Advancements in Automotive Applications of Fuel Cells—A Comprehensive Review

Newel Francis Thomas, Rishabh Jain, Nishanth Sharma, and S. Jaichandar

Abstract A fuel cell is an alternate source of power supply, and it has nearly zero emissions and has higher efficiency when compared to the conventional sources of power. This type of a power supply unit has a vast base of application; further, it has many automotive applications too. Since the growing risk of environmental hazards and depletion of the conventional fuels being used now, and the changing emission norms, a better fuel-efficient and environment safe power supply is required. The goal of this paper is to understand the various types of fuel cells that are used in this field and the various applications that it has and to understand the different experiments which were conducted previously, how these types of power units are better than the conventional power units, and various ways in which these types of power supply can be used and applied in the current day scenario; also, various future aspects of the same have been discussed.

Keywords Fuel cells · Hydrogen · FCV · PEMFC · Emissions

1 Introduction

Fuel cells are in the field of automobiles for quite some time, the first fuel cell was invented almost 150 years ago [1], and the idea however was the same that is to replace the conventional fuel system with something that is more reliable and more eco-friendly. Replacing is a bit difficult but when used in a hybrid system, the efficiency is higher and also better work output is received. In the past century, the development in the field of fuel cell has rocketed to sky high that which was initially used for space programs soon found its way to the commercial market into vehicles of daily usage [1]. In the early 1990s when the vehicles with fuel cell-fitted power supply came out, despite the efficiency it gave production of raw materials such as hydrogen and storing it was difficult and thereby very costly. It was soon thought that fuel cell

N. F. Thomas (✉) · R. Jain · N. Sharma · S. Jaichandar
Vel Tech Rangarajan Dr Sagunthala R&D Institute of Science and Technology, Avadi, Chennai, India
e-mail: newel.thomas7@gmail.com

L.-J. Yang et al. (eds.), *Proceedings of ICDMC 2019*,
Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-3631-1_6

may not be an economic answer to the energy crisis. But in recent decades, there has been massive development in fuel cells, research and development has shown that the cost price of production of hydrogen and usage has come down drastically by 75% [2], and further down the line it will even get lesser due to the technological advancements taking place every day. This paper discusses the ways in which such a power system can be used to increase the efficiency in the vehicle and ways in which such a knowledge can be used to improve the power generation aspects in vehicles and gives a free way to the ultimate goal of maximum efficiency without any hindrance.

2 Working of Fuel Cells

A fuel cell is an electrochemical device, which means that the chemical energy in the fuel is converted to electrical energy. This energy which is formed is a low voltage and also direct current. It works on the principle of electrochemical reactions. The system contains the reactants (fuel and the oxidizer), electrodes (positive and negative), and the electrolyte. The reactants are fed through the porous electrodes, and the reactants react with the electrolyte and produce a voltage. Now when an external load is connected, the ions travel from one electrode to the other through the electrolyte and also electrons are conducted through the load. The operation of a fuel cell is continuous as long as the fuel is supplied, the oxidizer is supplied, the current flows through the load, and the structural integrity of the chemical is maintained. The emf of fuel cells is at the order of 1v. Many cells are therefore connected in a series, and it is called a module [1].

The Gibbs free energy change is given as

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

where ΔG is Gibbs free energy, T is the absolute temperature of oxidation, ΔH is the change in enthalpy, and ΔS is the change in entropy.

ΔG determines the maximum possible electromotive force (emf) of the cell in terms of

$$E = -\Delta G / nF$$

where E is the emf, F is the Faraday value, and n is the number of Faradays transferred.

To function, the ion exchange membrane must be kept moist. Therefore, some of the water produced by the fuel cell is used as a humidifier for the hydrogen and the oxygen coming inside the fuel cell. The water which is left is exhausted from the fuel cell. Some heat is also emitted from the fuel cell. The heat is either released to the outside or captured and used to heat the fuel cell or can be used for other purposes, such as heating the passenger compartment if needed in cold temperatures.

2.1 Diagram—From [3]

See Figs. 1 and 2.

