Technology Advancements and Trends in Development of Proton Exchange Membrane Fuel Cell Hybrid Electric Vehicles in India: A Review

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Abstract

With the beginning of more stringent regulations related to fuel economy, global warming, and emissions as well as conventional energy resource limitations; electric, hybrid, and fuel-cell vehicles have been attracting increasing attention from vehicle constructors, consumers and governments. Especially, Proton exchange membrane fuel cell vehicles (PEMFCVs) based automobile industry has gained attention in the last few years due to rising public concern about urban air pollution and consequent environmental problems. However, design of power trains is difficult in fuel cell electric vehicle and maintaining on board hydrogen tanks as challenge in the system. Alternative power trains for automotive applications aim at improving an emissions and fuel economy. This paper provides an overview of a background of fuel cell vehicles history, different types of fuel cells based on the types of electrolyte used in the membrane electrode assembly (MEA), different types of powertrains have been used in the automobile industry especially in hybrid sector, achievements of fuel cell based automobiles in Indian terrain, various research challenges and comparing among the Internal Combustion Engines (ICE), Battery Electric Vehicles (BEVs), Fuel Cell Vehicles (FCVs), FCHEV. Moreover, fuel cell

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hybrid electric vehicles (FCHEVs) have huge scope in the Indian terrain because it would be easy to control of emission and global warming with economically suitable powertrain. In order to further promote the sector, initiatives are being undertaken by the Government of India to promote innovation and create a favourable policy regime to make India a prominent manufacturing hub.

Keywords: Energy Storage Subsystems (ESS), Membrane Electrode Assembly (MEA), Proton Exchange Membrane Fuel Cell Vehicles (PEMFCVs), Zero Emission Vehicles (ZEVs).

1 Introduction

The fuel cell concept was invented and demonstrated in the beginning of the 18^{th} century by Humphrey Davy. Later, William Grove, a chemist, developed the fuel cell in 1839. Grove lead a series of experiments with what he termed as a gas voltaic battery [1–4]. Newer technology developments in the field of electrical power generation using thermal power plants with coal as primary source led to popularization and widespread use of coal fired power plants and caused a slowdown of research and development in the area of fuel cell technology.

In the 1980s, the detrimental effects of greenhouse gases (GHGs) and their effects over the ozone layer became apparent to the research community and hence the move to decrease the emission of such gases was started by the governments [5–7]. The decision to decrease the usage of coal fired power stations and the internal combustion engines (ICEs) and similar polluting equipment were taken in line with this policy. Fuel cell electric vehicle are zero emission vehicles and have longer life [8–10]. Government policies in India are encouraging to development of proton exchange membrane fuel cell (PEMFC) vehicles in automotive applications [11–12].

The government has taken steps for the development and deployment of green energy and has extended support to the public and private players who are in the field of green energy like ISRO and TATA Corporation Ltd [13–19]. India still being a part of the developing world, the major technical challenges in this area include identification and development of suitable fuel cell technologies for applications often unique to the developing world [20–24].

This article is divided into eight sections. The first section gives an introduction to the advance technology and trends in fuel cell vehicles. The second section deals with the description of the fuel cell and their classification.

The third section gives brief introduction to the power trains. The fourth section gives statistics of the technology advancements and trends of fuel cell. The fifth section describes about the developments of the fuel cell vehicles in India. The sixth section describes about the challenges of the fuel cell vehicles in India and last section is comparison among the different power trains of the fuel cell vehicles.

2 Fuel Cell and Its Classification

A fuel cell is the main energy source of the modern electric vehicles and fuel cell based electric vehicles will become very common in the future due to their zero emission and the other beneficial use as distributed storage when used with advanced converter and battery technologies in the smart grid apart from their use in the transportation sector [25]. There is a need for much wider research to enhance the efficiency of fuel cells and associated electrical power delivery systems. The block diagram for basic fuel cell operation is shown in Figure 1. The classification of the fuel cell is mainly based upon the type of membrane used in the MEA of the fuel cell. The characteristics of various types of fuel cells are summarised in Table 1 [25–32].

