleration indicates a high level of its performance.

Maximum power of the fuel cell during acceleration is reached after 3.5 seconds. Hydrogen injectors are switched on gradually with the power demand.[118]

The third injector was used only after obtaining about 70 kW cell power generation. With the increase in electric current, the maximum voltage of the cell is reduced, which is in line with the typical characteristics of its operation.[118]

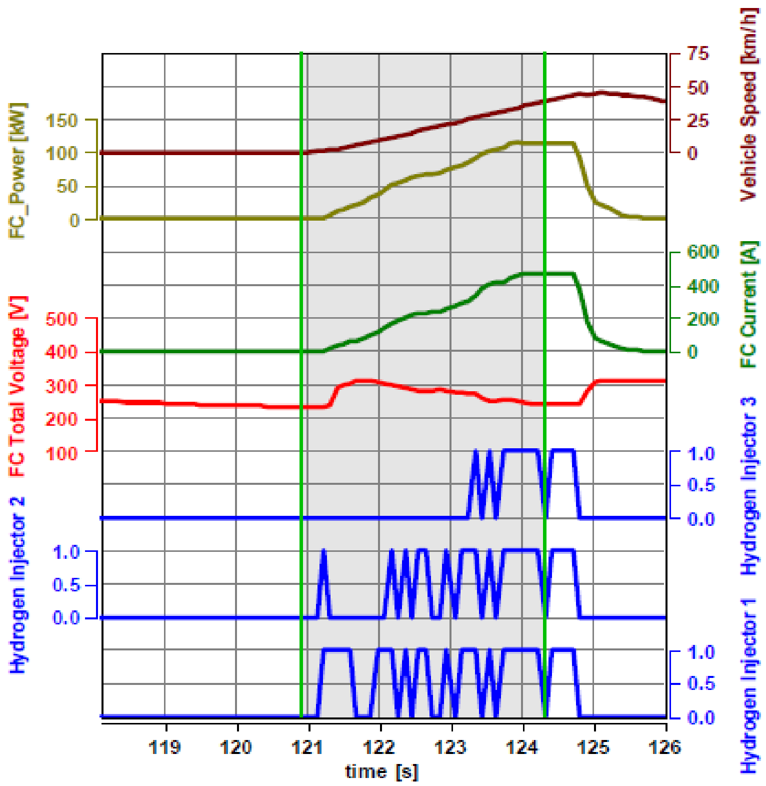


Fig 3.37 Example of changes in hydrogen fuel supply (three injectors) against speed variations (average speed) of driving a Toyota Mirai

Table 3.15 Specifications of Toyota Mirai

Parameter		**Value**
Vehicle	Mass	1850 kg
	Maximum Speed	179 km/h
Vehicle range	Type Approval Cycle	approx. 550 km.
Fuel cell	Type	PEM (polymer electrolyte)
	Power	114 kW
	Power Density	2.0 kW/kg. 3.1 kW/dm^3
	Cell Number	370
	Humidification	Internal circulation
Electric motor	Type	synchronous AC
	Maximum Power	113 kW
	Maximum Torque	335 N-m
Battery	Type	NiMH
Hydrogen storage	Volume Of Tanks Pressure/Mass	front – 60 dm^3, back – 62.4 dm^3 70 MPa/5 kg H_2
Refueling	Time	3 min

The name Mirai means “future” in the Japanese and it was decided by the Toyota to adopt this name in every country around the world. The name symbolizes the Mirai as a car that will lead the way into the future for the next generations.

Toyota is focussing on the development of FCVs as one of the most promising for achieving sustainable mobility and diversification of energy.

Table 3.16 Comparison of MIRAI with similar performed fuel cell vehicles in the automotive sector

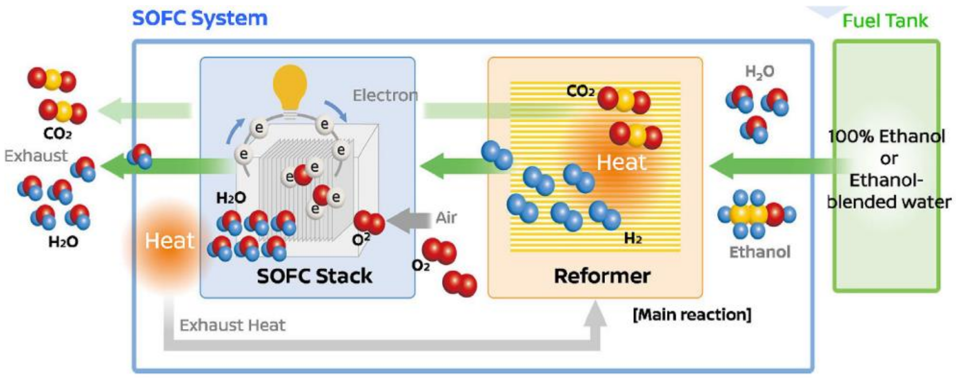
	Toyota Mirai	Hyundai ix35 Fuel Cell	Honda Clarity Fuel Cell
			