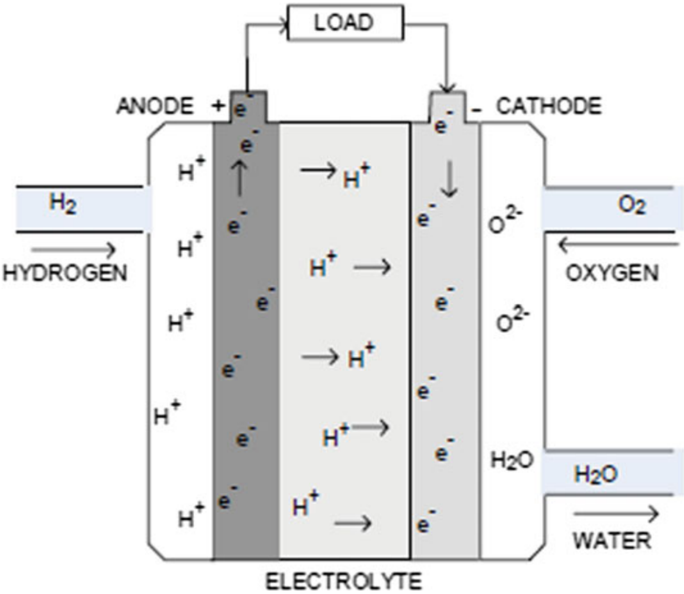

Fig. 1 Fuel cell working

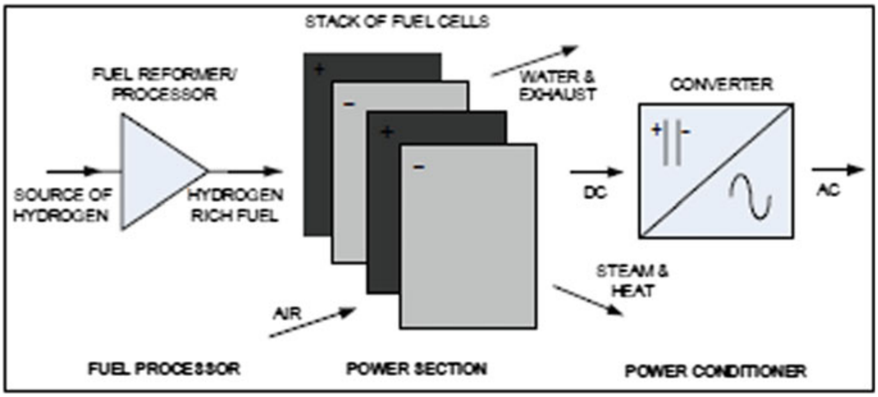

Fig. 2 Assembly of a fuel cell

3 Types of Fuel Cells

The types of fuel cells based on the electrolyte used are as follows.

3.1 Direct Methanol Fuel Cell

The DMFC is a low-temperature fuel cell, it is based on the PEMFC, and it is similar in all aspects, except for the fact that the DMFC uses methanol as the fuel. Thus, the methanol is converted to hydrogen ions and then the usual process of the reaction takes place [4].

3.2 Proton Exchange Membrane Fuel Cell

This type of fuel cell contains the reactants, the electrolyte, and a membrane, and this type of fuel cell has high power density, is smaller in size, and works at low temperatures of about to 90 °C. Platinum stacks are used as the catalyst usually. There is also a high-temperature operating PEMFC, which operates at around 200 °C. This high-temperature PEMFC gives better tolerance to carbon monoxide and also does not need an external cooling system such as water flow to keep it humidified [4].

3.3 Alkaline Fuel Cell

This type of fuel cell was one of the first types of fuel cell to use hydrogen as the fuel. It contains potassium hydroxide as electrolyte. And it uses platinum as the catalyst, due to which it can easily operate in low temperatures of about 50–100 °C. They also have an efficiency of around 50%. This type of fuel cell is costly; thus, it is only used in high-profile sectors such as the military and space exploration [4].

3.4 Phosphoric Acid Fuel Cell

This type of fuel cell again operates at low temperatures of about 160–220 °C. Its efficiency is around 37% but when combined with another power generation source (hybrid system) it can give an efficiency of about 87%. Compared to other fuel cells, this gives less output efficiency therefore not suitable for vehicles, but can be used in stationary places such as hospitals and factories [4].