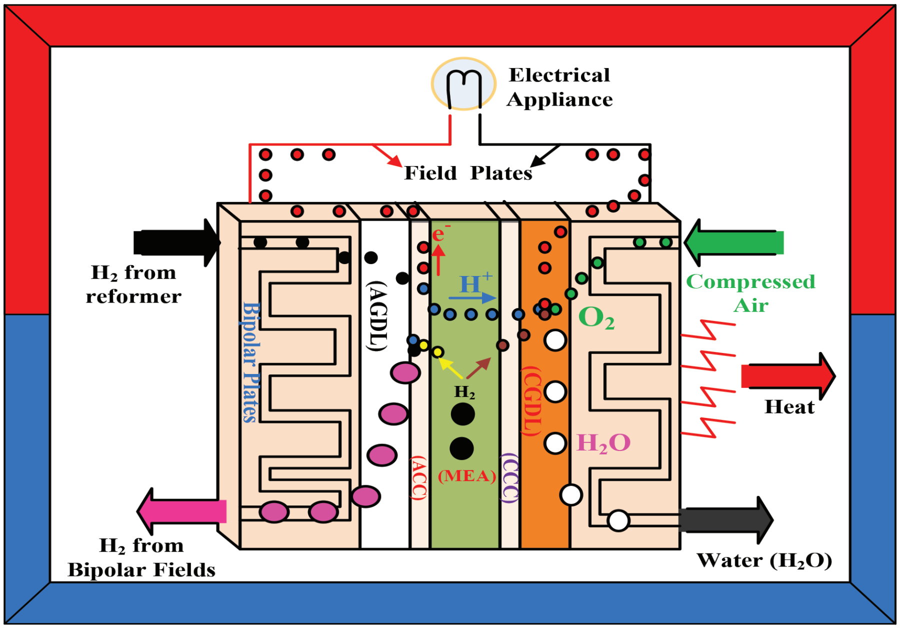

Figure 1 Description of operation of fuel cell.

Table 1 Characteristics of major fuel cell types based on the usage of membrane electrode assembly (MEA)

Parameters / Types	Direct Methanol Fuel Cell	ProtonExchange Membrane Fuel Cell (PEMFC)	Alkaline Fuel Cell (AFC)	Phosphoric Acid Fuel Cell (PAFC)	Molten Carbonate Fuel Cell (MCFC)	Solid Oxide Fuel Cell (SOFC)
Fuel	Methanol	Hydrogen	Hydrogen	Hydrogen	Hydrogen & carbon	Hydrogen & carbon
Anode Reaction	CH_3OH+H_2O $=6H^++6e+CO_2$	$H_2=2H^++2\ e^-$	$H_2+2(OH)$ $=2H_2O+2e$	$H_2+=2H^++2e^-$	$H_2+CO_3=H_2O+$ CO_2+2e^-	$H_2+O_2=H_2O+2e^-$
Cathode Reaction	$1.5O_2+6H^++6e^-$ $=3H_2O$	$0.5O_2+2H^++2e^-$ $=H_2O$	$0.5O_2+HO_2+2e$ $=2(OH)^-$	$0.5O_2+2H^++2e^-$ $=H_2O$	$0.5O_2+CO_2+2e^-$ $=CO_3{}^{2-}$	$0.5O_2+2e^-=O^{2-}$
Total Reaction	$CH_3OH+1.5O_2$ $=2H_2O+CO_2$	$H_2+0.5O_2=H_2O$	$H_2+0.5O_2$ $+CO_2=H_2O$	$H_2+0.5O_2=H_2O$	$H_2+0.5O^2+CO_2$ $=H_2O+CO_2$	$H_2+0.5O_2=H_2O$
Temperature	Low	Low	Low	High	High	High
Efficiency	40%	(48–58)%	64%	42%	50%	(60–65)%
Power range	watts range	watts/Kilo watts range	Kilo watts	Kilo watts	Kilo/Mega watts	Mega watts
Applications	portable products (Torches, Battery Charges)	Block Type Heat & Power stations (BTHPS)	Space appliances	BTHPS	Power plants, CHPs	Power plants, CHPs

3 Topologies of Drivetrains of Electric Vehicles (EVs)

The drivetrains are the heart and soul of any vehicle which is under use in transportation especially for the four-wheel category [33–36]. Drivetrains connect the power sources to the wheel section of electric vehicles through the power electronics interface. Advances in the drivetrains are playing key role in PEMFC vehicles because of the new techniques to control the acceleration and deceleration of the drive trains by using front wheel drive (FWD) [37–42]. Rear wheel drive (RWD) and all wheel drives (AWD) are being developed for the effective usage of fuel and improvement in the efficiency of fuel cell vehicles (FCVs). Various types of electric vehicles are detailed in the following subsections.

3.1 Battery Electric Vehicles (BEVs)

A purely electric drive system principally replaces the internal combustion engine (ICE) and the various transmission systems with an all-electric system (power electronics and super batteries). The practical EVs still use lead-acid batteries, with the more sophisticated ones using (Nickel Metal-Hydrate) Ni–MH batteries. The block diagram of the battery electric vehicle is shown in Figure 2.

