International Journal of Science and Research (IJSR)
ISSN: 2319-7064
ResearchGate Impact Factor (2018): 0.28 | SJIF (2019): 7.583

Hydrogen as an Automotive Fuel

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Abstract: ***Hydrogen has always been a strong contender for being the primary energy source for transportation and domestic use, but it has always been outweighed by additional investment in its alternative technologies. In this paper, hydrogen is being analysed as fuel for vehicles on technological, economical, and ergonomic fronts. Major challenges limiting the use of this technology are discussed with painkillers for these issues. There are multiple future opportunities that can be a game-changer for this technology, making it a one-stop-shop for different energy requirements and it can transform the car into a powerplant to reduce the grid dependency. The mass electrification of vehicles also poses a challenge for the power infrastructure to fulfil the huge demand expected and this is exactly where hydrogen fuel can step-in to acts as an independent load sharing technology. The vast size of the vehicle market allows multiple technologies to co-exist and mature with time and reach the highly efficient levels where the ICE engines have reached.***

Keywords: Hydrogen fuel, energy, transportation

1. Introduction

It is not possible to stop the fossil fuels from running dry and stop the greenhouse gasses coming from its use. The toxic pollution has filled the environment with fumes that are making the earth rotate in a new direction which has made the climate change erratically. In a short period, these hydrocarbons have spread their roots very deep into human lives. Machines and mechanisms have evolved to ensure the efficient integration of these resources.

The role of these fuels in transportation was integral and helped the civilizations flourish and spread with no boundaries. This widespread adoption also made these vehicles one of the culprits in the season change. After decades of research and consummation, the reign of these fuels and their auxiliaries are being challenged by greener, renewable and sustainable sources. The source of energy being investigated here is the same from which the sun also derives its energy. The focus from the hydrogen economy has been distracted multiple times with hydrocarbons in the past and batteries in present. Hydrogen being the most abundant element on earth is still not easy to use as a fuel directly or capsuled as efficiently as hydrocarbons. To have a birds-eye view of the problems and developments in the adoption of Fuel Cell Electric Vehicles (FCEVs), the technical, managerial, and psychological aspects are being scrutinized in this review.

1.1 Problem definition and objectives

With the growing concerns over the emissions and the gigantic amounts of greenhouse gases being added to the atmosphere with each passing year, there is an exigent need to get a sustainable alternative fuel, gives out fewer emissions, and most important is feasible to accommodate in the present market tableau. Hydrogen can be seen as a very good fill-in as research is being conducted to harness energy from hydrogen for a long time. In this investigation, the aim is to find out the best ways for the promotion of hydrogen as a fuel for the automotive industry.

1.2 Course of the investigation

The background contains the fundamentals of the functioning of fuel cells and how the FCEVs integrate the fuel cells to facilitate mobility. The methods of production of hydrogen and the storage technologies are then described. Then in the methodology, a justification of research methods are provided. After which the expectations of the customer and the behaviour of the firms are discussed to get an idea about the current market scenario. The challenges and advanced technologies that can help to improvise the system identified from the literature and their implications are shared under Findings. These results are analyzed in the discussion section. In the final section, all the data is elucidated with scope for future developments.

2. Theoretical Background

2.1 Fuel Cell Technology

Fuel cells are electrochemical devices having two electrodes which are coated with a catalyst, typically platinum, and are separated by a polymer membrane (PEM). At the anode, hydrogen gas is supplied which is split into protons and electrons. The protons flow through the electrolyte to reach the cathode whereas electrons flow through an external circuit generating electric current. At the cathode, oxygen is supplied which combines with electrons and protons by the catalyst to produce water as a by-product, as shown in Figure 1. The fuel cells can be stacked to get the required voltage (Francis, 2002, p. 34) [1].

