Integration of Fuel Cells in Transportation

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Report

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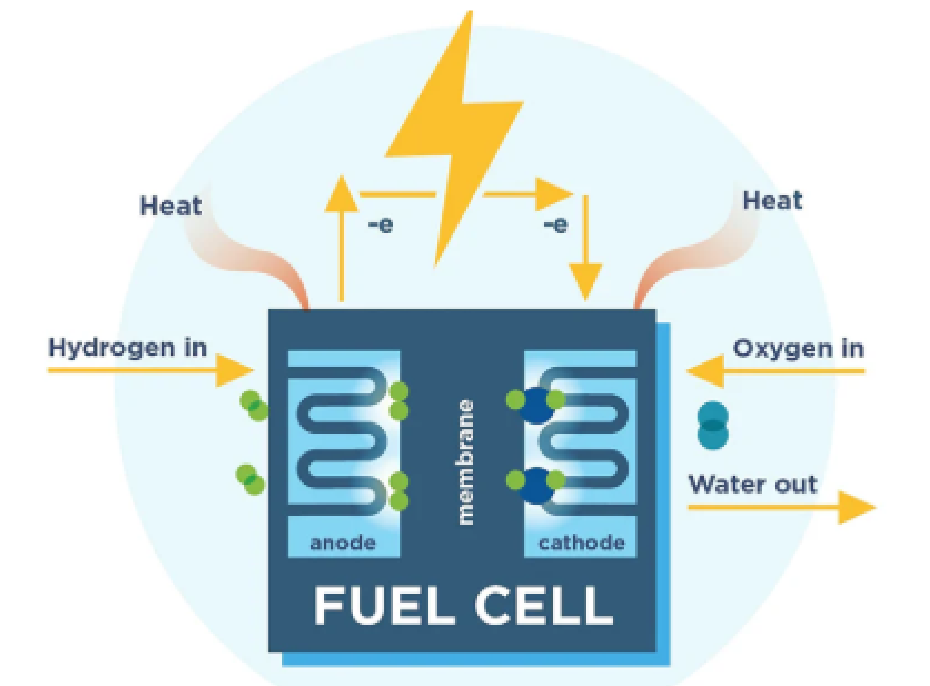

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1 Introduction

The global transportation sector is currently transitioning away from fossil fuels in an effort to decarbonize, and fuel cell technology has emerged as a promising alternative to conventional propulsion systems. Fuel cells generate electricity through electrochemical reactions and produce only water and heat as the byproducts making them an appealing option for achieving low emissions. They offer several advantages such as high efficiency, short refueling times and quiet operations, making them suitable for the automotive domain. However their widespread adoption is hindered due to factors such as technological limitations, underdeveloped infrastructure and economic barriers.

This report aims to explore how fuel cell technology is currently being integrated across various segments of the transportation industry. It also examines the feasibility of adopting fuel cells into cars, buses, trucks, ships and aircrafts, analysing their performance, economic viability and infrastructure requirements in comparison to the traditional systems.

2 Current State of Fuel Cell Technology

2.1 Cars

Over the recent decades, the fuel cell technology for cars has developed significantly, making it a potential alternative to the current internal combustion engine (ICE) technology. Among the different types of fuel cell technology (FC) technology available today, the Proton Exchange Membrane Fuel Cells (PEMFCs) that uses a polymer electrolyte membrane for converting the hydrogen and oxygen to electricity with water being the only byproduct, are becoming the most viable option for the automotive industry. This is mainly due to factors pointed out in the study by Aminudin et al. (2023) such as low operating temperatures, high power density and fast start-up capabilities. Automotive manufacturers such as Toyota, Honda, and Hyundai have developed commercial models like the Mirai, Clarity Fuel Cell, and Nexo respectively which utilize the aforementioned PEMFC technology. These vehicles offer driving ranges similar to those of the conventional cars with the Toyota Mirai providing up to 650 km, the Honda Clarity Fuel Cell around 589 km, and the Hyundai Nexo about 666 km on a full tank (Toyota 2024; Honda 2024; Hyundai 2024). Additionally, these vehicles can be refueled in a very short time compared to battery electric vehicles.