3.2 Series Hybrid Electric Vehicles (SHEVs)

A series hybrid electric vehicle is fundamentally an electric vehicle with an on-board battery charger. An internal combustion engine (ICE) is generally run at a desired efficiency point to drive the generator and charge the on-board battery. When the state of charge (SOC) of the battery comes down

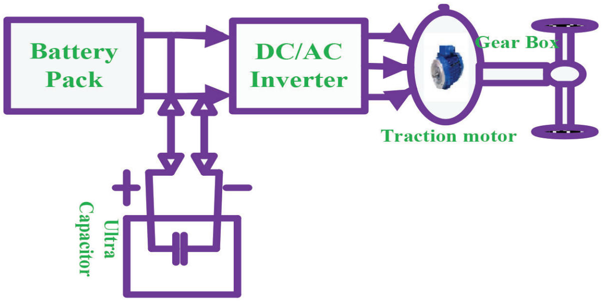

Figure 2 Block diagram of battery electric vehicle.

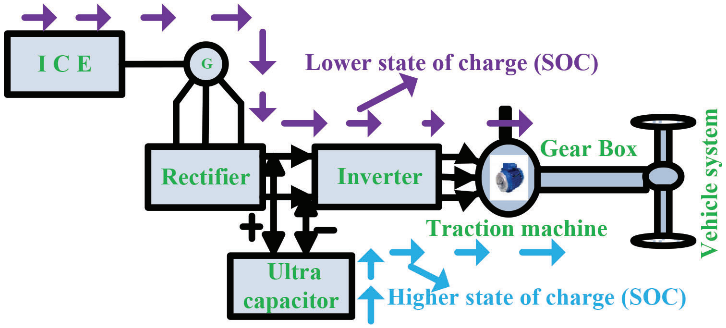

Figure 3 Block diagram of series hybrid electric vehicle.

to a predetermined threshold level, the internal combustion engine (ICE) is turned on to charge the battery and simultaneously provide power to the chassis of the vehicle [43–45]. The engine turns off when the state of charge (SOC) of the on-board battery increases and reaches a predetermined value i.e. say 80%. Series hybrid electric vehicles (SHEVs) would run at their optimal torque and speed and thus save fuel and improve efficiency of the system. However, some of the energy is lost because of the two-stage power conversion process. Moreover, the engine/generator set maintains the battery charge around 65%–75%. A series hybrid vehicle is more useful for city driving. The block diagram of series hybrid electric vehicle is shown in Figure 3.

3.3 Parallel Hybrid Electric Vehicles (PHEVs)

In the PHEV, the traction motor and generator of the system are mechanically connected through the torque coupler. The PHEV has various modes of operation based on the usage of generator and traction motor. The most commonly used strategy is to use the motor alone rather than ICE at low speeds to increase the efficiency of vehicle under low speed conditions, and then let the ICE work alone at higher speeds. When ICE is active, generator is used to provide energy to the battery for charging. In PHEVs, the torque coupler is designed using digital concepts like continuous variable transmission (CVTs) rather than the conventional fixed variable transmission (FVT) system for efficient usage of fuel and optimal operation [46]. The transmission losses are lesser when compared to the SHEVs but PHEVs have much bigger size and have more complex operation and control. The block diagram of the parallel hybrid electric vehicle is shown in Figure 4.

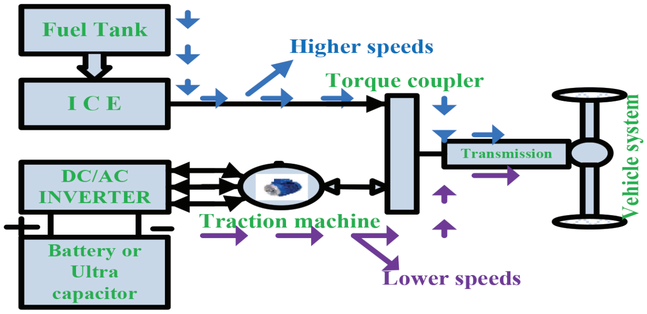

Figure 4 Block diagram of the parallel hybrid electric vehicle.

3.4 Series-Parallel Hybrid Electric Vehicles (SPHEVs)

It is possible to combine the advantages of both the series and parallel HEV configurations. When acceleration is required, the electric traction motor is used in combination with the ICE to give extra power in both the configurations. During braking or deceleration, the traction motor is used as a generator to charge the battery. In standstill, the ICE can continue to run and drive the generator to charge the battery, if needed [47–49]. However, it must be highlighted here that the series-parallel HEV is also relatively more complicated and expensive. The performance indices of a series-parallel hybrid electric vehicle are shown in Table 2. The block diagram of the series-parallel hybrid electric vehicle is shown in Figure 5.

