*Aceh Int. J. Sci. Technol., 11(2) 114-127*
*August 2022*
*doi: 10.13170/aijst.11.2.24592*


**Aceh International Journal of Science and Technology**
**ISSN: p-2088-9860; e-2503-2398**
**Journal homepage: http://jurnal.unsyiah.ac.id/aijst**

# Proton Exchange Membrane Fuel Cell (PEMFC) and Its Prospect for Powering Automobile in the Future: A Review

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Received : January 29, 2022
Received in revised from July 29, 2022
Accepted : July 9, 2022
Online : August 29, 2022

**Abstract –** Increasing responsibility toward the environment forced the transportation sector to shift its gear toward electric vehicles. While battery electric vehicle (BEV) has started enjoying success, it poses a question as to whether or not fuel cell vehicle (FCV) becomes redundant even before being widely deployed. The commercialization of FCV usually only comes after a long period after the prototype was introduced, signifying certain barriers to large-scale utilization. Aside from the various LCAs, studies have also tried to estimate the future cost and model FCV adoption. Due to the limited data and different regional conditions in which the project was done, these researches used vastly different scenarios and assumptions, making the result differ significantly. The lack of a clear-cut answer might indicate that the fate of FCV is not yet decided, and the PEMFC might still play a part in the green transportation era, albeit not as the dominant technology. Alternative uses and the condition required to utilize them were discussed in this short review.

**Keywords:** Fuel cell, PEMFC, hydrogen, FCV, BEV

## Introduction

Vehicle emission is undeniably a great source of greenhouse gas (GHGs) emission, which as of 2010, contribute 14% of the total 49 Gt $CO_2$-eq (IPCC, 2014). Vehicles produce a quarter of the world's fossil fuel emissions, and 74% of that comes from the exhaust pipe, commonly called tailpipe emission (International Energy Agency (IEA), 2018). The increase in vehicle ownership also concerns and is still expected to grow over the next decades (World Health Organization, 2014). People are also becoming more mobile. Before the Covid-19 pandemic, a study expected that global transport, in passenger-km, will be more than doubled from 2005 to 2050 (Akashi and Hanaoka, 2012). As much as global transport decreased during the Covid-19 pandemic, it remains to be seen if the trend will stick.

Since data has shown that tailpipe emission has the largest share of vehicle carbon footprint, most vehicles are now designed to keep their tailpipe emission at a minimum. Europe Parliament plans to ban sales of conventional cars, which burn fossil fuel in their internal combustion engine (ICE). Although the final decision on the start time of this policy is yet to be official, many countries in Europe have, to various extent, adopted the battery electric vehicle (BEV) as a cleaner alternative (Abnett, 2022). Meanwhile, another type of electric car that has been overlooked since BEV started to gain popularity is a fuel cell vehicle (FCV). FCV uses hydrogen as a fuel; hence only has water as the tailpipe emission.

Interestingly, the first ICE car designed by Francois Isaac de Rivaz used hydrogen fuel during the demonstration in 1807 (Kantola, 2017). With zero emission and very high energy density, hydrogen is an attractive energy carrier, prompting the term hydrogen economy. While BEV uses a battery stack to store electricity to power the vehicle, FCV utilizes a mix of hydrogen and electricity to power them. There are several fuel cell types, but for automotive applications, a proton exchange membrane fuel cell (PEMFC)—also referred to as a polymer electrolyte membrane fuel cell—is considered the most suitable (Niakolas et al., 2016). Hydrogen is dangerous to burn directly; thus, oxidation and reduction occur in the fuel cell at different

doi: 10.13170/aijst.11.2.24592


anode and cathode places. The energy produced is electrical rather than heat and is also more efficient for shaft work.

The first PEMFC vehicle is Honda FCX, launched in 2003 for leasing after being approved by the U.S. government (Grobart, 2003). It decidedly falls short of public expectation after the road use test (Ettel, 2005). Since then, several notable car companies such as Honda, Toyota, and Hyundai have tried to build another model with improved performance. Some even use a hybrid power source with a battery (Wang *et al.*, 2018). Unfortunately, there is no breakthrough, whether in the technological or commercial sense. The first successful PEMFC car that people can buy is Toyota Mirai, released in 2015. Despite being successful, the sale is slower than BEV, which accumulated sales surpassing million in 2017 (ZSW, 2022). Nowadays, the green or zero-emission vehicle is synonymous with BEV in people's minds, with nary a thought for FCV. While FCV fades into the background, the question is whether decades of research on FCV will be for nothing, or can FCV still have a place in future transport systems? The environmental impact of FCV also needs to be addressed since, despite the zero-tailpipe emission, current hydrogen production is not carbon-free.

## PEMFC Technology and Its Application

Fuel cell harvest the chemical energy of a fuel, converting them into electric current. The fuel comes to the anode to oxidize. The electron released from the oxidation process flow on the external circuit as electric current, finally reaching the cathode and being accepted by the oxygen. Hence, the reaction between fuel and oxygen occurs in two separate places. The fuel cell types are named based on the electrolyte, which only allows specific charged species to pass between the two electrodes. Using hydrogen as a fuel is not necessary, but it is the most common, as explained in the term hydrogen economy.