3.5 Molten Carbonate Fuel Cell

This fuel cell operates at high temperature around 650 °C. They also provide high efficiency that is around 55% singularly, and when in a hybrid system it can reach about 87%. Due to high temperatures, no carbon poisoning happens. Nickel is basically used as the catalyst [4].

3.6 Solid Oxide Fuel Cell

The electrolyte used in this kind of fuel cell is a solid, and it is non-porous metal oxide. The electrolyte used is yttria-stabilized with zirconia. The cost of production is low, and also it can withstand high temperatures from the range of 550–1000 °C. In this, the fuel can be reformed internally, and the excess heat can also be used for preheating the incoming air [4].

3.7 Microbial Fuel Cell

In this, biochemical energy is converted to electrical energy. The catalyst used is microorganisms, and it can be either bacteria or yeast. In this, the chemical transformation is into protons, H^+, and electrons, and H^+ crosses the membrane made of Nafion arriving at cathode. Protons there react with ${O_2}^{2-}$, reach external circuit, and produce water [4] (Table 1).

4 Output

When compared to an IC engine, the values of a fuel cell are as follows (Fig. 3).

5 Application of Fuel Cells

Fuel cells are used abundantly in automotive industry from primary power source to secondary to backup, and given above were the different types of fuel cells. So now further we are going to discuss the various areas in which different types of fuel cells are used, and its applications.

Table 1 Classification of fuel cell [4]

Fuel cell types	Polymer electrolyte membrane (PEM)	Alkaline fuel cell (AFC)	Phosphoric acid fuel cell (PAFC)	Molten carbonate fuel cell (MCFC)	Solid oxide fuel cell (SOFC)	Microbial fuel cell
Common electrolyte	Perfluoro sulfonic acid	Aqueous solution of potassium hydroxide soaked in a matrix	Phosphoric acid soaked in a matrix	Solution of lithium, sodium, and/or potassium carbonates	Yttria-stabilized zirconia	Microbes
Operating temperature	50–100 °C 122–212° typically 80 °C	90–100 °C 194–212 °F	150–200 °C 302–392 °F	600–700 °C 1112–1292 °F	700–1000 °C 1202–1832 °F	Ambient temperature
Anode reactions	$H_2 \rightarrow 2H^- + 2e^\bullet$	$H_2 \rightarrow 2OH^\bullet \rightarrow 2H_2o + 2e^\bullet$	$H_2 \rightarrow 2H- + 2e^\bullet$	$H_2 + CO_3^{2\bullet} \rightarrow H_2O + CO_2 + 2e^\bullet$	$H_2 + O^2 \rightarrow H_2O + 2e^\bullet$	
Cathode reactions	‘$1/2O_2 + 2H^- + 2e^\bullet \rightarrow H_2$	$1/2O_2 + H_2O + 2e^\bullet \rightarrow 2OH^\bullet$	$1/2O_2 + 2H^- + 2e^\bullet \rightarrow H_2O$	‘$O_2 + CO_2 + 2e^\bullet \rightarrow CO_3^{2\bullet}$	$1/2O_2 + 2e^\bullet \rightarrow O^{2\bullet}$	
Efficiency	60% transportation 35% stationary	60%	40%	45–50%	60%	50%
Applications	• Backup power • Portable	• Military • Space	• Distributed generation	• Electric utility • Distributed	• Auxiliary power • Electric utility	Bioenergy process

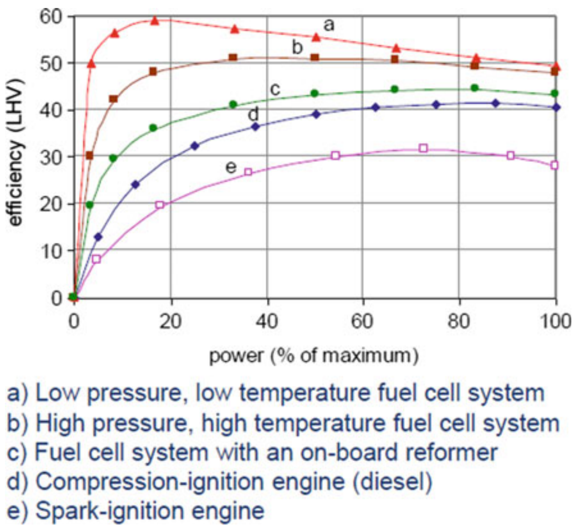

Fig. 3 ICE versus fuel cell [10]

5.1 Transportation

Since the beginning, vehicles have been powered by chemicals (fuels) for power generation of steam, and the hunt for a low emission fuel has always been a topic of research in the automotive field.