3.5 Complex Hybrid Electric Vehicles (CHEVs)

Another form of series-hybrid configuration is the complex hybrid electric vehicles (CHEVs), which is a split power HEV topology. This topology

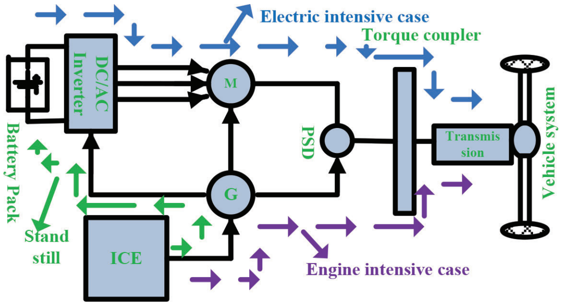

Figure 5 Block diagram of the series-parallel hybrid electric vehicle.

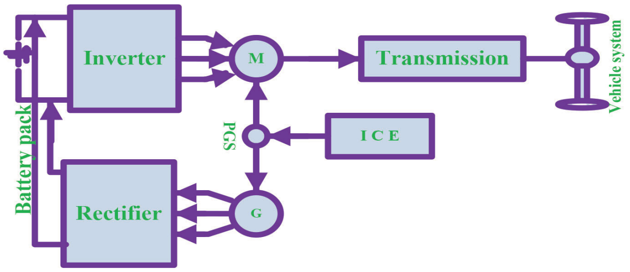

Figure 6 Block diagram of the complex hybrid electric vehicle.

consists of a planetary gearbox, which interlinks the ICE, traction motor, and generator. In the CHEV, the energy flows in a fashion similar to either that of a parallel HEV or a series HEV. In parallel HEV mode, energy flows from ICE via the gearbox to the wheels, whereas in the series HEV mode of operation, the energy flows from generator and motor to the wheels [50]. The performance index of a complex hybrid electric vehicle is shown in Table 2. The block diagram of the complex hybrid electric vehicle is shown in Figure 6.

3.6 Fuel Cell Hybrid Electric Vehicles (FCHEVs)

The potential for superior efficiency and zero (or near zero) emissions has long attracted interest in fuel cells as the potential automotive power source of the future [51–53]. The overall goal of on-going fuel cell research and development programs is to develop a fuel cell engine that will give vehicles the range of conventional cars, while attaining environmental benefits comparable to those of battery-powered electric vehicles [54]. The power conditioner must have minimal losses leading to a higher efficiency [55]. Power conditioning efficiencies can typically be higher than 90%. The block diagram of the fuel cell hybrid electric vehicle is shown in Figure 7.

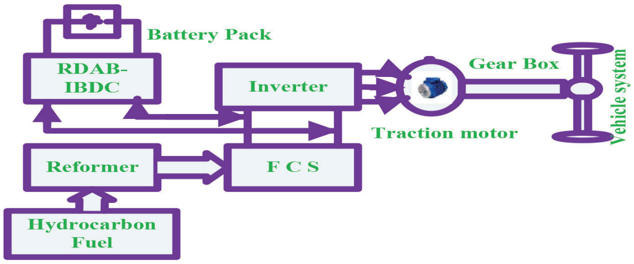

Figure 7 Block diagram of the fuel cell hybrid electric vehicle.

4 Statistical Analysis and Trends of Fuel Cell Electric Vehicles in India

The technology of fuel cells is extremely advanced in the European and American market spurring a growth in their sales whereas in comparison the sales of fuel cells have been very sluggish in the Indian market [56]. The early 2010s saw the development of prototype fuel cell systems for transportation applications and in the later part of 2015, the country started producing fuel cells for portable and transportation applications [57]. The production and sales of FC based electric vehicles is expected to reach a peak of around 3 lakh vehicles by 2020 and the predicted world market especially for buses and cars is shown in Figure 8.

India does not have sufficient knowledge in the technology of the fuel cell electric vehicles (EVs) compared to the western countries. It will take some time to reduce the cost per kW for fuel cell based EVs. In the early 2004, the cost was Rs. 9000 per kW for FC system, which later has come down because of advances and availability of material to make the fuel cell system and availability of skilled labour for production [58]. India has a target of reducing the cost to Rs.1800 per kW of FC system (PEMFC) by the year 2020 and Rs. 1000 per kW by the year of 2030 shown in Figure 9 [58].