Figure 1 summarizes several types of fuel cells and shows the general schematic of the fuel cell device. PEMFC is the most popular, as indicated by the most shipped units (Today, 2012) and most studied (Jiao and Li, 2011). It is deemed the most suitable for automobile applications because it has a lower operating temperature and power density than others (Mekhilef *et al.*, 2012). The existing fuel cell car uses PEMFC and has averaged 43-57% energy efficiency, with the lowest efficiency happening at full power (Kurtz *et al.*, 2017). It was about double the efficiency of the ICE system, which is around 20-25% on average. Aside from automotive, the other current application for PEMFC is for stationary auxiliary power sources (Wee, 2007)

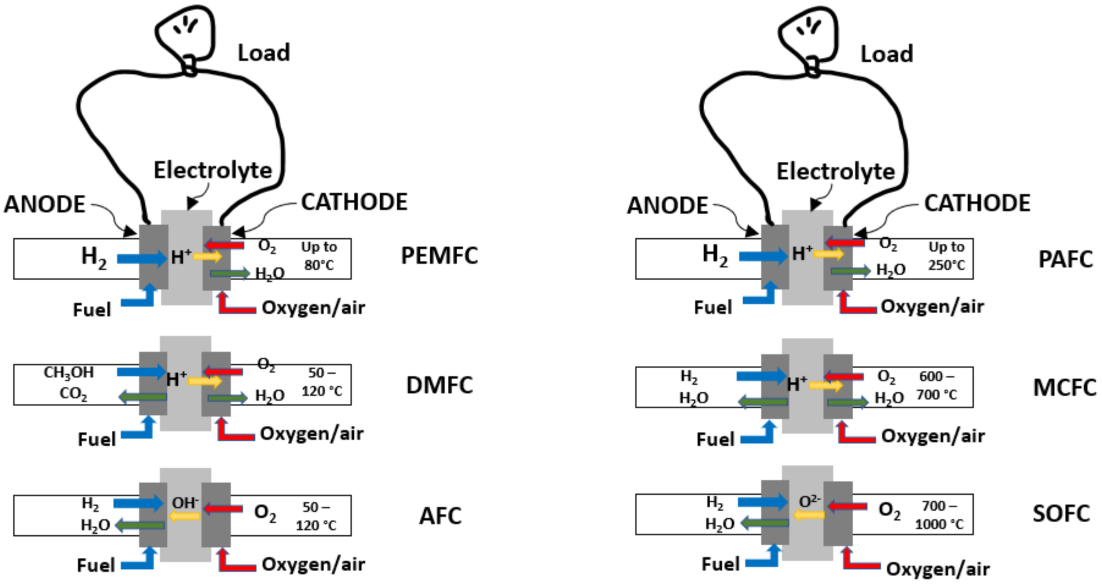


**Figure 1.** Schematic of different fuel cell types, redrawn (Kraytsberg and Ein-Eli, 2014).

The electrolyte of PEMFC is a membrane made from polymer, as the name indicates. Proton may pass through to the cathode but gases cannot, combining with reduced oxygen at the cathode to produce water as the only emission. The proton comes from hydrogen splitting at the anode. The splitting of hydrogen into proton and electron requires a catalyst, which usually is platinum supported by carbon. However, another member of platinum group metals (PMG) also gets the job done. A gas diffusion layer (GDL) is situated before the catalyst to make the active site will be filled uniformly. Since membrane, catalyst, and GDL act simultaneously, it was a package and manufactured as such, termed membrane electrode assembly (MEA). The flow channel and connection into the external circuit are provided by a bipolar plate that caps both ends

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of the MEA (Figure 2). DMFC sometimes fall under the classification of PEMFC since they use the same membrane electrolyte, only different fuel, and also has been considered for vehicle application (Mekhilef *et al.,* 2012). The stack's fuel cells are adjusted to gain the desired power.

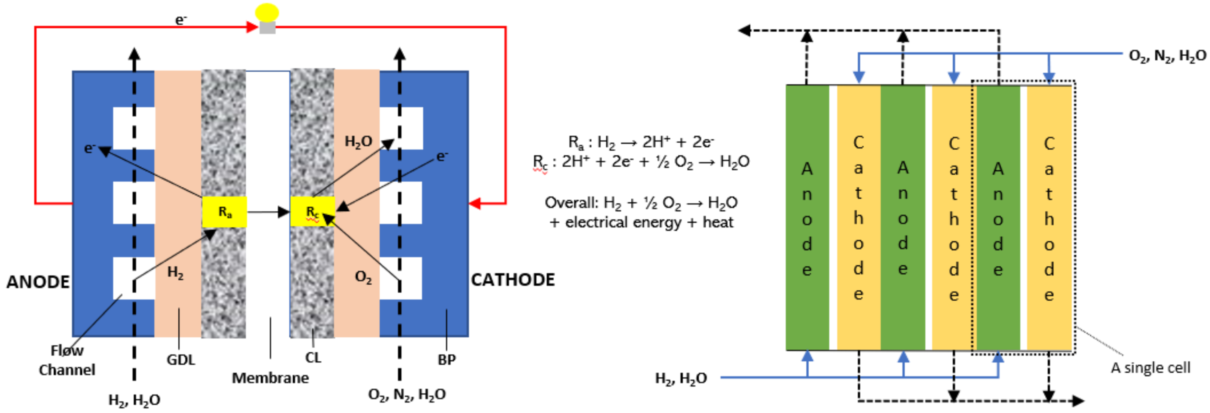


**Figure 2.** The more detailed schematic inside a single PEMFC (left) and a PEMFC stack consisted of 3 cells (right). They were adapted from Jiao and Li (Jiao and Li, 2011).

PEMFC can be used to power vehicles as the only source or combined with an electricity storage system such as a battery and/or supercapacitor (Figure 3). Although there is a clear difference between straight fuel cell and hybrid fuel cell vehicles, the definition varies. Both are usually only referred to as FCV as long as the stack contributes the majority of power. One of the main issues of FCV is the size since, at the minimum, it requires space for the FC stack, hydrogen tank, current converter, and electric drive system. There are also the auxiliaries, the additional equipment maintaining the condition inside the stack to ensure an optimum working environment. Since the MEA is quite sensitive, a change of condition such as water content or temperature marked a significant efficiency drop. The auxiliaries vary between vehicle designs; for example, some use an external humidifier(s) to raise the humidity of the inlet air (Wang *et al.*, 2018), and others prevent flooding of the stack by pumping air into the channel near the cathode (Jiao and Li, 2011). The common things are that these auxiliaries are making a drop in efficiency and taking up space. Process intensification on flow design has to continue to enable operation without several auxiliary components. The case of Toyota Mirai, which configuration is without a humidifier, $H_2$ diluter, and internal $H_2$ detector, is proof of that (Hasegawa *et al.*, 2016).