Scientists have been searching for alternative that can replace the conventional fuel for transportation. Fuel cell vehicles came into the transportation arena in the late 1990s. One of the most notable types of fuel cells into production was the PEMFC due to its characteristics of high power density, low temperatures of operation, high efficiency, thus giving faster start-up time.

USCAR launched a fuel cell vehicle (FCV) in 2002 to spread awareness and encourage the FCVs.

However, challenges like durability, high cost estimates, and hydrogen storage led to waning research and questions were raised toward the viability of fuel cell of transportation but still recent studies show that the FCV offers potential for larger size and lower cost for long-range vehicles and also faster rate of refueling.

Study by Jih-Sheng Lai et al. [2] Department of Energy's (DOE) Hydrogen and Fuel Cell Multi-Year Research, Development, and Demonstration Plan (MYRDDP) has established cost targets for the FCVs; they have been tracking it since 2002. The cost as of 2017 based on 500,000 vehicles being produced is said to be \$53/Kw with a goal to reach around \$30/Kw. This shows a drastic cost reduction of about 75% in 2002 when it was \$200/Kw. For example if taken into consideration a fuel cell system of 80 Kw with a 5 kg, 700 bar hydrogen tank, which should give a range of 300 miles, the cost target of this system would be approximately \$4900.

5.2 Cars

Zehra Ural Bayrak et al. [5] Daimler-Benz built a series of PEMFC cars; in 1997, they released a methanol-powered car which had a range of around 640 km. Toyota built another hydrogen-powered car which used metal hydride storage fuel cell, and it was a hybrid with battery as alternate source. In 1997 again on the same RAV4 platform, Toyota again created a methanol fuel vehicle. The FEVER prototype is being carried on by Renault and PSA Peugeot. All other major manufacturers are also in the quest of fuel cell vehicles. Ballard Power, Plug Power, and International Fuel Cells, these companies are working on 50–100 Kw fuel systems for cars.

The NECAR 5 is a prototype vehicle of DaimlerChrysler. It is fueled with methanol. It is a DMFC system, the methanol is converted to hydrogen onboard, and thus the reactions take place and the power supplied. The vehicle has no pollutants, the efficiency is higher than conventional fueled vehicles, and the output of carbon dioxide is considerably very low [5].

Jürgen Garche et al. [6] Hyundai started innovative worldwide leasing program for the ix35 car, the Toyota Mirai, the latest in the segment has a 100 kW PEFC stack with a power density of 2 kW/kg and has two hydrogen tanks of 700 bar which thus provides a range of 650 km, and it is still a hybrid with a Ni–MH battery. Recently, Toyota has also reported that the platinum demand has gone done to less than 30 g for a vehicle propulsion system.

5.3 Buses

Transit buses were the early application of fuel cells, since it is a mass transport and it operates in cities and places where pollution is already a major problem; thus, changing to such vehicles would be a huge help. It produces zero emissions and is also economic, but still at many places fuel cells are used as a hybrid system than an independent system. In 1997, Ballard provides a 205 kW PEMC units for a fleet of buses [5].

Clean Urban Transport for Europe (CUTE) was carried out for Europe from 2003 to 2006, where 27 Mercedes Citaro buses were equipped with a 250 kW Ballard PEFC and 40 kg of compressed hydrogen at 350 bar which gave a range of 200 km was used for transport. Cost ranging for buses in the year 2018–2022 is expected to be $400–$600 K [6].

5.4 Electric Battery Hybrid

Cairns et al. [7] As we already know that fuel cells can produce low powers for a long amount of time, it also operates at a low temperature, but there comes a problem when specific power of higher range (100 W/lb.) is required. At such times, we need a hybrid system which can provide the needful power. Thus due to this, we combine the fuel cell with high specific secondary cell which can provide us the required values. Thus, this makes the system hybrid. Thus, the hybrid design provides a combination of high specific power capability and also high specific energy of fuel cells. The hybrid design of the power system consists of two types in it—one is the series-type hybrid system, and the other is parallel-type hybrid system. In a series-type hybrid system, the auxiliary power unit is connected in series with the electric motor and the battery which is also connected to the drive system. In a parallel system, the battery is connected parallel to the main auxiliary power and the drive, and only when needed the secondary power will be activated (Fig. 4).