The fuel cell system is manufactured in separate parts and assembled like a transformer. The fuel cell system has several components like MEA, GDL,

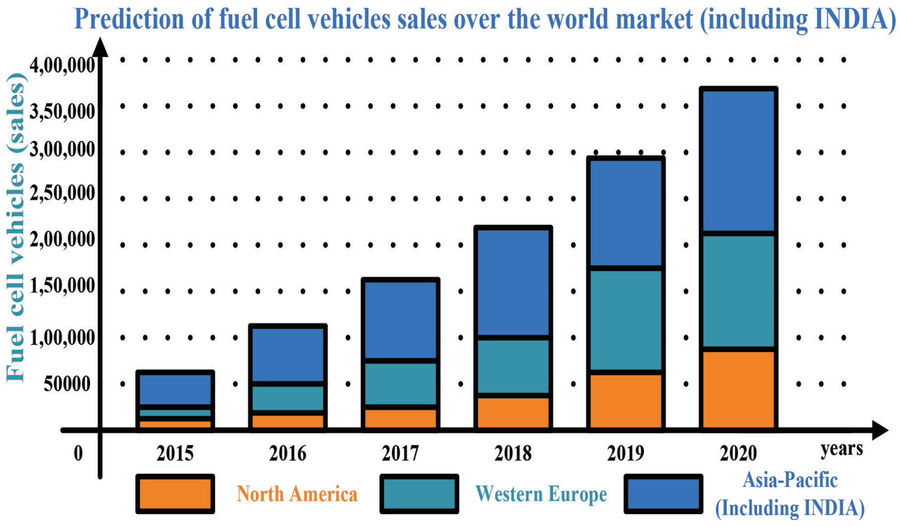

Figure 8 Prediction of Fuel cell vehicles sales over the world market.

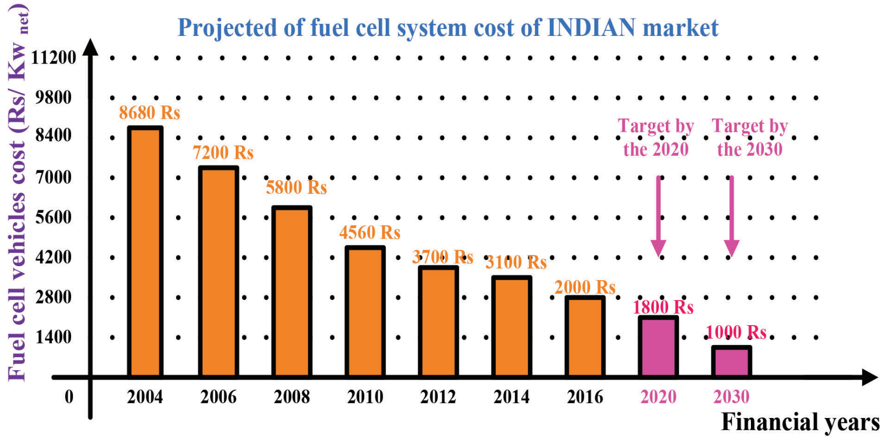

Figure 9 Projected PEM fuel cell system cost in the Indian market.

bipolar plates, field plates and so on [59]. The breakdown cost of PEMFC system components in the year 2008 is shown in Figure 10 and by 2016 the cost of a PEMFC system was expected to decrease by 15% compared to 2008. This price reduction has been feasible because of reduction in the manufacturing cost of catalyst and better fuel management. Reduction of PEMFC system cost achieved is 15% and is shown in Figure 10. as the hatched portion [59].

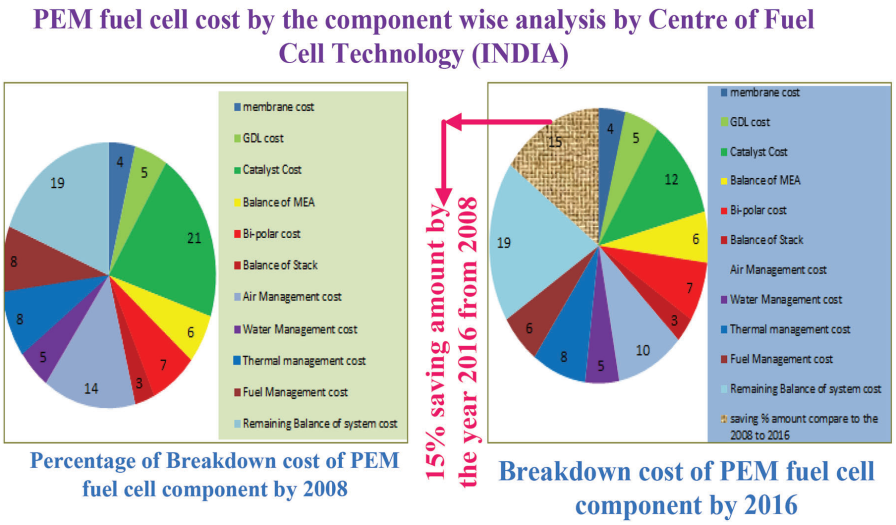

Figure 10 Breakdown cost of PEM fuel cell component in financial year 2008 and 2016.