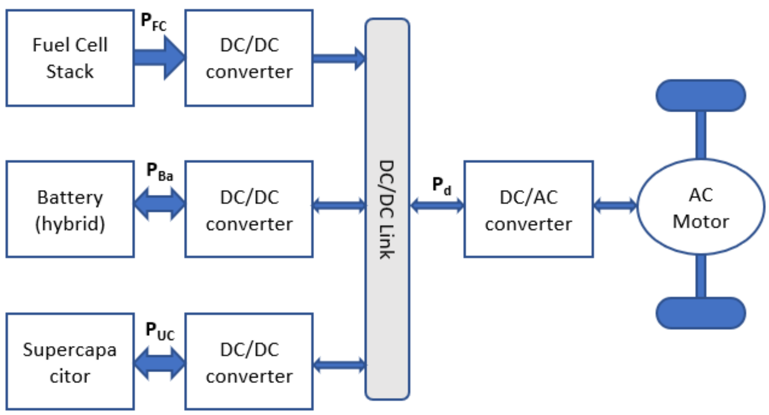


**Figure 3.** Powertrain of a fuel cell vehicle (FCV). Adapted from (Lü *et al.*, 2018).

## The barrier to Wide-Scale Deployment of PEMFC Vehicle

The first PEMFC vehicle was launched almost 3 decades ago but failed to meet expectations(Ettel, 2005). The first FCV vehicle for sale was Toyota Mirai in 2015, and sales are still growing but slowly. Although the

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bleak fate of many commercial PEMFC cars launched, it does not mean the amount of PEMFC-powered vehicles is as small as the sales figure. PEMFC is also used to power buses and heavy-duty trucks in several countries. Using PEMFC to power the bus is advantageous for data gathering and demonstration to the public. Public transport is also usually operated under a monopoly by the government. Hence there is no competitor for technology adoption.

Meanwhile, non-public transport has a more significant contribution to GHGs emissions. Hence PEMFC will be more beneficial if applied to them (DfT, 2017). For this to happen, FCV has to go against several barriers first

**Technical performance and infrastructure**

Table 1 listed notable FCV (private passenger car only) that has been commercialized. Only ten thousand units are adopted worldwide, most of which are divided between Toyota Mirai, Hyundai Tucson, and Honda Clarity. Honda FCX fate is one that befell many FCV, where the production halted after only so few amounts managed to be sold or leased. Even with the most sales compared to other FCV, Honda still decided to stop Clarity 2018 production by the end of 2021 due to declining sales, although leasing is still available until 2022 (Capparella, 2021).

**Table 1.** List of notable FCV (private passenger car only).

| FCVs (year launched) | Driving range (km) | Max. Speed (km/h) | Price ($) | Fuel economy ($kgH_2$/100 km) | Adoption |
|---|---|---|---|---|---|
| **Toyota Mirai (2015)** | 502 | 179 | $57,500 | 0.76 | 5300 sold by 2017, over 10000 by 2019 |
| **Honda Clarity Fuel Cell (2016)** | 589 | - | $369/month on the lease | 0.97 | |
| **Hyundai Tucson (2016)** | 426 | 152 | $499/month on the lease | 0.95 | 914 sold |
| **Honda Clarity FCX (2008)** | 430 | 160 | $600/month on the lease | - | 45 leased in U.S. 2008-2014, stopped |
| **Hyundai Nexo (2018)** | 609 | 179 | Around $59,000 | 0.84 | 10144 sold by 2020 |
| **Toyota Mirai 2nd Gen. (2021)** | 646 | | | - | - |

The development of FCV is supported by many governments, with several bands and car companies. The United States (DOE), Japan (NEDO), European Union (FCU JU), and China (MOST) are the most active campaigner against FCV. They fund research on FCV in their country and create a set of targets for several technical parameters, as listed in Table 2. Even in 2018, the target is not yet set to outperform conventional vehicles. The reluctance to set a low-cost target also might indicate the belief of government bodies that FCV deployment is still far off compared to BEV, which has gained much traction after that time.

**Table 2.** Technical targets of FCV from several government bodies adapted from (Wang et al., 2018).

| Parameters | DOE | NEDO | FCU JU | MOST |
|---|---|---|---|---|
| Peak power efficiency (%) | 65 | 60 | 55 | 55 |
| Rated power efficiency (%) | - | - | MOST | 50 |
| Power density ($WL^{-1}$) | 650 | - | - | 600 |
| Specific power ($Wkg^{-1}$) | 650 | - | - | - |
| Cold start-up time (seconds) | 30 | 30 | - | - |
| Cold start-up temperature (°C) | -30 | -40 | -25 | -30 |
| Durability in automotive drive cycle (hours) | 5000 | 5000 | 5000 | 5000 |
| Durability for start-up/shutdown (cycles) | 5000 | - | - | - |
| Top operation temperature (°C) | 90 | 95 | - | - |
| Storage hydrogen pressure (MPa) | 70 | 70 | 70 | 70 |
| Cost (/kW) | $40 | $97 | €100 | - |

Driving range, acceleration prowess, and durability are the technical parameter most often considered when consumers buy a car. Tables 1 and 2 show that the performance of the current commercial FCV is average at best compared to conventional ICEV. Several drawbacks have not been mentioned in the stat. For example, despite the maximum speed being quite good, the FCV is less energy efficient during the fast

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drive, meaning that their annual fuel cost is likely higher than the rating suggested (Gold, 2021). Another drawback is that due to the still low reliability of FCV, there are many additional costs aside from the initial price of the car and fuel expenses. For example, in the Honda Clarity series, the fuel cell version does not include a warranty, taxes, registration fee, and dealer fee, unlike the hybrid (battery and gasoline) version, which even offers a battery warranty of up to 8 years (Honda, 2018).