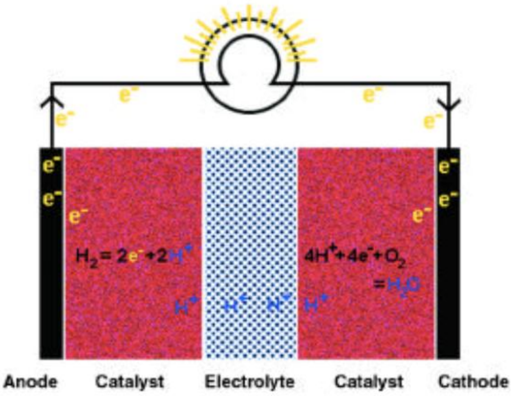

Figure 1: Working of a fuel cell(Francis, 2002, p. 35) [1]

2.1.1 Advantages of fuel cells

- There are no moving parts that help to neglect the vibrations and wear of the parts of the system.
- Theby-product of the electricity generation is not a pollutant.
- They are more efficient than conventional engines.
- The maintenance of Fuel cell vehicles is easy as there are fewer moving parts.

2.1.2 Types

The fuel cell can be differentiated based on the type of electrolyte used, which also influences the necessary catalysis and the operating temperature. The different types of fuel cells in the market are listed in table 1 (Sahaym & Norton, 2008) [2].

Table 1: Types of fuel cells

Type	*Electrolyte*	*Op. Temp. (^oC)*	*Applications*
PEM	Perfluorosulfonic acid	<120	•Backup power •Portable power •Distributed generation •Transportation
AFC	Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane	<100	•Military •Space •Backup power •Transportation
PAFC	Phosphoric acidsoaked in a porous matrix or imbibed in a polymer membrane	150–200	Distributed generation
MCFC	Molten lithium, sodium, and/or potassium carbonates, soaked in a porous matrix	600–700	•Electric utility •Distributed generation
SOFC	Yttria stabilized zirconia	500–1,000	•Auxiliary power •Electric utility •Distributed generation

2.2 Hydrogen production

Hydrogen is produced using multiple primary agents that have different end uses. A schematic with all the processes used to produce hydrogen is given in Figure 2.

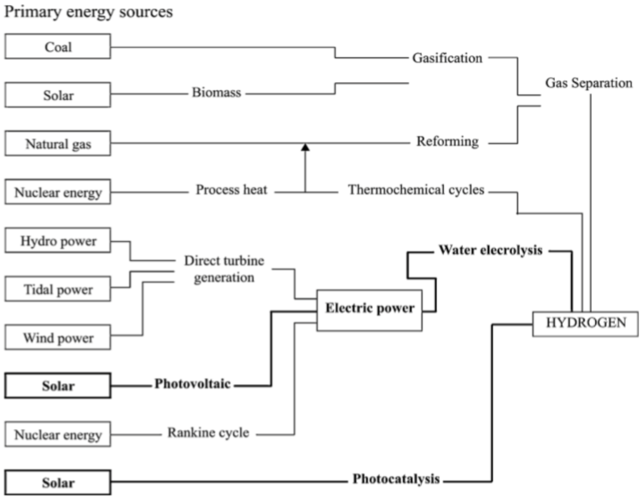

Figure 2: Primary hydrogen sources and their use in hydrogen production (Sahaym & Norton, 2008, p. 5397).

- **Steam reforming:** It is one of the most widely used methods with 95 percent of the hydrogen being generated with it. Hydrogen is produced by the reaction of natural gas with high-temperature steam.
- **Electrolysis:** Electricity is used to split water into hydrogen and oxygen.
- **Gasification:** Coal or biomass is converted to gaseous components and then reacted with steam to get hydrogen.
- **Photobiological process:** Green algae consume water in presence of sunlight and release hydrogen as a by-product.

2.3 Storage of hydrogen

"An ideal storage system should be able to discharge the fuel to meet the power demand under all the driving conditions. The average fuel consumption of a hydrogen-powered midsize crossover Sport Utility Vehicle (SUV) can go from about 0.1 to 0.2 g/s for city drive(30 km/h and 50 km/h; corresponding to about 10 kW fuel cell power) to 0.4—0.6 g/s for a highway drive(at 100km/h and 120 km/h; about 30 kW fuel cell power)" (Miguel, Acosta, Moretto, & Cebolla, 2015, p. 14769) [3].

