OTC
Owner Team Consultation

Hydrogen for Vehicular Transport

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Introduction

I have had very few opportunities to use a motor vehicle during the past several months of Covid-19 induced incarceration. Not being able to travel, affords one the opportunity to reflect on what the future may hold for vehicular transport. In other words, what will power your car in 20 years' time.

The automotive industry is currently in the middle of a product-driven phase of disruption. No single type of vehicle drivetrain will predominate in the medium term, and we can expect to see vehicles with many different configurations of energy carriers, drive motors, and combinations, or hybrid vehicles. Irrespective of the drivetrain configuration, we can also expect a steady increase in the number of autonomous, or self-driving, vehicles, although KPMG's Automotive Institute (KPMG, 2020) found that more than 20% of automotive executives don't expect this to occur before 2040.

Hydrogen has great potential for use as a fuel in the future. It is estimated that, by the year 2030, the cost of ownership of fuel cell vehicles will be competitive with internal combustion engine vehicles, based on the technological improvements being made and the benefit of scale (Offer et al, 2010). Hydrogen, as an energy carrier, can also benefit regions with abundant solar and wind resources, such as South Africa, by producing and exporting low-carbon hydrogen.

In this article we first look at the colourful naming convention for hydrogen, consider several potential drivetrain configurations for passenger vehicles, and discuss vehicles from each category (internal combustion, electric, hybrid and fuel cell) in more detail.

Colourful hydrogen

Hydrogen is, of course, a colourless gas. However, in recent years, it has become practice to assign colours to hydrogen to identify how the hydrogen was produced.

In a previous article, Steyn & Render (2020) discussed the production of hydrogen and possible applications thereof. Readers who are interested in an overview of how hydrogen is produced, especially in a reformer or a hydrolyser, are encouraged to revisit that article.

Hydrocarbon-based hydrogen is formed in a methane reformer. Hydrogen produced from coal or oil as starting material is referred to by some authors as black and brown hydrogen. If the starting hydrocarbon feed is natural gas, the hydrogen produced is referred to as grey hydrogen. If the reformer used is fitted with a carbon dioxide capture and storage system, the term blue hydrogen is used. Some even referred to this as a 'synthetic' blue hydrogen and reserve the term blue hydrogen for hydrogen produced in a hydrolyser but using nuclear power. All other hydrogen produced by hydrolysis using renewable energy is referred to as green hydrogen. This is perhaps taking the colour descriptors too far...

The colour confusion is illustrated graphically in Figure 1.

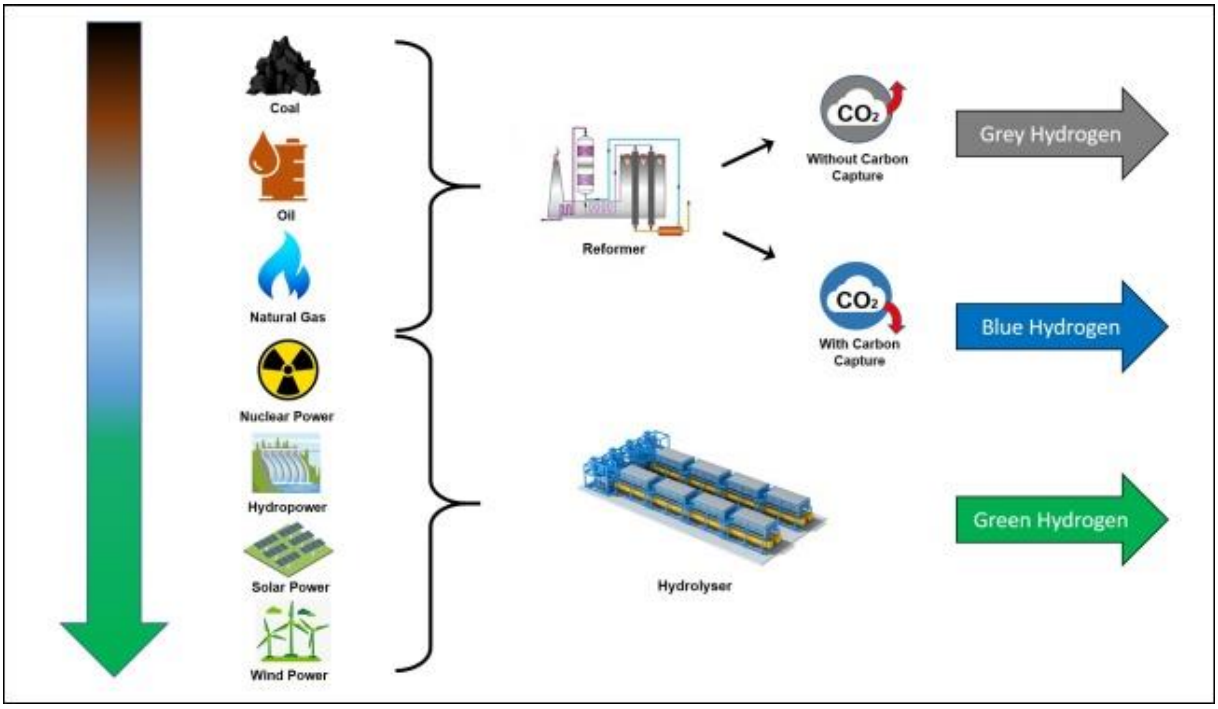


Figure 1: Colourful hydrogen

For this article, we will use the simpler approach of three colours only, as follows:

- **Grey Hydrogen:** Grey Hydrogen is hydrogen produced using fossil fuels such as coal, oil, or natural gas as the starting source of hydrocarbon. Methane from these sources is converted in a reformer to produce hydrogen and carbon dioxide. No provision is made for carbon capture and storage. Unfortunately, this accounts from roughly 95% of the hydrogen produced in the world today;
- **Blue Hydrogen:** Blue Hydrogen is hydrogen that meets the low-carbon threshold. Hydrogen produced in a reformer, fitted with a carbon capture and storage system that traps >90% of the carbon dioxide produced, is referred to as blue. This also

includes hydrogen formed by hydrolysis, but generated using non-renewable energy sources (e.g. nuclear); and

- **Green Hydrogen:** Green Hydrogen is hydrogen that not only meets the low-carbon threshold but is generated by hydrolysis using renewable energy sources such as solar, wind, geothermal or hydro-energy.