While the higher price for an average performance can be a dealbreaker, the most grueling hurdle for FCV adoption is the refueling infrastructure or lack thereof. While most people do not travel even half of the FCV driving range regularly (Plötz et al., 2017), Hydrogen Refueling Stations are only operating in a particular part of the world, and a limited number are even there. The Number is not considered enough for comfortable service. Even California, the pioneer city for FCVs operation, at the time of writing, had only 48 available stations(California Fuel Cell Partnership, 2021). The development was slow since the initial target was 100, of which 28 were built in 2017 (Sprik *et al.*, 2017). The situation is even more unfortunate in Europe, where the rival alternative car BEV already has a considerable market. One country which is very serious with FCVs is Germany with its German Energiewende. However, out of the final target of 400 stations (Ehret and Bonhoff, 2015), only about 90 are currently in operation (FuelCellsWorks, 2021).

**Production cost**

Table 1 shows that the fuel cell car prices are still about double the of conventional fossil fuel vehicles, primarily because of the production cost. While the car is more fuel-efficient, the operational cost is approximately similar to a conventional car due to the hydrogen price (U.S. Environmental Protection Agency; U.S. Department of Energy, 2016). This high cost is still too significant to attract buyers, as the previous survey stated that most people in the US would not want to pay an extra $5000 for a cleaner car even when they identified themselves as environmentally aware people (Krupa *et al.*, 2014). A parallel can be drawn in Norway, where BEV was well received. A survey of about 50,000 owners of BEV concludes that 84% of them felt that the BEV is worth purchasing with VAT exemption despite still being more expensive than fossil fuel vehicles (Bjerkan et al., 2016). The parallel is evidence that the market attitude might differ, and in certain parts of the world, FCV can still succeed if they can compete with BEV, if not ICEV.

The small scale of production means a higher cost for FCV. From Toyota Mirai's experience, it was estimated that if the production is only 1000 units/year, the cost for an 80 $kW_{net}$ power system is about $183/kW (James *et al.*, 2017), while the US Department of Energy calculated it to be around $280/kW(Satyapal, 2016). Compared with fossil fuel cars is difficult as production varies greatly; it is more just to compare the car with a similar specification, which was how $30/kW is considered the ultimate target (Offer et al., 2011). Government usually offers an incentive, whether in the form of a grant, tax exemption, or rebate scheme. This is necessary for introducing the new vehicle to the public and for an actual condition test run that tests the car, infrastructure, and supporting system. However, economic incentives will not last forever, and more extensive market interest needs to be obtained before the company starts mass production. Current FCV technology is mostly the same from 2017, which DOE predicted could decrease the cost up to $45/kW if 500,000 units/year were manufactured (James et al., 2017). It still has not fulfilled the DOE target of $40/kW in Table 2, meaning another technological breakthrough is required while simultaneously attracting enough market to enable mass production. The significant cost reduction in the last twenty years, from about $1833/kW in 2000 (Tsuchiya and Kobayashi, 2004) to $183/kW in 2015, is convincing enough to promise continuous reduction.

It was estimated that 40% of the production cost is the fuel cell stack and 30% of the credit goes to the hydrogen tank, and the FC stack comprised several components, which the PEMFC attributed to almost half (Miotti *et al.*, 2017). Another model from US DOE estimates the breakdown for pilot and mass production, which notably differ (Figure 4). The membrane cost is higher in small-scale production, while in mass production, the high cost comes from bipolar plates and catalysts(Marcinkoski *et al.*, 2015). Another expensive component is the hydrogen tank made from carbon nanofiber, which has to withstand the pressure of 70 MPa but is still light not to burden the car (Hua *et al.*, 2011). Unfortunately, the storage tank technology has only improved very slowly since it was established (Ruffini and Wei, 2018). Therefore, technological cost-reduction advances must have come from the membrane, the catalyst, or the MEA. As mentioned before, this part of the FCV is relatively sensitive, and improving them meant a lot more than the cost of MEA itself. Some of the auxiliaries can be eliminated if it is more durable or can work optimally in a broader range of conditions.

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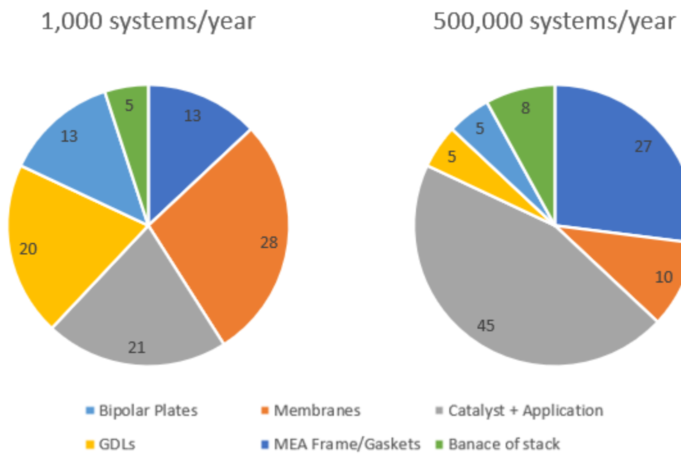