The hydrogen can be stored in the following ways:

- **Compressed hydrogen:** A compressed hydrogen assembly comprises of the check valve, shut-off valve, a thermally activated pressure relief device, and a high-pressure storage tank that has two layers of the outer layer to provide structural rigidity and the inner layer to prevent a gas leak. The storage of compressed hydrogen is done at 35 MPa or more commonly 70 MPa. It doesn't meet the volumetric density requirements even at high pressures of 650 bar. Compressed hydrogen has very high flammability, which can be destructive in case of a collision.
- **Liquid hydrogen:** Insulated cylinders hold cryogenic liquid hydrogen cooled to -253°C. It meets the volumetric and gravimetric requirements, but refrigeration consumes a lot of energy. There is also a chance to boil off and refuelling is not safe with it.
- **Hydrides:** They have sufficiently high gravimetric density. The hydrogen is bonded to the metal sublattice

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via covalent bonds. The separation of hydrogen from the lattice also requires an ambient temperature range of (-20 to 100°C) but the desorption process is slow and that leads to greater refuelling times. The use of a catalyst can be one solution to this problem to speed up the absorption and desorption. Magnesium is currently being used as a catalyst, but it also gives limited success. With the decrease in refuelling time, the heat generation in separation would also require thermal management. (Birnbaum, 2005, p. 64) [4].

3. Findings

3.1 Challenges

3.1.1 Acceptance of innovation

"It is not unusual for there to be a long time from when the innovation first becomes available to the point at which it is widely adopted" (Fry, Ryley, & Thring, 2018, p. 2) [5].

Rogers' Theory of Diffusion of innovation says there are five stages through which an individual passes before making the final decision of adoption and rejection as shown in Figure 3. The consumer is made aware of the technology in the knowledge stage and persuasion depends on the favourable or unfavourable attitude of the consumer.

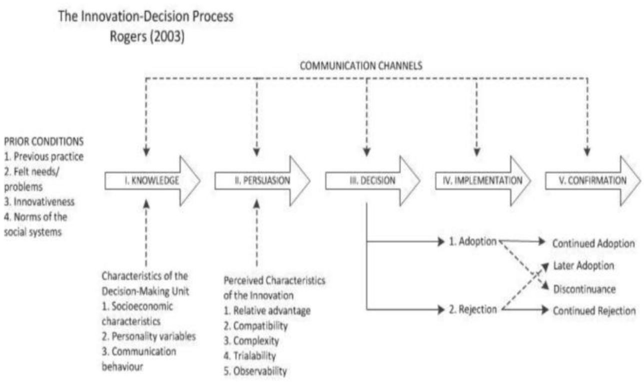

Figure 3: The Innovation-Decision Process (Fry, Ryley, & Thring, 2018, p. 3) [5].

"The decision is likely to be affected by the risk and uncertainty that are associated with adopting new technology, which concerns financial risk, performance risk, the uncertainty of future consequences, image, and the changes to lifestyle that may be required" (Fry, Ryley, & Thring, 2018, p. 5) [5].

The adoption of FCEV should not seem like a sacrifice in any way rather it should boast of the benefits over conventional vehicles. The most important factors that affect the decision of new buyers are shown in Figure 4.

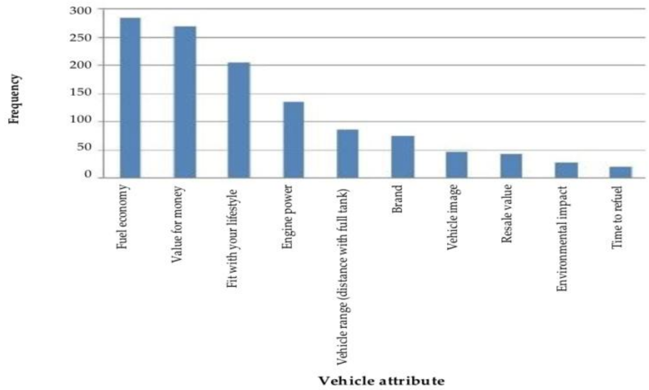

Figure 4: Vehicle attributes in order of importance (Fry, Ryley, & Thring, 2018, p. 14) [5].

3.1.2 Awareness

The consumer awareness study suggested that only eight percent of the population of the USA were aware of the FCEV technology and the incentives that are associated with them. The study conducted by consumer awareness was able to highlight that the main sources of influencing the decision making of the consumers are media, friends, and family. These mediums can be used to reach the target audience to make sure that technology is made known in the market and assure people about the reliability of the vehicles (Fry, Ryley, & Thring, 2018, p. 12) [5].