Acceleration 0-60 mph	9.6 s	12.5 s	11 s
Fuel Cell power	113 kW	100 kW	103 kW
Engine power	113 kW	100 kW	130 kW
Top speed	179 km/h	161 km/h	200 km/h
Range	ca. 550 km (NEDC test)	594 km	482 km
H_2 storage	70 MPa	70 MPa	70 MPa

3.2.4 Nissan e-Bio Fuel cell vehicle with SOFC system

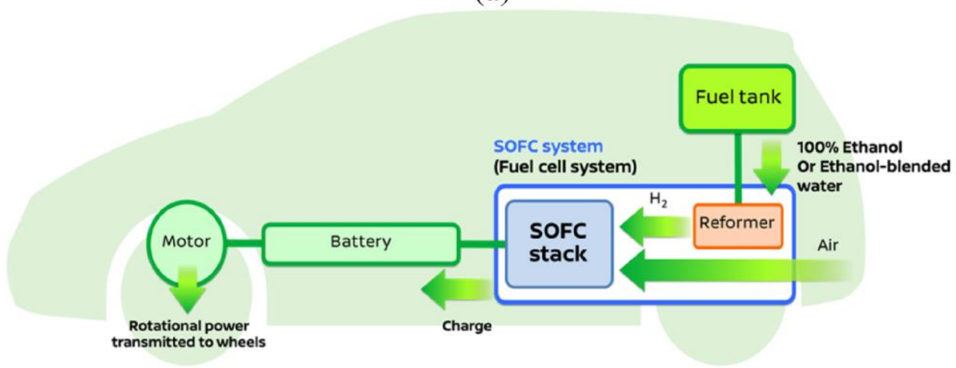
In 2016 Nissan announced Solid oxide fuel cell powered vehicle that runs on Bio ethanol power.it is employed with the Range extender SOFC system, comprises of SOFC stack , heat exchanger, reformer, burner and gas processing unit.

This system is world’s first automotive use that a Biofuel cell with SOFC generator. SOFC uses the reaction of the multiple fuels such as ethanol and natural gas with oxygen to produce High efficiency electricity. The e-Biofuel-Cell uses transformed hydrogen from fuel via reformer and oxygen at atmospheric conditions, with substantial electrochemical reaction producing electricity to power vehicle.

In contrast to conventional systems, e-Biofuel-Cell features SOFC as its power source, affording greater power efficiency to give the vehicle cruising ranges similar to Internal combustion engine cars (greater than 600km). In addition, the e-Biofuel-Cell car’s discrete electric-drive features including silent drive, linear start-up and brisk acceleration—allow clients to enjoy the joys and comfort of a pure electric vehicle (EV).



(a)



(b)

***Fig. 3.38.** The architecture (a) and energy conversion principle (b) of the Nissan SOFC vehicle*

1. Battery system

The Nissan e-bio FCV carries a Lithium-ion Battery pack with 24 kWh energy capacity, a weight of 267.5 kg and thus an energy density of 157 Wh/kg, which is almost similar to the BAT pack from the world best sell EV products. [119,120]

2. Motor system

The Nissan e-bio FCV is equipped with an 80 kW AC synchronous electric motor [121], and the maximum torque output can reach 280 Nm, which presents strong dynamic performance and driving demand. The drive motor provides tractive power for the entire vehicle and regenerative braking, showing great benefits in saving the power and endurance.

3. Working

Hydrogen produced through the process of reformation of 100% ethanol or ethanol blended water. Power is generated by Solid Oxide Fuel Cell (SOFC)stack from reformate air and hydrogen. Electricity generated is utilised to charge the battery and powers the drive motor.[121]

Other fuel cell vehicles which are limited manufactured items and commercially once available but not now are,

1. Ford Focus FCV : 2003-2006
2. Nissan X-Trail FCV : 2003-2013
3. Mercedes-Benz FC (A class based) : 2005-2007
4. Chevrolet Equinox FC : 2007-2009

4.Economical, Energy and Environmental Impact Analysis of FCEV with respect to BEV, ICE

4.1 History and Evolution of Fuel cell and fuel cell vehicles

It can be traced back to 1839 when it was first invented by a Welsh scientist by the name of William Grove[122]. However, the first time fuel cell vehicles were in the international spotlight was during the oil crisis in the 1970s [124]. In the next few decades, carmakers from different countries spent various degrees of effort developing fuel cell vehicles. The year 2014 was marked by the world's first commercialized fuel cell vehicle by Toyota, representing a culmination of years of R&D efforts.[167]

From then on, in the eyes of the public, fuel cell vehicles were no longer experimental but were recognized as one of the key driving technologies of the future of mobility. In the next 5 years (till now), countries such as China, US, Japan, and various countries in Europe focused their efforts on driving this technology forward. [124]

4.2 Hydrogen development overview in Europe

The European Union ("EU") regards hydrogen as an important part of energy security and energy transformation [125]. In 2003, the 25 EU nations launched the European Research Area ("ERA") project, which includes the building of the European hydrogen and fuel cell technology research and development platform, focusing on key technologies in the hydrogen and fuel cell industries[123].