**Figure 4.** The cost breakdown of a fuel cell stack with different scales of production.

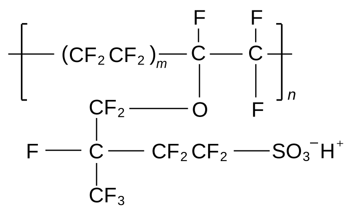

**Figure 5.** The structure of the Nafion membrane.

Currently, FCV uses a membrane called Nafion (Figure 5). It is far from a new material, developed by DuPont chemical almost half a century ago. Despite that, Nafion is still a benchmark material for polymer electrolyte membranes throughout the years. It was sold in various thicknesses; as expected thicker membrane has better conductivity (Tsampas *et al.*, 2006) and can operate in higher pressure differences. Any studies developing other solid polymer electrolytes compared their synthesized material with Nafion; to date, all of them fall short in one crucial area. Despite its high performance in optimal working conditions, Nafion's undesirable quality shows when it is outside the optimum condition. The membrane is susceptible to temperature change and hydration, hence the need for complex auxiliaries in FCV (Kraytsberg and Ein-Eli, 2014). At 75°C, Nafion 117 membrane's conductivity drops from 0.13 S $cm^{-1}$ to 0.065 S $cm^{-1}$ when the relative humidity falls from 100% to 80% (Bauer et al., 2005). When the temperature is below 25°C, the conductivity drop significantly, falling below even 0.01 S $cm^{-1}$ (Bauer *et al.*, 2005). Nafion also becomes unstable at temperatures above 100°C (Mališ et al., 2016) since its internal structure changes at high temperatures(Mališ *et al.*, 2018).

If the manufacturer deemed sacrificing some of Nafion's conductivity, several polymer electrolytes might offer lower-cost alternatives (Kraytsberg and Ein-Eli, 2014). One example is polybenzimidazole (PBI), with has been tested for fuel cells and is inexpensive and operable at high temperatures. However, the instability due to the acid content has to be mitigated (Oono *et al.*, 2009). Another alternative is a modified Nafion membrane to achieve greater mechanical strength despite being thinner. A thinner membrane has been predicted to be able to lower the cost (Miotti *et al.*, 2017).

The precious metal catalyst is yet another essential and high-cost MEA component. Other catalysts based on non-PGM are still under investigation and do not perform to the desired level. Since platinum is expensive and scarce (Vesborg and Jaramillo, 2012), many efforts have been made to increase catalytic activity to reduce the amount of platinum used in catalysts. Several synthesis techniques and supports have been examined to increase the activity and stability of Pt/C commercial catalyzing *et al.*, 2015; Seger et al., 2008), including to protect the catalyst from CO poisoning (Lu *et al.*, 2014; Masao *et al.*, 2009). The current platinum loading is around 0.4 mg/$cm^2$ (Miotti *et al.*, 2017), and the Toyota Mirai, the most popular model, requires approximately 30 grams of Pt in one car. Many cost analyses include the assumption that the Pt loading a 0.15 mg/cm2 (James *et al.*, 2014; Marcinkoski *et al.*, 2015); however, based on the current FCVs, this figure may be overly optimistic for achieving a good power density. Nevertheless, 0.125 mg/cm2 has been set as the DOE objective for cost-competitive production.(Marcinkoski *et al.*, 2015), At the same time, the ultimate target in many kinds of literature is less than 0,1 mg/$cm^2$ (Pollet *et al.*, 2019).

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**Scale-up problem**

The state of fuel cell research is not lacking any advancement, particularly at the scale of a single fuel cell. It is important to note that success usually does not translate into advancement on a bigger scale. This problem makes the development of commercial FCVs not proceed as quickly as anticipated. The progress is often marginal, and the target is not met on schedule (Bakker, 2010; Blanchette, 2008). Furthermore, despite improving material, water, and heat management studies, scaling up the fuel cell stack still makes it more susceptible to performance degradation (Miller and Bazylak, 2011; Radev *et al.*, 2013). All of these indicate unresolved issues during the scaling-up process, making the fuel cell stack performance less than the sum of its parts and less reliable than expected (Wang, 2015). Important to note that while vehicle lifetime was targeted to be a minimum of 5000 hours (Wang et al., 2018), there is no set target from the government on how long the car can be driven without being repaired. To summarize, consumers would not risk purchasing an FCV while it is still inferior to at least BEVs in terms of reliability and durability.

At first glance, the failure stems from the same factors in single cells and stacks: hot spots, drying, flooding, poisoning of the catalyst, and hydrogen starvation stack (Miller and Bazylak, 2011; Radev *et al.*, 2013). However, a study by Wang determined that the uneven flow distribution is the main reason for these scale-up problems (Wang, 2015). A single-cell experiment usually assumes uniform flow, uniform heat distribution, and negligible pressure drop. The assumption is taken for granted since the absolute deviation value for a single cell is usually only around 5%. Meanwhile, in a stack, the flow distribution deviations on every single cell are added, becoming more pronounced as the stack gets bigger. A cell with a different flow rate might have a different reaction rate, yielding uneven temperature distribution and different water content from its neighbor. In the long term, it will accumulate into phenomena such as hot spots or flooding; both can result in cell degradation if they happen for a prolonged time. The easiest part to break in cell degradation is the PEM which is not immune to thermal stress. As the membrane breaks, some of the hydrogen or oxygen will be able to flow through the membrane and react directly, exacerbating the break due to the exothermic nature of the reaction. It becomes a chain of events that leads to the impairment of many more cells in the stack.

Although the significance of creating optimal flow configurations has been recognized and examined by researchers, it is still mostly disregarded during the scale-up. Due to the increasingly complex manifold systems at such commercial size, the industry may not have the resources necessary to examine them or may have assumed they were an established technology. (Wang *et al.*, 2018).

## Competing technologies

The major rivals of FCV for providing passenger transportation are undoubtedly ICEV, which continues to offer superior technical performance at a lower average production cost. The only benefit of FCV is its zero-tailpipe emission. However, tailpipe emission is not the correct criterion to fairly assess the environmental aspect of FCV and ICEV. While hydrogen yields only water after oxidation, the primary method of hydrogen production leaves an undesirably large carbon footprint as most industrial hydrogen comes from steam methane reforming (SMR) (Mueller-Langer et al., 2007). FC systems also have many components, each with its footprint and impact during manufacturing. With multiple scenarios to consider, a life cycle assessment (LCA) is the most accurate tool to compare the various environmental impacts of FCVs and ICEVs, mainly when technical improvements make it possible to use less of some materials.