Ahluwalia et al. [16] Experiment was carried out for a mid-sized sedan vehicle, gross weight 1695 kg, the drag coefficient of 0.32, 2.2 m^2 frontal area, coefficient of rolling friction of 0.009. At the rated power point, the PEFC stack operates at 2.5 atm and 80 °C to yield an overall efficiency of 50%. Thus in the layout, a two-way DC motor is used which gives 95% average efficiency used to step up the voltage to match the PEFC stack voltage or step down during regenerative braking. The mechanical energy at the motor shaft is transmitted to the wheel with one-step gear reduction and then final drive. The study was conducted to check the power needed to reach the top speed that is 100 mph and to accelerate from 0 to 60 mph in 10 s.

Shinji Aso et al. [8] Toyota created a similar FCHV which consisted of a parallel hybrid system; in this, the main power supply was connected parallel with a high-voltage battery. The fuel cell stack is directly connected to an inverter which is then connected to the electric motor and then the drive. The parallel power source (battery)

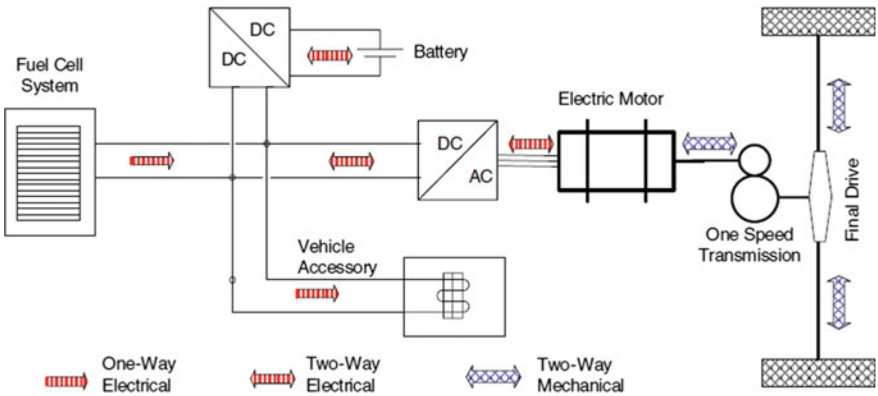

Fig. 4 Electric hybrid drive train [16]

is connected to a converter, which means in times of high power requirements the battery is used and the rest of the time the fuel cell is used. The power regeneration and the efficiency of the system are increased by the addition of the battery, thus making it a hybrid.

Peled et al. [9] Honda created a similar system in which a lithium-ion battery is used, the power output is 100 kW, it has a 288v lithium-ion battery, 4.1 kg hydrogen at 500 psi, and the range 280 km. The Kia new Borrego FCHV again was a hybrid fuel cell vehicle, and it had an 115 kW fuel cell with a lithium-ion battery and had a range of 315 miles. GM HydroGen 4 FCHV was a FCHV too, and it went for testing for 400,000 miles and has a range of 200 miles and 0–60 mphin 10 s. Mercedes blue zero hydrogen concept was again a FCHV, and it had a range of about 400 km for full tank of hydrogen and 100 km for 17.5 kWh on the lithium-ion battery.

5.5 IC Engine-Combined Fuel Cell

Edwards et al. [10] Here, an experiment is conducted to reduce the energy that is destroyed from the engine and which is left out as exhaust; nearly 40% is due to heat transfer and 20% exhaust, and 30% is wasted in combustion; thus, the main motive of the experiment is to reduce the level of energy wasted and thereby increase the efficiency. Thus to solve this, experiments add two power sources for power production, the conventional IC gasoline engine, and the FCV. Thus in such cases, an approximate of 70% efficiency is expected form the whole system. So in this, the process is still in the development stage. The proposed system combines both the systems in such a way that the waste is very low. Thus for that, a normal gasoline engine is taken, then a few of the cylinders are fed with rich fuel equivalence ration, and then the result from that can be used as a hydrogen reformer for hydrocarbons from the fuel; it is later passed through a shift reactor to reduce the carbon monoxide contents, and the rest is fed into the fuel cell for the reaction to occur to produce electricity. Then, any unreacted fuel leaving the fuel cell can again enter into the other few cylinders of the gasoline engine, combust, and give full combustion without any loss (Fig. 5).