3.1.3 Charging infrastructure

Hydrogen is stored as compressed gas in the hydrogen storage cylinders in the FCEVs but refuelling them is not just a matter of nozzle change at petrol stations. High-pressure compressors force the hydrogen into the cylinders through a tightly sealed nozzle until the required pressure is reached (Tollefson, 2010, p. 1264) [6]. The hydrogen leaving the production plant needs to be conditioned first using a process called pressure swing adsorption. After this, the hydrogen is either compressed or liquified. The bulk hydrogen is stored at pressures of 20 MPa and for transportation cryogenic liquid hydrogen at 21 K is preferred. Another novel approach can be the production of hydrogen on-site by using small electrolysers. It helps to reduce the transportation and distribution energy sink (Bünger & Michalski, 2017, p. 116) [7].

3.1.4 Temperature and mass flowrate

The major parameters that influence the refuelling thermodynamics of the hydrogen tank are the tank volume and material, the initial temperature of the tank, pressure rate, and mass flow during filling of the tank. The temperature of the hydrogen while input needs to be less to ensure that the State of Charge (SoC) is high. In other words, SoC represents the content of the storage tank. Similarly, the mass flow rate has a negative relationship with the SoC. The target of the standard authority is to have an average mass flow rate of 25 g/s, which can refill a 5 kg tank in about 200 s (Cebolla, Acosta, Miguel, & Moretto, 2015, p. 4699) [8].

"At full throttle operations, the mass flow rates of the fuel may reach up to 1.5—1.8 g/s. The removal of hydrogen at a very brisk rate can result in depressurization of the hydrogen tank and decrease of the internal energy of the gas which results in a decrease in temperature. This decrease of temperature when combines with the buoyancy effect where the warmer air moves up, a vertical gas temperature gradient is set up" (Miguel, Acosta, Moretto, & Cebolla, 2015, p. 14769) [3].

The effect of this heat exchange is especially visible towards the end of the discharge when the MFR becomes smaller and the gas mass in the tank is considerably reduced". Exactly opposite of this happens in the case of refuelling where the internal energy of the gas increases and as a result temperature increases. The standards limit the temperature to a window of -40^{O}C and +85 ^{O}C in operating conditions as well as refuelling and defueling.

3.1.5 Freezing of water vapour

The water vapor can freeze in extremely cold environments and cause the whole internal system of the fuel cell to fail under stress. This problem was handled smartly by General motors by allowing the exhaust system of the fuel cell even after the car is shut down to allow the heat of the cell to drive out all the residual water from the system. Now, the companies have come a long way where the FCEVs are manufactured that can start even at -37°C (Tollefson, 2010, p. 1263) [6].

3.2 Future opportunities

3.2.1 Nanotechnology

Nanotechnology can be a saviour for the hydrogen economy as it helps to increase the surface area by multiple folds that can make the catalysts and storage material extremely efficient. It can also improve solar water splitting viable by increasing the area of adsorption (Sahaym & Norton, 2008, p. 5396) [2].

3.2.2 Car as a power plant

The hydrogen here doubles up as a storage solution at the time of excess generation and as a fuel for transportation and when the generation is less. With the additional ability to exchange power with the main grid, the microgrid also reduces the congestion of the power network and the power plants are not overloaded to fulfil the demand. The tariff rates will influence the decision of the owner to calculate the amount of energy that is should be exported or stored for transportation depending on the load profile.

- **System:** CaPP microgrid consists of a wind turbine, an electrolyser, a photovoltaic system, some residential loads, and a hydrogen storage system as shown in Figure 5.
- **Working:** Wind energy and solar energy are used to power the household and the buffer energy generated is used to produce hydrogen by electrolysis. This hydrogen is stored in the central storage system that is used at the hydrogen refilling station by FCEVs. The FCEVs can be used for mobility when required and when not in use they can be used to supply energy to the neighbourhood. The generation using the renewable sources may fluctuate with outside weather, the system can import power from the main power grid in that case and vice versa feed the energy back to the grid. The rates of bidirectional flow are determined by the power supplier of the region based on the load and generation units of the firm.
- **Limitation:** Excess heat is generated as a by-product when the fuel cell is at work. To regulate the temperature bigger radiator and cooling fans are installed in the FCEVs. In the stationary mode when the vehicle is generating electricity, the fuel cells are operated at a partial load to ensure that the heat generated can be controlled by the additional modifications done to the cooling system of the vehicles. The heat can also be harnessed by using a heat exchanger that can put the heat energy to use directly, say in keeping the building warm at night (Alavi, Lee, Wouw, Schutter, & Lukszo, 2016, p. 297) [9].