The worldwide electrification of vehicles started from 1997 as a result of the Kyoto protocol for improving of environmental conditions. It is a big challenge for the automobile industry to develop vehicles which are zero emission and emit lesser harmful particulate in the environment. Due to this protocol, a lot of advancement in the vehicle technology and drive trains of vehicles have started appearing in the market like mild hybrid, full hybrid, PHEV and so on and advancement of technology in the vehicle sector is shown in Figure 11.

The cost of different types of FC systems is shown in Figure 12., wherein it can be seen that the cost of the SOFC is highest compared to the other FC systems. The reference FC system cost is the Rs. 37000/kW and a huge

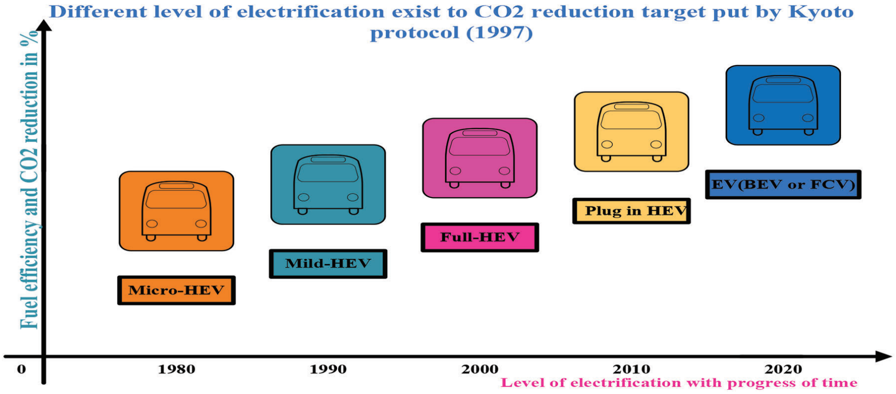

Figure 11 Different level of electrification to reach the target set by the Kyoto protocol over the world market to reduce GHGs.

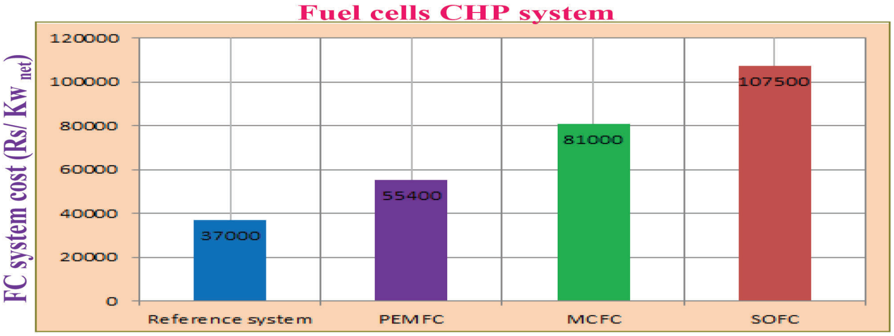

Figure 12 Comparison among the different FC systems over the reference system.

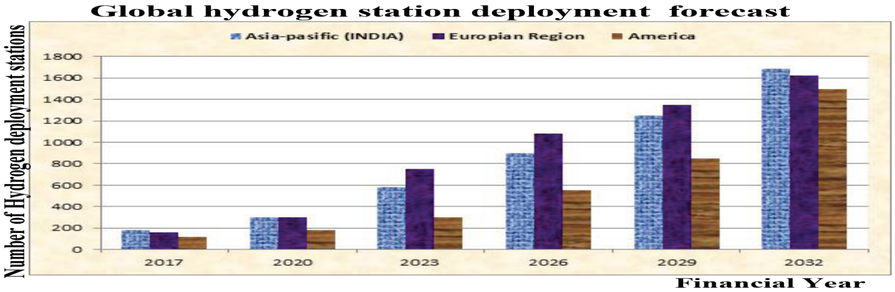

Figure 13 Deployment of Hydrogen fuel stations in the world market with including the Faridabad hydrogen fuelling station.

difference exists between the PEMFC system and reference system [60]. The cost of the FC system would become equal to the reference system by the 2020s according to data from the Centre of Fuel Cell Technology (CFCT) of India.