5.6 Military Vehicles

Andrukaitis et al. [11] Onboard regenerative design, this is an idea of regeneration of the power while on a mission or operating condition. So by using other electronic components, regeneration can be accessed. The fuel cell works on hydrogen and oxygen, and gives out water. So, the idea is that if you make a closed system, there might be advantages in fuel regeneration. In this closed system, an electrolyzer is

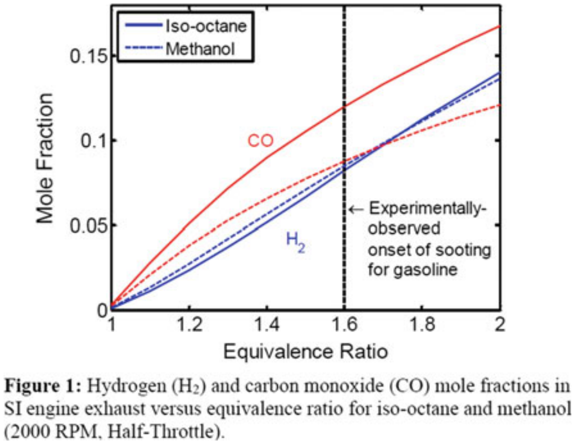

Fig. 5 IC-combined fuel cell [10]

used and the overall reaction occured is reversed. Thus distributing hydrogen and oxygen separately and again feeding it back to the fuel cell, this may increase the range of the vehicle and result in less fuel depletion, thus giving out less vapors and fuel signatures (Fig. 6).

Das et al. [12] Auxiliary power units are used in a vast applications including military, therefore it is necessary that the system be able to withstand certain conditions which relate to the battle fields such as rough terrains, harsh weathers and climate, humidity, and shocks and vibrations, in short has to be sturdy and rigid in various conditions. They should give out very less thermal signatures or any other emission of smoke, light, sound. It should be highly reliable, and also human intervention should be minimum. Such conditions are required in military for silent watch protocol. NMRL has developed 10 kW generator car that uses methanol reformer for hydrogen generation.

Campbell et al. [13] Some of the fuel cells which are used in military applications are H3 350 methanol power system by SER energy, and it has a power output of 350 W.

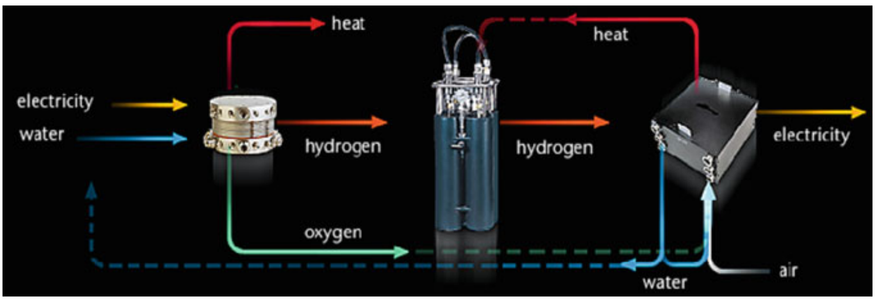

Fig. 6 Military vehicle regenerative design [11]

Power pac is the product made by the company Power cell and it has two variants 2kW and 4kW, which is specially used in military for its low sound applications which maybe used in military operations such as silent watch. Emily 2200 by SFC energy, it is a 90 W and 12/24 VDC system. The Defender series by Ultra Electronics AMI consists of the D300 and D245XR fuel cells. The D300 is a 10.9 kg, 300 W system that can output 12, 14, 24 or 28 V. Nordic power is used as an APU and can make 1 kW. Power core by Topsoe fuel cell can make 2 kW which is again used as an APU. Delphi solid oxide fuel cell auxiliary power unit, it produces 5 kW. Python by Merlin Power Systems produces 1.2 kW at 28 V.