In 2008, the EU established a public private partnership called the Fuel Cells and Hydrogen Joint, which played vital role in development and deployment of hydrogen and fuel cell technologies in Europe[127].

In February 2019, FCHJU released the Hydrogen Roadmap Europe: A sustainable pathway for the European Energy Transition, which proposed a roadmap for hydrogen energy development towards 2030 and 2050, paving the way for large-scale deployment of hydrogen power and fuel cells in Europe [126].

4.2.1 Hydrogen roadmap plan by 2030 in Europe.

Table 4.1 Hydrogen roadmap plan by 2030 in Europe.

Hydrogen Roadmap Europe	**Roadmap Plan by 2030**
Hydrogen production & distribution	1.One-third ultra-low carbon hydrogen production in industrial applications, including refineries and ammonia production at-scale conversion of "surplus" renewables into hydrogen. 2. large-scale demonstrations of power generation from hydrogen renewable-hydrogen generation plants.
Hydrogen Infrastructure	3,700 hydrogen refueling station by 2030
Support for passenger vehicles	a fleet of 3.7 million fuel cell passenger vehicles
Support for commercial vehicles	1. 500,000 fuel cell light commercial vehicles on road. 2. 45,000 fuel cell trucks and buses projected to be on the road. 3. Fuel cell trains replace 570 diesel trains

Germany is one of the key leaders in hydrogen and fuel cell development in Europe. To promote the fuel cell and hydrogen energy strategy, the German federal government set up the National Organization for Hydrogen and Fuel Cell Technology, responsible for the coordination and management of the National Innovation Programme for Hydrogen and Fuel Cell Technology (NIP) and the Electromobility Model Regions programme of the Federal Ministry of Transport and Digital Infrastructure (BMVI).[155]

In 2006, the Federal Government initiated the National Innovation Program for Hydrogen and Fuel Cell Technology ("NIP") together with representatives from research organizations as well as from various industry sectors, to advance the role of hydrogen and fuel cell technology in Germany's energy system [128]. The 2006-2016 phase of NIP funded € 1.4 bn in research, development and demonstration projects. [129]

In 2009, Germany also established the H_2 Mobility initiative with Air Liquide Group, Linde Group, Shell and other companies, planning to invest € 350 million in the construction of world's first nationwide network of hydrogen filling stations in Germany.[130] By the end of 2018, Europe has 152 hydrogen refueling stations, 41% of which are in Germany [131].

EVs have a wide range of vehicle application types due to its simplicity and flexibility. FCEVs and BEVs are both alternative solutions to replace conventional gasoline and diesel vehicles to promote zero-emission and sustainable transportation systems. [131]

As shown in Table 4.2, many countries have introduced policies to ban internal combustion engine vehicles [131]. Using clean vehicles such as FCEVs and BEVs is an undeniable trend for the future. Compared to FCEVs, the development and adoption of BEVs are more mature in most applications but suffer from limitations due to battery weight and range issues[132 133].

Table 4.2 Planned ban on pure internal combustion engine vehicles

Country	**Year to Ban Pure ICEVs**
UK	2040
France	2040
Germany	2040
Spain	2040
Netherland	2025
Canada	2040
India	2030

FCEVs have been in various stages of prototyping and production since the early 2000s. Since then, with years of efforts made by governments and industry players, almost all vehicle types have fuel cell products or prototypes, as shown below in Table 4.3. For passenger vehicles, FCEVs are commercially available but have low adoption due to limited refueling infrastructure as well as high acquisition cost [131]. In the commercial vehicle sector, forklifts, buses, light and medium-sized trucks have been on the forefront of fuel cell commercial vehicle applications [132].

4.3 Current and future number of FC vehicles by type and geography[167]

Table 4.3. Summary of FCEV, BEV, and ICE application status in each vehicle type

		Passenger vehicles	Buses and coaches	Trucks	Forklifts	Refueling stations
US	Current	7,271	74	prototype test	>30,000	42 online
	Target		5,300,000 FCEVs on US roads by 2030	-----	300,000 by 2030	7,100 by 2030
China	Current	0	5000	5000	4	23
	Target	1,000,000 by 2030	11600	-----	-----	100 by 2020 500 by 2030
Europe	Current	1000+	76	100	300	152
	Target	3,700,000 by 2030	45,000 fuel cell trucks and buses by 2030	-----	-----	3,700 by 2030
Japan	Current	3,219	18	N/A	160	137
	Target	40,000 by 2020 200,000 by 2025 800,000 by 2030	100 by 2020 1,200 by 2030	-----	500 by 2020 10,000 by 2030	160 by 2020