Although these advantages do exist, there are several technical and economical constraints as well. One of which is that PEMFCs rely on materials such as platinum which is used as catalysts and perfluorosulfonic acid membranes like Nafion, both of which increases the overall production costs (Aminudin et al. 2023). Other challenges include durability and membrane degradation which can impact the long term performance. Furthermore, the current hydrogen storage systems such as the high pressure gas tanks and the cryogenic liquid systems have significant trade offs. While the high pressure tanks are widely used they require significant energy input during the compression process and also include safety risks under crash conditions. On the other hand the cryogenic systems provide higher density, it requires complex insulations and suffers from hydrogen boil off.. Then there is the solid state storage system such as metal hydrides that is both safe and provides denser storage but it results in high cost and has thermal management (Ajanovic et al. 2021).

Infrastructure is another barrier that limits the widespread adoption of fuel cell vehicles (FCVs). According to the data from H2Stations (2024), as of 2024, there were around 1,160 operational hydrogen refueling stations worldwide, the majority of which are located in China, South Korea and Japan. Whereas in Sweden, as shown in Figure 1 there are only a limited number of refueling stations that are operational with more under development. To establish a comprehensive hydrogen supply network, it requires more investments in production facilities, storage solutions, and distribution networks.

Figure 1: Operational H2 Stations Map (H2Stations 2024)

Therefore, to overcome these economical, technical and infrastructural challenges, it requires technical advancement in reducing the platinum usage and development of alternative durable membranes. Along with which the introduction of supporting policy frameworks and strong public private partnerships are required to increase both infrastructure development and consumer confidence for widespread adoption. In conclusion, while integrating the fuel cell into passenger cars do have significant challenges, it also holds the potential for attaining a zero emission future, provided these economical, technical and infrastructural challenges are properly addressed

2.2 Trucks

In 2021 FCEVs made up 2 percent of the total market share of pure electric trucks (Haseeb 2024). Since the market for FCEV-trucks is small there is not much data to be found on their performance compared to traditional combustion engine trucks. Two examples of fuel cell trucks on the market today are Hyundai's Xcient and Nikola's TRE Hydrogen-electric semi-truck. Hyondai claims their truck has a range up to 400 km and a max gross combination weight of 38 000 kg (Hyundai Motor Company 2024). Nikola claims their truck can drive approximately 800 km on a single tank with a gross combined weight rating of approximately 37000 kg (Range Trucking 2024). Refueling the Nikola truck takes 20 minutes or less. The driving range on a single tank for a traditional diesel engine truck differs greatly between models but is usually between 1400 and 3200 km (McPeak, Mike 2023). Refueling times also differ but is around 5 to 10 minutes. Based on this information it's evident that the traditional engines have an advantage when it comes to driving range and refueling.

Refueling times for traditional ICEVs differ greatly depending on tank size and pump flow rates. Gasoline pumps typically have a flow rate between 50 and 120 liters per minute (WFS Refueling Systems 2020). Volumes of truck fuel tanks vary hugely depending on brand and truck size. Small 4-wheelers used for light, local transports often have a tank capacity of 90 to 200 liters (Komal Kumari 2024) while larger trucks such as Volvo FH16 can carry up to 1500 liters of fuel (Volvo Trucks 2024). This means that the refueling time can be anywhere between 2 and 30 minutes depending on the pump and truck.

2.3 Buses

Inclusion of green energy systems in public transport can be the viable way of reducing fossil fuel consumption in transportation. The growth of fuel cell buses (FCB) has seen enormous growth in 2024 compared to 2023 (Solaris Bus Coach 2024). Data provided by Solaris demonstrates that the total number of FCBs sold around Europe in 2024 is 354, whereas the number was just 147 in 2023. This report explores FCBs, which operate using a proton exchange membrane fuel cell (PEMFC) as its primary energy source. Although fuel cells are being promoted as a promising solution, they come with some challenges related to technology, infrastructure, and total cost of ownership (TCO).

The work by Dawood et al. (2003) has conducted a comparative study on the performance of fuel cell bus and conventional diesel bus using ADVISOR simulation tool under Urban Dynamometer Driving Schedule (UDDS). Simulation was conducted for both the vehicles under the same parameters except for their power source. In order to satisfy the cycle requirements, the conventional diesel bus utilized Detroit Diesel Corporation Series 50 8.5L engine scaled to 350 kW. In contrast, the fuel cell bus was modelled with a 50kW PEMFC system, Battery for energy storage, and a traction motor. Both the setups were scaled in order to achieve the best fuel economy. Table below depicts the performance of both the power trains.