5.7 *Material Handling Systems*

Garche et al. [6] One of the areas where power systems are used and where fuel cells fit exactly is the material handling systems. In this, we require low power with long duration, which is the exact thing which we get usually from a fuel cell, and the major market for these systems is the forklifts. Forklifts need very less power but need for a long duration of time. The operating costs are low too here. Apart from just forklifts, other applications are tow tractors, lift trucks, pallet trucks, and other small-scale vehicles. Plug Power Inc. made a typical power system for these applications called GenDrive which worked at 3 and 14 kW according to the use with fuel capacity of 0.7–3.4 kg of hydrogen at 350 bar pressure.

Bobbett et al. [14] Another application of similar low-powered, low-temperature operating system is used in golf karts. Golf karts usually require small power just to navigate around the golf course and carry passengers and a few loads. Thus in the study, they have used a system which houses a 2 kW fuel cell air cooled, which is developed by Energy Research Corporation.

5.8 *Autonomous Vehicles*

Chraim et al. [15] Autonomous vehicles are vehicles which can operate on its own. It can travel choosing a particular path and reach a destination without any human interference. Thus for such systems, long-life auxiliary power supplies are used so that the range is huge and longer distances can be covered, without being hindered in performance. The shortest path and the least usage of fuel are what give the higher efficiency that is expected from a vehicle of such caliber. Thus, wireless network sensors play a major role in this type of vehicle, the applications of autonomous driving vehicles are vast, and research is going on in major fields to exploit the technology and get better results in the system.

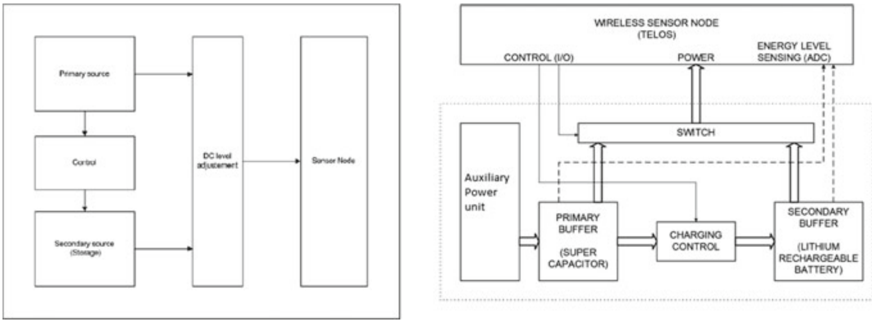

Fig. 7 Autonomous vehicle layout [15]

Wireless network systems, this plays as the most important thing in an autonomous vehicle, as the power and other factors can be provided to the vehicle, but for the vehicle to take decisions on its own and act accordingly is more important. In this, the auxiliary power unit is directly connected to the CPU, the CPU is connected to the various peripherals that are connected with the system, and also the CPU is connected to the communication system. Now when the vehicle moves, all the peripherals are monitored by the CPU and approximate conditions are checked and understood for the best optimal output (Fig. 7).

6 Future Aspects

- Substitution of platinum in a PEMFC would be a significant reduction in cost and would make FCVs more affordable. Research is ongoing in using carbon nanofibers which might be cheaper, lighter, and even more efficient when compared to the current platinum.
- Further onboard hydrogen formation can be achieved by recycling the exhaust vapors through a unit which again separate the hydrogen from the water and thus can give an added power output which can be stored for further use. However, the challenge for this concept is that the additional hydrogen which is generated should be cost-wise feasible when considering the additional costs that would go into the setup of an electrolyzer and a reformer. Also, the time taken for the reformation should be low and effective for the system to be brought into use.
- Further thermoelectric generators coupled with fuel cells can provide power at high operating temperatures for certain types of fuel cells.

7 Conclusion

So from the above paper, the applications of the different types of fuel cells in the different automotive fields are given briefly, the ways it has been used before and also the future applications in which they might be used. Fuel cells are the need of the hour, and shifting to a greener and more economic and even more efficient form of power supply should be the first priority, due to the climate changes and depletion of natural resources. Fuel cells in hybrid with the conventional system are also a viable option. Hydrogen as we all know is the most abundant element on the earth, we must use it as an advantage, and thus for the years to come hydrogen fuel cells are the safest and the best mode of power supplying.

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