4.4 Summary of FCEV, BEV and ICE application status in each vehicle type[167]

Table 4.4 Summary of FCEV, BEV and ICE application status in each vehicle type

Model		**FCEV**	**BEV1**	**ICE**
Passenger vehicles	Designed to carry people, usually less than 7 seats	Commercially available	Commercially available	Incumbent
Bus	Used for urban public transportation with 30-50 seats	Commercially available	Accepted	Incumbent
Van/Light-duty vehicles	Used in inner-city logistics with Gross Vehicle Weight ("GVW") less than 4.5 metric ton	Demonstration	Accepted	Incumbent
Medium-duty trucks	Used in inner and inter-city logistics, with GVW of 4.5-12 metric tons	Demonstration	Demonstration	Incumbent
Heavy-duty trucks	Used in long-haul transportation with GVW larger than 12 metric tons	Prototype	Demonstration	Incumbent
Forklift	An industrial truck used to lift and move materials over	Commercially available	Incumbent (Indoor Warehouse)	Incumbent (Outdoor Warehouse)

	short distances			
Mining truck	Off-road dump trucks designed for mining operations	Prototype	Prototype	Incumbent

4.5 Total cost of ownership analysis

To compare and contrast the economic efficiency of fuel cell vehicles, we built a Total-Cost-of-Ownership model that examines FCEVs in detail, in relation to BEVs and ICE vehicles. This TCO analysis is from the perspective of the operator. The operator may not care about detailed component prices, but rather a retail cost of the entire vehicle.[167]

The reason for such a deep level TCO analysis is to understand exactly what components are driving current and future costs, both from a vehicle-build and operational perspective.[155]

The TCO costs are broken down into purchase cost and operation cost. In purchase cost, gross margin, energy module and other vehicle components are included. An extra component markup for FCEVs and BEVs are considered, as explained earlier. For operation, fuel cost, charging station cost, maintenance cost, parts replacement cost and insurance cost are included.[155]

4.6 High level TCO framework

Table 4.5a High level TCO frame work for purchase cost

		FCEV	**BEV**	**ICEV**
	Gross profits	•Incremental costs to OEM COGS	••Incremental costs to OEM COGS	••Incremental costs to OEM COGS
	Components mark up	••Mark-up on propulsion agnostic components due to lower economies of scale of FCEVproduction compared to ICE vehicle	••Mark-up on propulsion agnostic components due to lower economies of scale of FCEV production	•• N/A due to assumed full economies of scale

Purchase cost			compared to ICE vehicle	
	Drive train	•• Electric motors and other associated components	•• Electric motors and other associated components	•• Internal combustion engine
	Energy storage	•• Hydrogen tanks •• Fuel cell system •• Battery (around 1/10 size of BEV battery)	•• Battery •• Battery management system	•• Gasoline/diesel tank

Table 4.5 b: High level TCO framework on operation cost

		FCEV	**BEV**	**ICEV**
	Fuel	• Hydrogen cost multiplied by consumption per 100km	Electricity cost multiplied by consumption per 100km	•• Diesel cost multiplied by consumption per 100km
	Charging station	•• Hydrogen fueling station	•• Dedicated onsite chargers and related	•• Assume stations cost has been include in

Operation cost			infrastructure	fuel prices
	Maintenance	•• Daily vehicle maintenance cost	•• Daily vehicle maintenance cost	•• Daily vehicle maintenance cost
	Parts replacement	•• Fuel cell system replacement •• Battery replacement	•• Battery replacement	•• ICE replacement

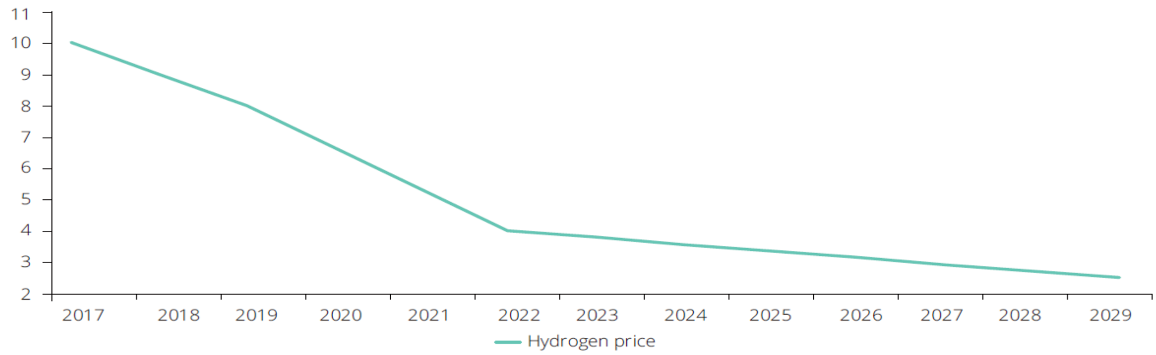


Figure 4.1 US hydrogen price (Unit: USD/kg)