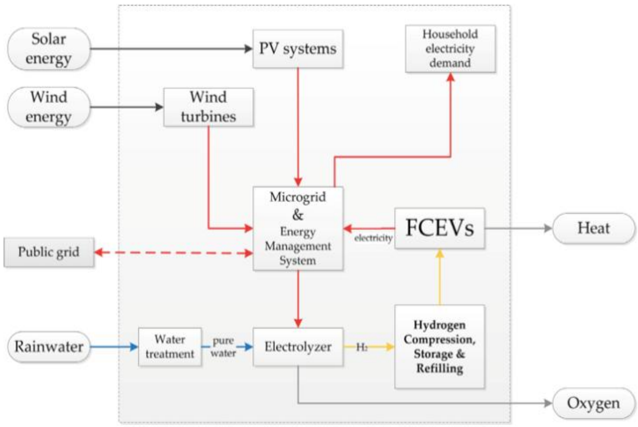

Figure 5: CaPP Microgrid system (Alavi, Lee, Wouw, Schutter, & Lukszo, 2016, p. 298) [9].

3.2.3 Zero energy building

"The conceptual understanding of a zero-energy building (ZEB) is that it is an energy-efficient building able to generate electricity, or other energy carriers, from renewable sources in order to compensate for its energy demand" (Robledo, Oldenbroek, Abbruzzese, & Wijk, 2018, p. 616) [10].

The European Union has mandated all the buildings to be close to ZEB from 2019. The use of batteries to store energy from renewable sources is a short-term approach but for long term hydrogen fuel cells are required to ensure the desired reliability. A ZEB ecosystem can look like the setup in Figure 6.

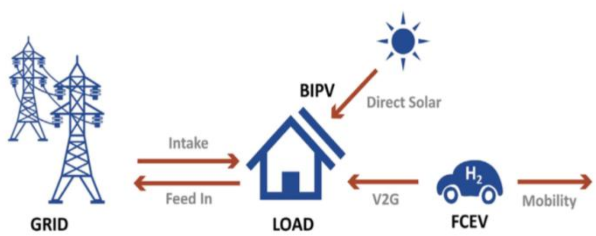

Figure 6: Schematic drawing of hybrid system under analysis with hydrogen FCEV (Robledo, Oldenbroek, Abbruzzese, & Wijk, 2018, p. 618) [10].

A simulation was done in the Netherlands with a building installed with solar panels, the FCEV, and integration of the vehicle to grid power generation yielded profiles for the production through solar and consumption by loads in the house depicted in Figure 7.

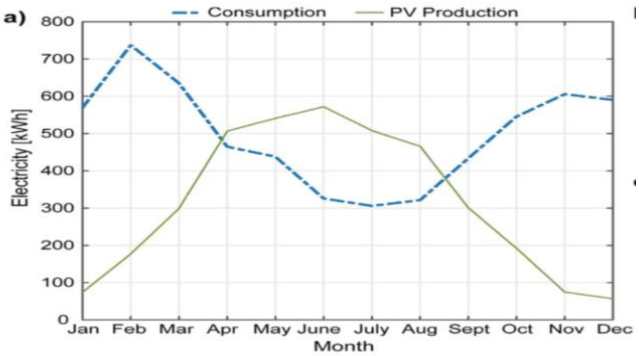

Figure 7: Electricity produced and consumed by the simulation house (Robledo, Oldenbroek, Abbruzzese, & Wijk, 2018, p. 619) [10]

To evaluate the energy performance of the system two factors were introduced, on-site electrical energy fraction (OEFe) and on-site electrical matching (OEMe) which are defined as follows

$$OEFe = 1 - \frac{E_{imp\ ,t}}{E_{cons}} \quad (1)$$

where E_{imp} is Electricity imported and E_{cons} is Electricity consumed.

$$OEMe = 1 - \frac{E_{exp\ ,t}}{E_{prod}} \quad (2)$$

where E_{exp} is Electricity exported and E_{prod} is Electricity produced.