In green transport, FCV's main competitor is BEV, which has enjoyed a significant increase in sales during the last few years despite starting around the same time as FCV. In 2016 the Number of electric cars worldwide reached 2 million while they existed in 2010(International Energy Agency, 2017), and 1 million more were sold in 2017 (ZSW, 2022). While BEV is undoubtedly a good alternative for reducing emissions and using fossil fuels, FCV has some advantages over BEV. Compared to BEV, FCV has a much faster refueling time, greater driving range, better driver experience, and longer time before the components need to be replaced. However, in the turf of the electric vehicle, BEV is currently dominating due to FCV's higher cost and lack of infrastructure (Staffell *et al.*, 2019).

The result of the Life Cycle Assessment (LCA) for BEV, FCV, and ICEV are compared in Figure 6. The impact categories displayed are Global warming potential (GWP), which is usually considered the most concerning, and human toxicity, which most people are unaware of despite the long-term severe health hazard. The results of the studies show a significant difference for the human toxicity impact assessment, for FCV operated using hydrogen obtained by electrolysis using Europe's grid electricity and for illicit assessment (Bauer et al., 2015; Miotti *et al.,* 2017). This outstanding result signifies the diverse assumption and scope in this field. One example is where Miotti et al. assumed Pt recycling to be equal to or less than 5%, while Pt contributes significantly to toxicity (Miotti *et al.*, 2017). In reality, Pt recycles rate can be above

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50% in the catalytic converter case(Xun *et al.*, 2020). Thus the very conservative assumption is most likely due to the lack of data regarding the recycling of FC stack. Two LCA results with differences between them are usually expected given the severely limited data for a system with only an entirely commercial operation of less than a decade, exacerbated by the variation in fuel production and vehicle manufacturing (Miotti *et al.*, 2017).

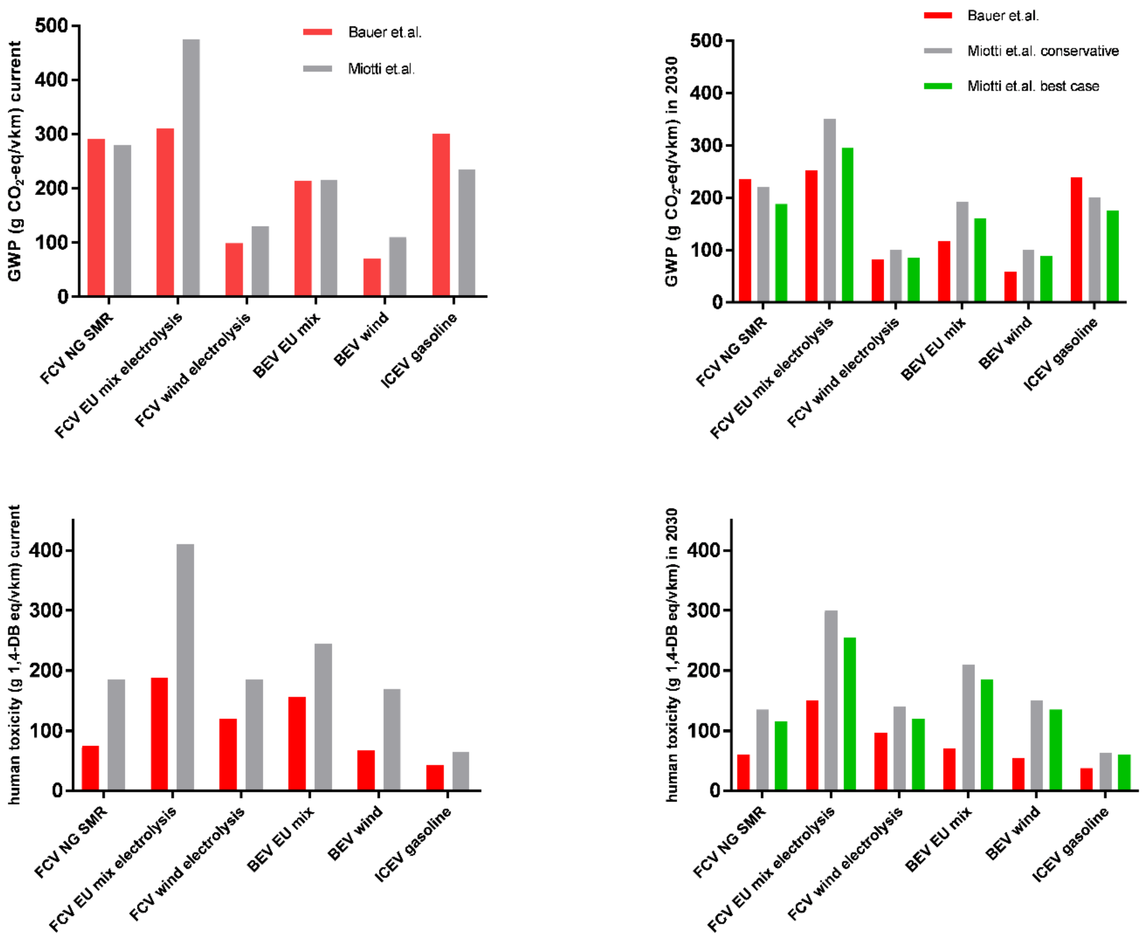


**Figure 6.** The global warming potential and human toxicity impact of different types of vehicles: value during studies (left side) and estimated future value (right side)(Bauer *et al.*, 2015; Miotti *et al.,* 2017).