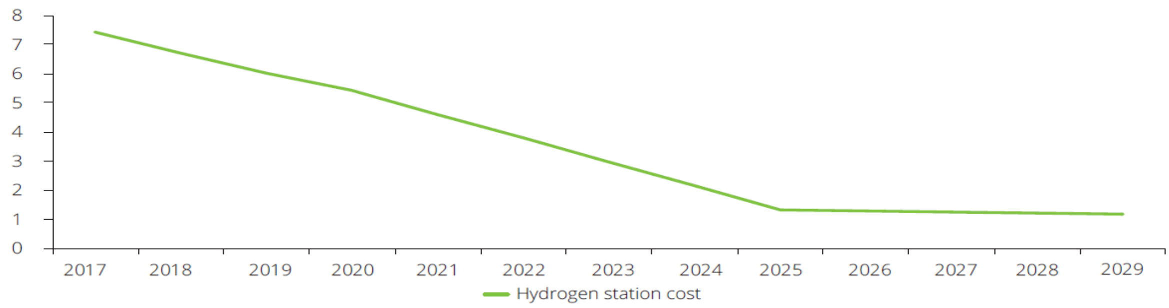


Figure 4.2 US hydrogen station trend (Unit: USD/per vehicle/per 100km)

Hydrogen fuel costs and infrastructure costs are two other significant components of the TCO model, accounting for over 50% of operational costs in 2019. At the moment, hydrogen costs are at a significant premium over diesel or gasoline used by conventional ICEV and the electricity used by pure electric buses. [167]

One of the reasons for this high cost is due to the extreme low density of hydrogen gas, making it difficult to store and transport. With the development of storage and transportation technology and the economies of scale brought by large-scale applications, the price of hydrogen fuel is expected to drop to below half of the current hydrogen price by 2029 [138] Figure 4.1

Hydrogen infrastructure also poses significant costs for fuel cell buses operation no matter if this cost is born by the operator, third parties, or public agencies. The current average infrastructure cost per bus per 100 km is around 6 USD based on our assessment. With the large-scale application of hydrogen energy and the improvement of scales of economy, the hydrogen infrastructure cost is predicted to drop below 2 USD per bus per 100 km by 2029. Figure 4.2[167]

4.6.1 High level TCO framework – results for Europe

In the Europe application the TCO of FCEVs appears to have a quicker decline than the U.S. application and China applications. In 2019, the TCO of FCEVs is around 190 USD per 100 km, while that of BEVs is around 150 USD per 100 km and that of ICE vehicles is around 124 USD per 100 km.[155]

In 2023, the predicted TCO of FCEVs would be lower than that of BEVs and reaching 124 USD per 100 km. In 2024, the predicted TCO of FCEVs would be lower than that of ICE vehicles reaching 116 USD per 100 km.

The overall cost of the vehicle is cheaper than the U.S. due to shorter OEM warranty periods as well as less manufacturing-location requirements. The fuel cell system price is predicted to decline around 60% in coming 10 years. Besides build costs, hydrogen prices and station costs are also predicted to decline rapidly. In the next 10 years, Hydrogen prices are predicted to decline around 44%. As most European countries, such as the U.K., add significant tax rates to diesel168, the TCO of FCEV and BEV are estimated to be lower than ICEV much sooner than in other regions.[155]

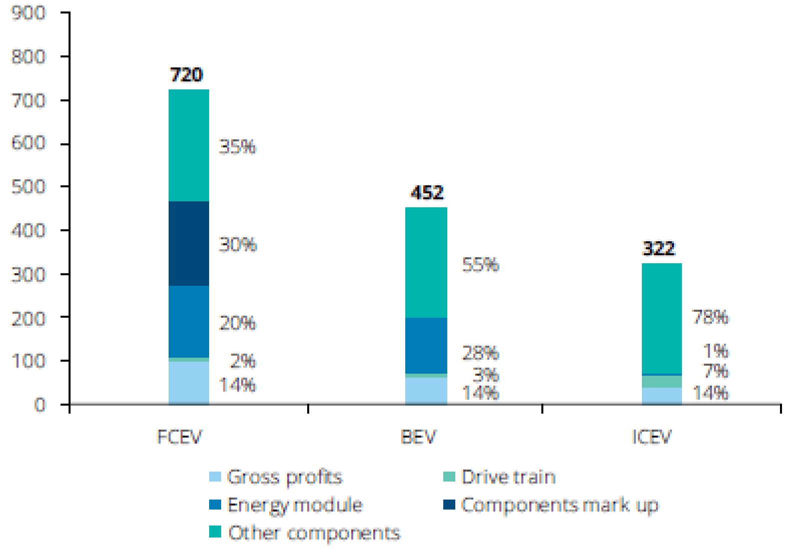


Figure 4.3 2019 purchase price for a bus in Europe breakdown (unit: thousands USD/per vehicle)