By 2032 the estimated deployment of hydrogen fuel cell stations worldwide would be 4500. India will have to deploy at least 50 stations by then while the present number of station is two (Faridabad and Dwaraka near Delhi) as shown in Figure 13. In the early 2030s, the Asia-Pacific region would have more hydrogen stations compared to the rest of the European zone as well as America as shown in Figure 13.

5 Development of Fuel Cell Vehicles in India

- A group of Banaras Hindu University (BHU) scientists and the ministry of new and renewable energy (MNRE) achieved a breakthrough event in cutting edge fuel cell vehicle technology. The fuel box for motorcycle weighs about 17 kg, or twice that of a tank with 10 litres of petrol. This lasts for 70–80 km before a recharge. During tests, the three-wheeler clocked a range of 50–60 km.
- A fuel cell (PEMFC) battery hybrid van has been developed in the country and has undergone field performance evaluation.
- Reformer for a 10 kW PEMFC system was developed and tested in the Centre for Fuel Cell Technology (CFCT).
- TATA Corporation Ltd and ISRO have taken the lead role to introduce the latest fuel cell vehicle technology with the new fuel cell based passenger vehicle "Starbus" in India during the financial year 2012–2013.

- Toyota unveiled a hydrogen fuel cell-powered car at the Indian Auto Expo 2016 show held recently in National Capital Region (NCR) near Delhi.
- Indigenous base for research & industrial production is being established for fuel cell vehicle through the research and development centres like ISRO, TATA and M&M.

6 Current Environmental Issues in India

6.1 Economic Developments Causes Environmental Issues in India

- Uncontrolled growth of urbanization
- Industrialization
- Expansion-intensification of agriculture
- The destruction of forests-deforestation

6.2 Major Environmental Issues

- Forest and Agricultural land degradation
- Resource depletion-water, minerals, forest, sand, etc.
- Public health
- Loss of biodiversity
- Loss of resilience in eco-systems
- Poor water supply and sanitation issues
- Natural hazards like floods
- Annual rainfall due to deforestation
- Poor agricultural practices

6.3 Population and Economic Growth

- Habitat destruction
- Changing consumption pattern has led to rising demand for energy
- The final outcome of this is air pollution
- Global warming
- Climate change
- Depletion of natural resources
- Water scarcity and water pollution

7 Challenges of Fuel Cell Vehicles in India

7.1 Infrastructure

7.1.1 Fuel infrastructure

- In the case of portable applications, the most commonly used fuel is methanol, which is sold in the form of liquid for usage on-board vehicles. Since the fuel cell reaction has slower dynamics it may not be able to respond to sudden acceleration demands and thus the FC EV may have to be supplemented with a storage battery or ultracapacitor to deliver the required power instantaneously [61].
- If vehicles are hydrogen fuel based then equipment for producing, distributing, storing, delivering and maintaining hydrogen fuel is important and needs to be in place.
- The current infrastructure for producing, delivering, and dispensing hydrogen to consumers cannot yet support the widespread adoption of hydrogen based FCVs.

7.1.2 Human resource infrastructure

- **Service:** This is a novel technology for the customer, so qualified service and maintenance personnel will be needed. It will require training of new/retraining of existing manpower for maintenance of the fuel cell vehicle unlike the ICEs and HVs which already have a large pool of skilled manpower [61].
- **Development:** A critical need today is for qualified technical personnel to assist in the development and commercialization of these products. It is a novel technology even for the skilled manpower and also requires awareness regarding the control and operation of the fuel cell vehicle and moreover, it is in still under development.

7.2 Cost

- A competitive cost of the order of Rs. 4000–6700 per kW in automobile sector would be acceptable for the FC power pack. As far as the power industry is concerned, the current cost of FC based power generation plant is in the range of 20 lakh rupees per kW when used with CHP.
- FCVs are currently more expensive than conventional vehicles and hybrids, but costs have decreased significantly and are approaching to more affordable rates in the coming years.

7.3 Durability and Reliability

- It would give longer life if and only if there would be a proper maintenance of hydrogen storing tank and proper cooling of the system.
- The long-term performance, safety and reliability of fuel cell vehicles have not been significantly demonstrated in the market.

7.4 System Size

- The size and weight of current fuel cell vehicles must be further reduced to meet the packaging requirements for automobile industry.
- Greater policy support and investment is essential to achieve market readiness. The Indian government must support fuel cell vehicle development through favourable policies and implementation of some pilot projects in reputed national scientific research labs and reputed organizations like IITs and NITs.
- Hydrogen fuel cell vehicles suffer due to lack of sufficient infrastructure for hydrogen refuelling, and the large cost of the catalysts. Platinum is one of the most commonly used catalysts for fuel cells, but it is very expensive. Catalysts are used to break the fuel into ions and electrons and act like barrier between the GDLs and MEAs of the fuel cell. It is very difficult to produce due to the huge cost of material as commonly usage material is carbon and platinum which are costlier than gold and other premium materials.