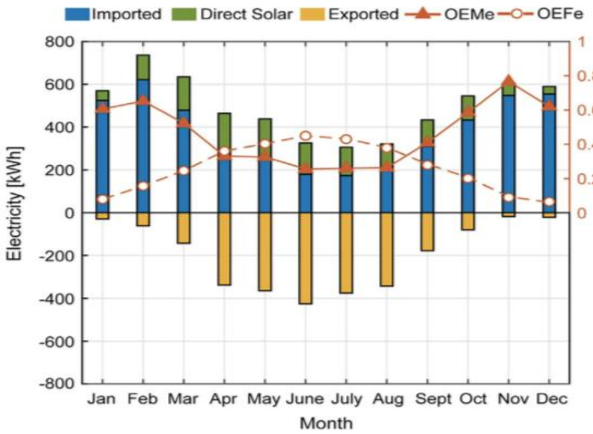

Figure 8: Bar Chart showing electricity consumed and exported monthly (Robledo, Oldenbroek, Abbruzzese, & Wijk, 2018, p. 620) [10].

3.2.4 Use of turbocharger

More air pressure would mean more power output and efficiency. This will cut down on the number of fuel cells required to generate the same power. It can be an effective way of weight cutting and downsizing that will extend the range even further. The use of turbochargers will also bring down the warmup time for the fuel cell to reach its optimum output (Kerviel, Pesyridis, Mohammed, & Chalet, 2018, p. 2) [11].

3.2.5 Driver monitoring and assistance

The online monitoring of the vehicle condition in various scenarios can help to predict the behaviour of the driver and vehicle in the journey and ensure the reliability and readiness of the components and the fuel tank according to the coming journeys. The sensors connected to the CANbus can store this data as all the actuation takes place with CANbus itself. When clubbed with a map and positioning system, the driver assistance software can generate a computer map of vehicle surroundings and alert the driver about any potential hazard that can affect fuel consumption(Perham, 2011, p. 23) [12].

4. Discussion

4.1 Requirements of the future energy market

The electric drive systems for the vehicles in the market are given in Figure 9. Using the electricity from the main power grid directly for transportation is not a good idea as it will overload the power lines as the production profiles don't overlap the load profiles. Therefore, storing the energy in the batteries and then using it provides flexible capacity. The integration of this approach with a mobile fuel cell technology can help to meet the electricity requirements at times of shortages. "E-mobility has moved into the focus of reducing greenhouse gasses. This focus is specifically sensitive next to identifying options to reduce energy use by, e.g., adapted user behaviour, as all energy not needed by the end-user does not require to be produced, transported, and distributed in the first place." (Bünger & Michalski, 2017, p. 115) [7].

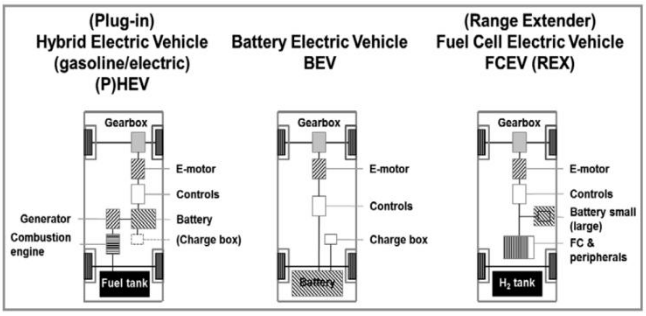

Figure 9: Potential Alternative drive-system options in the market (Bünger & Michalski, 2017, p. 115) [7]

4.2 Cost comparison with other sources

BEV depends directly on electricity and hence it can also overburden the grid at the peak demand times. Due to the low energy density, the role of charge speed and traffic at the refuelling stations becomes important. On the other hand, it is stored with a short term (Onsite buffer for days) or a long term (Central hydrogen storage in salt caverns) strategy. The hydrogen can bridge the gap between renewable sources. Adding the flexibility of electricity supply with a controlled charging and vehicle to grid technology.