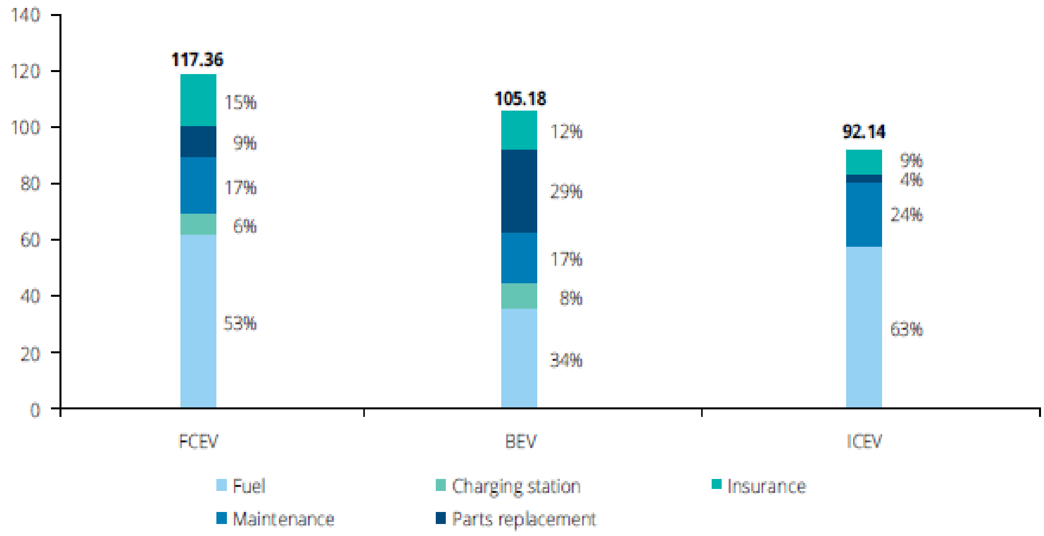


Figure 4.4 2023 Predicted purchase price for a bus in Europe breakdown (unit: thousands USD/per vehicle)

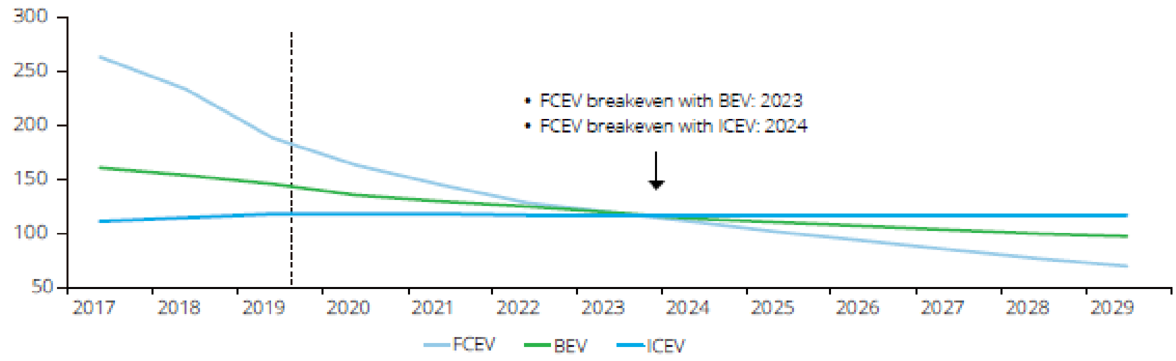


Figure 4.5 Bus TCO outlook in Europe (unit: USD/per 100 km)

4.7 Energy efficiency comparison of fuel production among FCEV, BEV & ICEV

- **Considerations of well-to wheel ratio :**

When considering the efficiency of an overall vehicle, a well-to-wheel ("WTW") analysis is typically used. This can be divided into 2 stages, typically known as well-to-tank, and tank-to wheel. Well-to-wheel energy efficiency of FCEVs vs. other vehicle types(energy conversion efficiency, energy consumption, and Greenhouse Gas ("GHG") emission during whole fuel cell lifecycle) [167]

The former usually refers to fuel production from feedstock to its delivery to the vehicle's energy carrier, while the latter refers to energy consumption during vehicle operation phase [140]. When considering different vehicle types, this analysis more specifically refers to:

• In the case of FCEVs: hydrogen production, delivery & storage to the vehicle hydrogen tank, as well as the fuel cell use during FCEV operation.

• In the case of BEVs: electricity generation, transmission in the grid, charging the BEV battery, and use during BEV operation.