Performance Parameter	Conventional Engine	Fuel cell
Fuel converter (kW)	350	200
Energy storage (kW)	-	300
Motor (kW)	-	250
Total propulsion power (kW)	350	250
Fuel economy (mpg)	5.1	7.5
0–60 mph(s)	25.7	19.1
Grade-ability (%)	6	2.3
Max. speed (mph)	86	86.2

Table 1: Performance comparison of conventional and fuel cell bus powertrains

From Table 1, it is evident that the performance of the fuel cell is much better than the conventional diesel engine except for the grad-ability factor. It is important to point out the fact that the work doesn't include the degradation of the fuel cell, battery ageing, infrastructure, and TCO. These factors are quite important to evaluate in order to determine the inclusion of fuel cells in public transport. Additionally, it is also important to compare parameters like range and refueling time to evaluate the performance characteristics. According to solaris the range of urbino18, a hydrogen fuel bus has a 350 km and refueling time of 15 to 20 mins. In comparison, conventional diesel engine buses offer slightly higher range and similar refueling time.

A better insight into the economic impacts of fuel cell bus can be gained by studying the total cost of ownership (TCO). Total Cost of Ownership (TCO) comprises Capital Expenditure (CAPEX) and Operational Expenditure (OPEX). CAPEX considers bus and infrastructure costs, OPEX deals with fuel, maintenance and insurance costs. According to the study by Danielis et al. (2024), the current TCO analysis for fuel cells buses is calculated to be €2.00/km - which compares to €1.44/km for diesel buses - largely due to the cost of hydrogen refueling stations at between €213,000 and €250,000 each per site. Every km will cost €0.45 on average to maintain, €0.31/km for diesel, though this is expected to decline with technological improvements. Furthermore, the type of hydrogen also contributes to the TCO, where grey hydrogen remains the cheapest compared to green hydrogen. The paper concludes by saying that FCBs are projected to be cost-effective or on par with diesel by 2030-2035, but more realistic modeling of infrastructure and non-European contexts is critical for a global perspective.

2.4 Ships

Fuel cell technology is not very common for ships and is only used for a small number of ships around the world. The technology is in its early development for ships and it will take time for the technology to become widespread. The fuel cell technology is most likely to be used for short- distance ships and coastal vessels. One of the biggest fuel cell projects for ferries is in China where a 65 meter long vessel can travel up to 380 km and it takes about 2-3 hours to refuel the vassel (World Cargo News 2024).

Fuel cells systems usually have an electrical efficiency of between 40- 60% which makes it more energy efficient than traditional combustion engines. The fuel cell system can be combined with heat systems and power systems, these systems can achieve efficiencies up to 90% (Ruivo 2023). The durability for fuel cell systems is much lower than for traditional combustion engines. Fuel cells can operate between 10 000 to 20 000 hours compared to diesel engines that can operate from 20 000 hours up to over 100 000 hours (Lind et al. 2023). The fuel cell system has lower operating hours but it also costs a lot more to maintain and replace. Another problem is that fuel cells have less power per unit of weight or volume compared to combustion engines which makes it difficult to use for ships that are traveling longer and for ships that carry a lot of weight.

There are many parts of the infrastructure that are required for expanding fuel cell use in ships and ferries (Aashna et al. 2024). Ships need large volumes of hydrogen and it must be produced reliably and sustainable. To make it widespread, regional hydrogen hubs are needed near big ports and ideally connected to renewable energy sources like for example offshore wind parks and solar parks. A well working fuel cell distribution network is needed to make it possible for fuel cells to be used widely in ships. The most efficient system is pipelines but it is also the most expensive alternative. The ships require specialized systems onboard that can store the fuel cell and this requires a lot of space and this is a major issue and it makes it very difficult to design the ships.

There are very many challenges for fuel cells in ships but there are also smart and potential solutions. A big challenge is that it is very expensive which makes it very difficult to invest in for many companies. The infrastructure is also very limited and there are very few ports that are equipped with refueling stations for hydrogen. The hydrogen storage is much bigger than the ones for diesel which reduces the space which is very problematic in many ways.

There are some potential solutions and this can for example be hybrid systems where combining fuel cells with batteries can improve the efficiency. If there will be government support and subsidies for the usage of fuel cells to make the marine more green more companies will invest in this technology. It also needs to be easier for ships to use this technology to make it more widespread and therefore there needs to be more infrastructure investments.