When compared with Battery electric vehicles the FCEV will require greater investments for hydrogen stations, hydrogen production, and delivery infrastructure. The specific investments when compared with the refuelling time and utilization will, however, come out less than the fast chargers for the battery electric vehicles. In the case of BEV, the cost is directly proportional to the number of vehicles and as a result, the increase in the number of BEV will result in a huge space and investment requirement. For the FCEV the case is exactly the opposite of it as shown in Figure 10, the required investment is higher for the small lot of beginners, but the costs will come down with the mass adoption. “The level and difference in costs for charging and refuelling stations are comparatively small: 0.22 €/100 km for BEVs and 0.54 €/100 km for FCEVs. In this context, the station costs include the supercharger in the BEV case and compressor, pre-cooling unit, and dispenser in the FCEV case” (Bünger & Michalski, 2017, p. 120) [7].

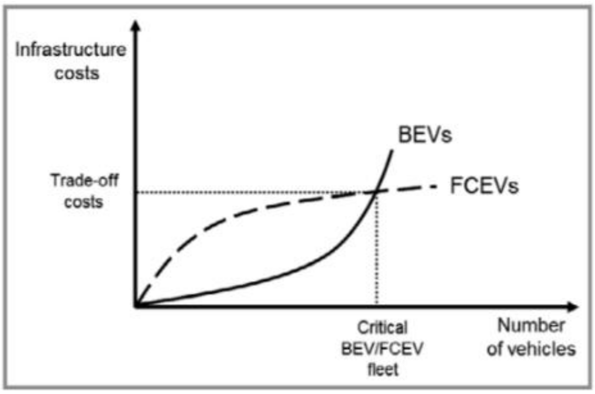

Figure 10: Qualitative investment needs for BEC and FCEV infrastructure (Bünger & Michalski, 2017, p. 117) [7]

5. Conclusion

With an energy demand approximated to reach about 30 TW in the coming years, cutting down on the use of fuels is not a solution. The increase in energy demand is an inevitable phenomenon that is very crucial for the development and growth of nations worldwide. The investment should be made on some of the highest potential alternative fuels that can go a long way without a need to replace them. Hydrogen with its multi-facet nature proves to be on the top of the list. Once the use of hydrogen is adopted with open arms the costs are expected to go down for production, storage, FCEVs, and even the infrastructure to make it available. Many projects are currently under progress and completed that have provided positive results and indicated the sensitive areas that need to be addressed with a higher degree of practicality. Being backed up with years of research and experimentation the use of hydrogen should be promoted as an automotive fuel and all the measures should be taken to ensure a stable transition to this new power source. Also, with a huge market space, there are enough opportunities for multiple technologies to co-exist and flourish at the same time. Coming back to hydrogen, there is still scope for some pillars to be enhanced to make sure the hydrogen economy is uncompromising, some of them are:

- The cost of hydrogen available from renewable sources, which is called green hydrogen is more than the grey hydrogen received from non-renewable sources.
- “The costs of driving BEVs or FCEVs will be much higher than for driving a conventional diesel or gasoline vehicle as both the vehicle purchase prices and the electricity or hydrogen fuel costs will be higher at least in the transition phase” (Bünger & Michalski, 2017, p. 124) [7].
- Oversizing of renewable power plants can also reduce the storage needs, which will bring down the need for hydrogen production and distribution.
- The hydrogen can also be diversified in its applications like for places where there is no electricity and fuel cells can be used to ensure a better return of costs.

6. Abbreviations

APA	American Psychological Association
PEM	Polymer Electrolyte Membrane
AFC	Alkaline Fuel Cell
PAFC	Phosphoric Acid Fuel Cell
MCFC	Molten Carbonate Fuel Cell
SOFC	Solid Oxide Fuel Cell
Op. Temp.	Operating Temperature
FCEV	Fuel Cell Electric Vehicle
BEV	Battery Electric Vehicles
MPa	Mega Pascal
ZEB	Zero Energy Building
CaPP	Car as a Power Plant
H2ME	Hydrogen Mobility Europe
K	Kelvin

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