7.5 Fuel Flexibility

It would be very difficult for consumer to get hydrogen like petrol and diesel in the market. There are some new hydrogen fuelling stations being setup in India like Vijayawada, Vizag and Tirupati etc.

7.6 Lesser Familiarity of the Public

Fuel cell technology must be embraced by consumers before its benefits can be realized. People must become familiar with this new kind of fuel and public education must be used to accelerate this process. As with all new technologies it could be a hurdle for the fuel cell market in the initial stage. The fuel cell technology would come into the market if and only if it is marginally higher or comparable in cost per KW when compared with the HVs and PHVs.

7.7 Environmental Security

Fuel cell vehicles do not produce sound and air pollution and are very human-friendly compared to the ICE and EVs.

8 Comparison

The drivetrains of electric vehicles are distinguished based on the key parameters such as propulsion, efficiency, refuelling time, speed (average maximum speed), acceleration (average), cost and technology. A comparison of the various electric vehicles is compiled in Table 2. The drive train of fuel cell vehicles have excellent advantages and good feasibility to be implemented if the technology is achieved by 2025 in India.

Table 2 Comprehensive comparison among the Electric Vehicles (EVs)

Electric Vehicles / Parameters	Internal Combustion Engines (ICEs)	Battery Electric Vehicles (BEVs)	Hybrid Electric Vehicle (HEVs)	Fuel Cell Vehicles (FCVs)
Propulsion	Internal Combustion Engines	Electric Motor Drives	Electric Motor Drives, Internal Combustion Engines	Electric Motor Drives
Energy Storage Subsystems (ESS)	Fossil Or Alternative Fuel	Battery/Super Capacitor	Fossil Or Alternative Fuel, Battery/Super Capacitor	Hydrogen Tank, Battery/Super Capacitor [23]
Energy Source & Infrastructure	Gasoline Stations	Electrical Grid Charging Facilities	Gasoline Stations, Electrical Grid Charging Facilities	Hydrogen, Hydrogen Production, Transportation Infrastructure and Facilities (For Plug in Hybrid) [24]
Efficiency	Converts 20% of the energy stored in gasoline to power the vehicle	Converts 75% of the energy stored in super capacitor to power the vehicle [32]	Converts 40% of the energy stored in gasoline and super capacitors to power the vehicle	Converts 50% of the energy stored in Hydrogen to power the vehicle

Refuelling Time	Typically 5 minutes	Normally (5–7) hours	Depending upon the usage	5 minutes
Speed (Average Maximum Speed)	124 miles per hour	80 miles per hour	110 miles per hour	40–95 miles per hour
Acceleration (An Average)	(0–55) miles per hour in 8.5 seconds	(0–50) miles per hour in (6–7) hours	(0–60) miles per hour (6–7) seconds	(0–60) mph in (4–6) seconds
Major Issues	Sound and Air Pollution	Battery Size and Management, Battery Life, Charge Facilities and Cost [39].	Battery Size and Management, Control, Optimization And Management of Multiple Energy Sources	Fuel Cell Cost, Life Cycle and Reliability, Hydrogen Production, Infrastructure Cost
Cost	(9,50,450–11,57,550) Rs	(13,62,500–17,70,750) Rs	(12,94,000–17,02,450) Rs	(4,08,600–60,12,000) Rs
Technology	Obsolete Technology	Fully Available	Huge Demand and Good Technology Available	Under Development, Require Huge Technology to Reach The Customers

9 Conclusion

This article has explored the Indian proton exchange membrane fuel cell vehicles (PEMFCVs) market with respect to the need for fuel cells in the transportation field, the need of zero emission vehicles (ZEVs) in logistic hubs, and identified specific fuel supply strategies to meet growth of fuel cells technology. Several environmental and economic drivers are inspiring the fuel cell technology players in developing countries like India. The development of new fuel cell technology for the logistic hubs and small automobile field that is suited to local needs, cost-effective, and uses cleaner fuels like hydrogen should be commercially successful. As mentioned before, the PEMFCVs have many merits compared to the internal combustion engine (ICEs) and hybrid vehicles. These are efficient and produce less or no effect of GHGs. According to experts, the future belongs to modern fuel cell vehicles. Therefore we can say that there is huge potential for fuel cells vehicles in the future in our country.

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