Despite the differences, the overall trend is consistent. BEV is always the better choice to minimize carbon footprint when using the same method of electricity generation. Unless the hydrogen is produced using non-carbon intensive technology, FCV will not have lower GHG emissions than ICEV. Even with the current electricity mix, BEVs may be slightly better, but the difference is insignificant. Meanwhile, both electric vehicles significantly impact human toxicity ICEVs because they require a glider and powertrain, which, unfortunately, have a large toxicity footprint. If we consider the possibility of increasing the Pt recycling rate, the human toxicity impact of FCV will be lower than ICEV and BEV. Interestingly, the study indicated that the hydrogen tank is the most significant contributor to GWP due to the assumption that a large amount of carbon fiber is required to withstand hydrogen pressure (Miotti *et al.*, 2017). However, recent advances in material technology enable hydrogen storage to be made from various materials with less carbon footprint, such as metal hydride (Lototskyy *et al.*, 2017; Whiston *et al.*, 2021), meaning that FCV is going to have an even higher GWP reduction in the future compared to the value indicated in Figure 5.

Since the three technologies use different fuel types, calculating life cycle cost (LCC) will enable a more fair assessment. Similar to the LCA, variations can be seen in the LCC estimation from the literature listed in Table 3. Despite that, the overall trend can still be observed. Future values are expressed as a range, with the lowest cost representing the most optimistic scenario, which typically originates from the mass assumption for FCV. The reference year is 2035, but one of the studies only predicted up to 2030.

doi: 10.13170/aijst.11.2.24592


**Table 3.** The comparison of Life Cycle Cost between FCV, BEV, and ICEV.

| Type | Current LCC($/km) | Future LCC ($/km) in 2035 | Assumption | Reference |
|---|---|---|---|---|
| FCV | ±$90,000/10 years | 0.20 or ±$50,000/10 years ownership | 114 kW FC stack | (Ruffini and Wei, 2018) |
| | 0.60 – 0.68 | 0.25-0.38 ($H_2$ from wind electrolysis) 0.20 - 0.32 in 2030 ($H_2$ from SMR) | 75% FC, 25% battery | (Miotti *et al.*, 2017) |
| | - | 0.21 - 0.25 | | (Nguyen and Ward, 2013) |
| BEV | ±$55,000/10 years | 0.28 or ±$47,000/10 years ownership | | (Ruffini and Wei, 2018) |
| | 0.24 | 0.19 - 0.21, in 2030 | | (Miotti et al., 2017) |
| | - | 0.19 - 0.21 for 100 miles range car 0.23 - 0.28 for 300 miles range car | | (Nguyen and Ward, 2013) |
| ICEV | ±$54,000/10 years | 0.22 or ±$54,000/10 years ownership | | (Ruffini and Wei, 2018) |
| | 0.21 | 0.18 - 0.19, in 2030 | | (Miotti *et al.*, 2017) |
| | - | 0.20 - 0.23 | | (Nguyen and Ward, 2013) |

BEV has been the more successful electric vehicle so far, supported by the fact that the LCC of BEV is already comparable to that of ICEV. In the case of BEV, the low operational costs from low electricity prices offset the more expensive initial purchase. Interestingly, while many researchers believe that the price of Li-ion batteries can be halved or reduced even further to $125-$200/kWh 2014 (Nykvist and Nilsson, 2015), the study predicted no significant change in the future cost of BEVs. This likely stemmed from a more conservative assumption as the Li-ion battery is the more mature technology. Meanwhile, the current cost of owning FCV is still too high, with the production cost comprising over 60% of the LCC (Ruffini and Wei, 2018). While FCV is expected to have a more significant cost reduction due to its novelty, many researchers have predicted that it is insufficient to tip the balance in their favor (Miotti et al., 2017; Offer et al., 2010; Ruffini and Wei, 2018). Another factor for the high LCC is the expensive fuel price, which is hydrogen made from electrolysis. The electrolysis has to be powered by wind-generated electricity or other renewables to minimize the environmental impact. Otherwise, FCV will have the same impact as ICEV, as shown in Figure 6. Unfortunately, renewable electricity is still much more expensive than regular grid electricity.

Another exciting alternative also comes in the form of HFCV (Hybrid FCV). However, as stated before, there is no consensus on when to call an FCV with additional electricity storage a hybrid. The author believes that the HFCV can be considered a different option when the mix of FC stack and battery offers shorter refueling time and further driving range in addition to the more flexible fuel choice. Life cycle cost assessment for HFCV indicates that it can be optimized to offer lower costs from FCV and BEV by selecting the proper battery size (Offer et al., 2011). Nevertheless, as with every life cycle assessment, the result will depend on the scope and assumption, including the cost breakdown. The theoretical design of HFCV also promises a better driving experience than pure FCV and BEV (Fathabadi, 2019).

## Discussion

As much as decreasing tailpipe emissions is paramount, many countries lack interested buyers. Most do not have an institution with the cutting-edge technology necessary to set up the supporting infrastructure: low carbon power plant, hydrogen production plant, supply network, refueling station, and facility for FCV, required maintenance. While foreign companies might open to investing in the hydrogen supply business, it will only happen if there is a guarantee of the market's continuous interest, which necessitate stringent government policy or another substantial incentive. At the time of the writing, the ban on the sales of ICEV or petrol cars was planned by only several governments, with a timeline between 2030 and040(Burch and Gilchrist, 2018). The most significant one, especially considering the number of car users, is the European Union's ban. Hence the future projection in this report is heavily based on the Europe transport system. It is interesting to note that while there is a significant portion of FCVs in the US compared to the rest of the world, only a small area possesses the supporting infrastructure. California was intended to be the pioneer city for FCV. While the success is debatable. The source data is still the source of data debatable and is the data for many studies.