• In the case of ICE vehicles: gasoline/ diesel mining, refining, transportation to gas stations, and fuel consumption during vehicle operation[140]

Table 4.6 energy efficiency comparison between FCEV,BEV and ICE

Energy Efficiency	Production	Delivery	Use	Overall AVERAGE WTW efficiency
FCEV	**23~69%** • Range is due to differences in hydrogen production pathways • Production efficiency = Feedstock extraction efficiency X fuel to hydrogen efficiency	**54~80%** • Energy loss during compressing, transportation (pipeline/truck) and storage (gaseous/liquid hydrogen)	**36~45%** • Conversion of hydrogen to electricity, and electricity to mechanical energy • The additional energy loss compared with BEV operation, is due to added step of hydrogen to electricity	5-30%
BEV	**35~60% [158 159 160]** • Range varies depending on different methods of electricity production, as well as grid-mix which varies dramatically between different countries	**81~84.6%[159 160 164]** • Average conversion rate during electricity transmission is about 90%-94% • 90% energy efficiency during charging process	**65~82%[156 157]** • Energy loss during electricity conversion to move vehicle, including loss in motor, AC conversion, auxiliary parts and transmission system, excluding the	18~42%

			charging process	
ICE	**82%~87% [158 162 163]** • 13~18% energy loss during fossil fuel mining, refining processes	**~99% [161]** • Small amount of energy loss during transportation process, due to evaporation, spilling or adhesion to containers	**17~21% [156]** •Majority of energy lost as heat • Current efficiency is near the limit of ICEs after years of improvements as the incumbent vehicle type	14~18%

4.8 Impact on overall efficiency

The impact on overall energy efficiency of FCEVs is primarily dependent on hydrogen production and transportation as well as the fuel cell technology in the vehicle by Converting the energy stored in hydrogen to drive the vehicle. Critics against FCEVs will argue that hydrogen is by nature inferior to battery vehicles. Simple fact is that hydrogen has to be produced from electricity (by electrolysis), and then back to electricity (which must have some loss of energy).[167]

For FCEV, the energy conversion of hydrogen production phases ranges from 23%~69%. The variety in efficiency is due to the different hydrogen production pathways, with different types of fuel or feedstock and different processing technologies.[155]

The energy efficiency of hydrogen production process is comprised of two parts:

1) the efficiency of feedstock extraction and recovery.

2) the efficiency of converting the fuel into hydrogen.

1) Energy efficiency comparison of energy transportation among FCEV, BEV & ICEV

For hydrogen delivery and storage efficiency of FCEVs, hydrogen can be stored and delivered as compressed gas, liquid, or solid, the former two being the most common methods. Compressing hydrogen into a liquid for transport and storage causes 40%~46% efficiency loss mainly due to the energy required to cryogenically compress the hydrogen. [143 144]. While compressing hydrogen as a gas form is more efficient, but still incurs a total system efficiency loss. The overall energy efficiency of gaseous hydrogen is approximately 72%~80%. [142 144 145]

Energy transmission for BEVs is relatively simple; the average loss rate during electricity transmission is about 7%-10% and is predicted to decrease to 6.00% by 2020 [148 149]. There is also a 10% energy loss during the charging process. It also should be noted that batteries can self-discharge, although we did not include these losses in this analysis due to difficulties on quantification.[150 151]

For ICEs, the overall loss rate during loading, unloading, transportation and retail is less than 0.4% for gasoline and 0.28% for diesel, mainly due to evaporation, spilling or adhesion to containers. [154]

2) Environmental impact of well-to-wheel stage

Although hydrogen fuel cell vehicle has been regarded as a new green energy vehicle that only produces

water during its operation, the process of how hydrogen is produced, stored, delivered and refueled produces greenhouse gas and causes environmental impacts. According to the Hydrogen Council, the CO2 emission of hydrogen pathways (well to tank period) from natural gas via SMR was ~75 g/km, accounting for ~60% of total CO2 emission of a FCEV from lifecycle perspective. [155]

Therefore, hydrogen production is a key part to ensure low-carbon performance of FCEVs. Largely due to energy efficiency and GHG emission of feedstock conversion, the total energy consumption and GHG emission varies among different hydrogen pathways.

Hydrogen produced from electrolysis from US grid electricity uses relatively high amounts of total and fossil energy and results in significantly higher GHG emissions. It is largely due to the relatively low efficiency and high emissions associated with the coal based power plants that dominate electricity generation in US.[155]

Overview

In conclusion, based on our analysis, fuel cell and hydrogen have great potential to drive the Future of Mobility. Regions including the U.S., China, Europe, and Japan, among others are recognizing this trend and focusing policy efforts on developing fuel cell technology, supply chain, and infrastructure on multiple fronts. Due to characteristics such as fast re-fueling (similar to ICEVs), high energy density (i.e. lower weight than BEVs), FCEVs is an extremely attractive solution for heavy duty and commercial vehicles.