2.5 Aviation

Like the other transportation modes, the usage of fuel cells in aviation is not widespread and is not yet implemented on a commercial scale. As of now, Airbus plans to launch a hydrogen airplane by 2040-2045, but smaller companies like ZeroAvia plans to produce smaller planes as early as 2026 (ZeroAvia 2025). The main hurdle for the usage of hydrogen fuel cells in aviation is the low volumetric energy density which is a problem when size, range and the inability to refuel easily and fast is of the utmost importance for the performance and success of these aircrafts.

To be able to do these long flights that we are used to, the solutions might involve high-pressure storage or cryogenic systems; both add weight and complexity to the aircraft design. Although the hydrogen fuel weighs less per litre, it is significantly less energy dense (Hydrogen Science Coalition 2023). Meaning it will require a much larger fuel tank, which will make the aircraft bigger and therefore generate a higher draft than a regular one. In the beginning, the price to fly a hydrogen plane will be high, although we will surely see some tax reliefs or green grants because of the zero emission released during flight.

Aviation has some very strict rules and regulations that these new aircraft will have to comply with before being allowed to fly passengers. They are mainly regarding durability, reliability and maintenance, to make it as safe as possible. As of now there are concerns regarding catalyst poisoning, water management and fuel cell contamination in hydrogen planes (Hoff et al. 2023; Knowles et al. 2010).

As for all other transportation modes, there will have to be implemented a new large system for fueling. Unlike the road vehicles with the ability to more easily set up new fueling stations, the aircrafts are much more limited because the charging spots need to be at or in direct connection to an airport. This might make some airports smaller, to be able to accommodate the fueling demand and some smaller airports might have a hard time to change, although they might be most suitable for this new type of smaller and shorter ranged aircraft.

A challenge when adapting to a new way of flying, moving away from the jetfuel to the fuel cells, is the public skepticism, due to the inability to do anything regarding your own situation when up in the clouds and at the mercy of the technology of the aircraft. It may be very hard for the public to be convinced to leave the reliable aircrafts and jet fuels that we have used for the past 100 years for this new solution, even though it is way better for the environment.

3 Results

Table 2 below summarizes driving ranges and refueling times for fuel cell vehicles compared to traditional combustion engine vehicles.

	Fuel Cell Vehicles		Traditional Combustion Engines	
	Range	**Refuelling time**	**Range**	**Refuelling time**
Cars	550–650 km	3–5 mins	400–600 km	3–5 mins
Trucks	400–800 km	$\sim$20 mins	3200 km	5–10 mins
Buses	300–400 km	20 mins	500–600 km	10–15 mins
Ships	380 km	2–3 hours	37 000 km	Up to 1 day
Aviation	650 km	75 min	3700 km	30 min

Table 2: Comparing Results of Range and Refuelling Time.

4 Discussion

It can be derived from table 2 that traditional ICEVs generally have longer driving ranges than FCEVs. The refueling times are hard to estimate because of variations between different vehicles and also a lack of data, especially when it comes to FCEVs. This result was expected, traditional combustion engines have been around since the mid 19th century and have completely dominated the vehicle sector the last century. FCEVs are in more of an experimental phase and compared to ICE.

The ICEVs however have an obvious downside in that they release carbon dioxide and NOx gases when in use and in the future we won't be able to use them if global environmental goals are to be met. This makes the comparison between FCEVs and ICEVs somewhat irrelevant, in the future we need to use green energy sources and it will not matter if the ICEVs perform better than the FCEVs. A more interesting comparison would be between BEVs and FCEVs since they both can be net zero-emission vehicles.

Whether the way forward to a greener heavy vehicle sector is through BEVs or FCEVs is a hot discussion topic. Generally FCEVs are suitable for long range, heavy duty operations while BEVs are suited for shorter, lighter operations. This is due to hydrogen having a low weight-to-energy ratio compared to batteries which allows heavier loads for longer distances.

5 Conclusion

Fuel cell technology is getting more popular as a clean alternative to conventional propulsion systems in different transportation sectors. There are many benefits with the fuel cell technology as for example zero emissions, high efficiency and rapid refueling. The fuel cell with the most potential is PEMFC because of its high power density, low operating temperature and compact design. The usage of fuel cells is more common for passenger vehicles than the other sectors where it is still in its early stages. There is much potential in fuel cells but there are still very many difficulties that need to be solved such as technological, economic and infrastructural. If the fuel cell system continues to develop it could become something that is used across all transport modes but there is still a long way to go.

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