The ownership rate of passenger cars in Europe was 494 cars per 1000n in 2015, slightly higher than 479 in 2011(European Automobile Manufacturers Association, 2017). The growth has been slowing down due to the saturation of ownership; added with the increased preference toward public transport might enable the rate to decrease slightly in the future. Therefore, the worst-case scenario in this study is assumed to be where the 2050 ownership rate is still as high as in 2015. The EU countries (EU27) were estimated to have approximately 494 million populations in 2050 (Akashi and Hanaoka, 2012), accounting for a minor decline. Initially, the ban for ICEV sales is expected to start iit in 2030 but is moved back to 2035, which is still subject to further delay appeal (Abnett, 2022). suppose the ban does start in 2035 for the next two decades; after that starts in 2035 for the next two decades. In that case, every car owner who intends to replace their ICE car will have to buy 2 electric vehicles assuming 10 years vehicle lifetime as in previous studies. This is equivalent to the demand for 473 million electric cars during the said period for 100% replacement. Even if only a fifth of the car owner replaces their car, choosing to hold to their old ICEV car, it is still almost 100 million units in demand. The automotive industry needs to ramp up its production, surpassing the best-case scenario in various studies, which usually only assume production of 500,000 cars/year. However, on the other hand, greater production means the production cost; therefore, LCC will fall much further. Realistically, the market will be shared between various electric or semi-electric vehicles.

Many previous articles claimed that Pt availability is a concern in producing massive quantities of FCEV. Previously, the dynamic depletion index of platinum was estimated to be 72 years in the conservative scenario or 42 years with the growth of FCV production (Alonso et al., 2012). However, Pollet et al. recently estimated that even with the current Pt loading of 30 grams per vehicle, there would be no problem supplying up to 2.5 billion of FCV using the mine in South Africa alone (Pollet *et al.*, 2019). Although the previous estimation of the EU needing about half a billion cars every 10 years means that the reserve in South Africa will be depleted in half a century, it is unlikely to come to that. Research in the laboratory scale shows that Pt loading continues to decrease, making a target of 0.1 mg/cm$^2$ and less than 10 grams per vehicle looks possible to achieve in 2050 (Podleschny *et al.*, 2018). In addition, at the end of the car's life, material recovery from the FC stack or catalytic converter is still feasible. Currently, the recycling rate of Pt in North America, Japan, and Europe is a little above 50%, increased significantly from 2 decades ago (Xun et al., 2020). Therefore, although requiring continuous improvement in FC and recycling technology, one can say optimistically that the sustainability of Pt ore will not be an issue.

This paper has stated and discussed that BEV currently outperforms FCV in terms of cost, environmental impact, and reliability. While future breakthroughs might happen in FCV favor, BEV technology is still advancing and steadily adopted into the transport system. By the time FCV can reach the mass production stage, the population will most likely already utilize BEV. The popularity of BEV might be aided even more in the countries where renewable has a large share in their energy mix since only then will they act as green transport. Meanwhile, a country invested in a hydrogen economy or possessing a substantial amount of excess electricity might benefit from using the electricity for hydrogen production. This is the only scenario where hydrogen can be available at a competitive price and with a minimal environmental footprint, favoring the adoption of FCV.

Aside from the hydrogen economy scenario, the different types of electric vehicles can also have their niche in the market, thus existing together to satisfy their market segment. BEV will be the winning choice for people who use the automobile for routine short-distance travel, especially if electricity is cheap. As stated before, FCV is more attractive in countries invested in the hydrogen economy. FCVs are most likely to conquer heavy-duty automobile markets, which require more excellent driving ranges, such as trucks and buses. Some studies predicted that fuel cell trucks will start to dominate in China just a decade from now (Tan *et al.*, 2021). Some people might also like a different model to adjust to their lifestyle, such as a plug-in hybrid electric vehicle (PHEV). In contrast, hybrid electric vehicles (HEV) might be appealing during the transition from ICEV.

As the ICEV is getting phased out, several studies have predicted the uptake for several types of vehicles and their market share during the progressive adoption process. It is predicted that PHEV will be the dominant type of automobile in 2050, followed by FCV and BEV, respectively (Contestabile *et al.*, 2011). As with most predictions, any significant change in the technology and automotive industry can change the projection course. Due to the slow uptake of FCV compared to BEV, some people have already decided that the battle for the future automobile is over. However, others believe that if the cost of all the vehicles is level, FCV will have a slight advantage in the far future because it has a lower environmental impact than BEV, as discussed in the previous section. The supporter of BEV argued that FCV would not replace BEV, merely strengthening it, signing that the dominant powertrain will be a battery with a fuel cell picking up the slack when required, such as during fast driving on longer distances like the highway. Meanwhile, a supporter of FCV would state a similar thing only in reverse, with battery improvement will strengthen FCV. A recent study of FCV has supported this campaign in the actual driving condition, which found that the share of the fuel cell in the vehicle's propulsion is more than 3 times that contributed by the battery in urban condition and even reach 28 times on highway condition (Szałek *et al.*, 2021).

## Conclusion

The production cost, scale-up complexities, and supporting infrastructure are the three main obstacles to the large-scale deployment of FCVs. Mass production and technological improvement, particularly concerning catalysts and membranes, may significantly reduce the capital cost. However, it is still expected to be slightly higher than competing technologies. Government incentives might enable them to be competitive with ICEVs in the future. While studies agree that they will not have the dominant share of the private passenger car market in the future—BEVs have more established technology that for several more years are more attractive economically and environmentally—FCVs still have a role in the automobile market. With current technology, FCVs are not better environmentally than ICEVs except when hydrogen is produced using non-carbon intensive energy, which is still more expensive. However, when the cost production target of FCV is reached, it should be only a matter of time to establish infrastructure before FCV's sales can be level with BEV's. Another future role of FCV lies in the heavy-duty vehicle and becoming the dominant powertrain in a hybrid electric vehicle. The future automobile will be a mix of several electric-type, depending on the use and user choice of lifestyle.

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