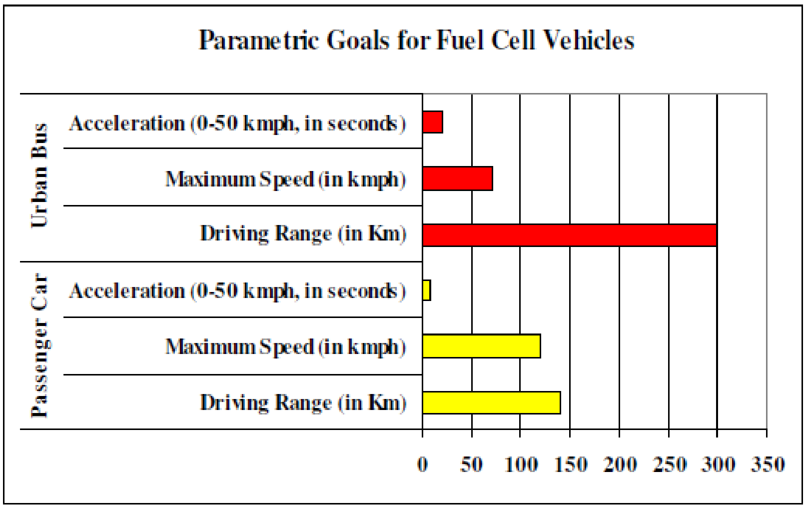


Fig. 4.6 Parametric goals for fuel cell vehicles.

We have also demonstrated that the economics of FCEVs are forecasted outperform BEVs and ICEVs for specific applications. Overall, we estimate that the TCO of FCEVs will decline by almost 50% in the next 10 years, driven by several factors such as fuel cell system price decrease, economies of scale, usage of renewable energies to produce hydrogen, as well as maturation of hydrogen infrastructures. Lastly, FCEVs demonstrate the lowest lifecycle greenhouse emissions compared with BEVs and ICEVs and showcase the highest potential room for improvement room, due to increased use of renewable energies in hydrogen production.

Conclusion

Primary Objective of this Thesis is to present the Fuel cells with respect to electric and hybrid system makes one of the best alternative power train systems. fuel cell cars have great characteristics as to become the future in the automotive world. Fuel cell integrated vehicles are quite and eco-friendly without losing the range and power. Advantages explain why major automobile left their Long-range battery all-electric vehicle developments in 1990s and started devoted most efforts to the FCEV.

Automotive companies see in them a great future as to invest lots of money. Now, some of them see the commercial launch really close, 2014-2015,2019,2020 like GM, Daimler, Hyundai, Toyota, Honda…Partnerships between automakers have taken place with the aim to develop fuel cell technology together.

Among the various Fuelcell Technologies, PEM Fuel cells reached to the phase of partial level of commercialization because of many developments around the world in many practical applications PEMFC provides several advantages over the internal combustion engine, which are the formal power source in Automotive and Power industry, including higher efficiency and lower emissions. Although PEMFC applications has two issues, namely Network of Hydrogen distribution and Use of Platinum as catalyst, which raises Cost of the fuel cell production. Also other fuel cell technologies also using the same Pt as catalysts limits the performance with higher content of Pt. AFC also proved to be efficient in mobile applications especially for the Space applications. PAFC bus technology is one of the promising in the vehicular applications. Latest developments that aim to approach the planned targets and to break the commercialization barriers of the PEMFC technology.

PAFC and SOFC are more suited for the Stationary power generation applications. PEMFC, AFC and DMFC holds main interest in the applications concerning Distributive power generation and automotive and transportation field.

However, to meet the full requirements as power sources for transport applications, the fuel cell researchers have to overcome serious challenges related to high cost, low durability, hydrogen refueling infrastructure and hydrogen storage on the fuel cell vehicles (FCVs).

It should be noted that along with electric vehicles, Hydrogen Fuel cell vehicle and Hybrid electric vehicles also emerged as the substitution for Internal Combustion engine vehicles offers least environmental damage among all the advanced options.

PFCEVs are an appealing future automotive vehicle choice which provide benefits to the driver over BEVs and FCEVs. The 40-mile BEV of the PFCEV, which covers most trips, can conveniently be replenished by charging at home or where charging infrastructure allows.

Similarly, the PFCEV will require lesser hydrogen stations than pure FCEVs as the 40-mile BER will satisfy the majority of the trips, which will also greatly reduce infrastructure costs due to the high cost of hydrogen stations.

While the plug-in aspect of the PFCEV will require battery charging infrastructure, the dependence is less than that for BEVs due to the hydrogen drivetrain, and the need for costly charging stations is reduced.

PFCEVs have very low WTW GHG emissions of all vehicle types considered, which includes PHEVs, BEVs, and FCEVs.

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