For maximum environmental benefit, green hydrogen is the preferred option. Dickel (2020) maintains that developing blue hydrogen is essential, since green hydrogen will not be available in substantial volumes until the power sector is fully decarbonised by renewable electricity, i.e. not before 2040. This is confirmed by Parnell (2020), who posits that blue hydrogen is not a perfect solution, but neither is green hydrogen because of the cost of production.

Drivetrain configurations

Many different drivetrain configurations for motor vehicles exist, or are being experimented with, but they all fall into one of four categories. These four categories are:

- Vehicles powered by internal combustion engines (ICE);
- Vehicles powered by batteries and electric motors;
- Hybrid vehicles, incorporating battery powered electric motors plus ICE; and
- Fuel cell powered vehicles with electric motors.

Some possible motor vehicle configurations are listed in Table 1.

Table1: Motor vehicle configurations

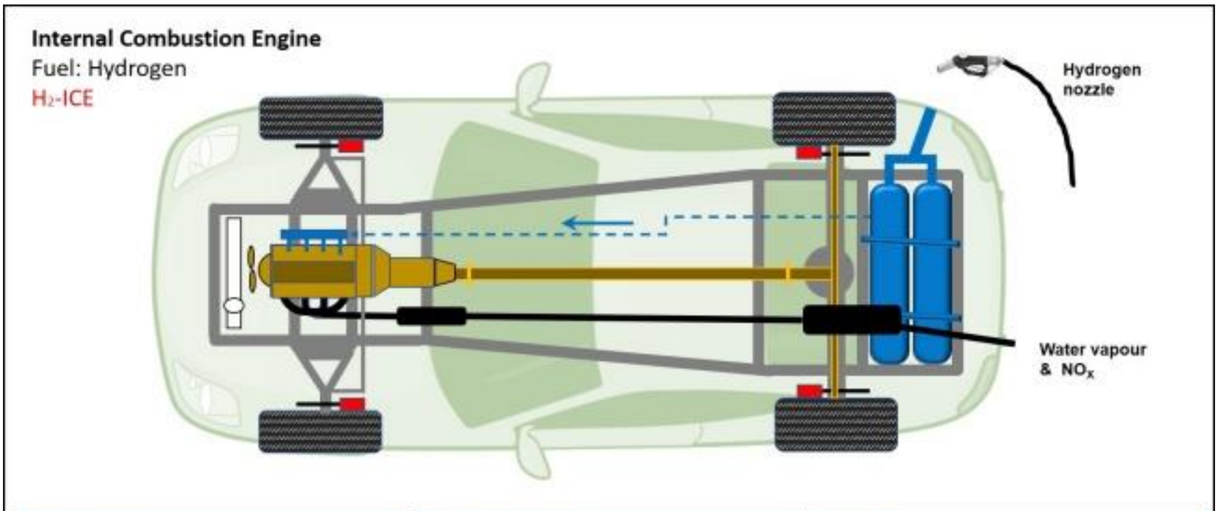
Category	Configuration	Shorthand	Future growth	Technology
Internal Combustion Engine	Petrol-fuelled ICE	P-ICE	Declining	Proven
	Diesel-fuelled ICE	D-ICE	Declining	Proven
	LNG/CNG-fuelled ICE	NG-ICE	Increasing	Proven
	Hydrogen-fuelled ICE	H_2-ICE *	Increasing	Developing
Battery Powered Electric Vehicles	Battery pack plus electric motor	BEV	Increasing	Proven
	Battery pack, electric motor, ICE & generator	BEV-X *	Increasing	Proven
Hybrid Vehicles	Battery pack, electric motor, plus ICE drive	HEV	Stable	Proven
	Battery pack, electric motor, ICE drive, charge plug	PHEV *	Stable	Proven
Fuel Cell Electric Vehicles	Hydrogen fuel cell with electric motor	H_2FC	Increasing	Developing
	Hydrogen fuel cell, electric motor and battery pack	H_2FC-B	Increasing	Developing
	Hydrogen fuel cell, electric motor, battery & charge plug	H_2FC-BP *	Increasing	Developing
	Hydrogen fuel cell, electric motor and supercapacitor	H_2FC-S	Increasing	Concept

This list is expected to grow in future as improved battery systems and alternative energy storage methods are developed. Alternative energy storage includes capacitors (the electrostatic battery), flywheels (the kinetic battery), compressed air (the pneumatic battery), superconducting magnetic energy storage (the magnetic battery) and radioisotope thermoelectric generators (the nuclear battery). Table 1 also gives the state of the technology development and an indication of whether this is a growing or declining technology.

There are variants of battery-powered electric vehicles available with one or more electric motors. In this article, we steer away from that type of added complexity, and all examples are based on a single drive motor. One example from each of these categories, as indicated by an asterisk in Table 1, is discussed in more detail in the sections that follow.

Internal combustion engine vehicles

Conventional petrol- and diesel-powered vehicles with an internal combustion engine (ICE) will probably not be available for purchase in 2040, although there will still be some such vehicles on the road. We will see ICE vehicles fuelled by compressed, or liquid, natural gas (NG-ICE), as well as blue or green hydrogen fuelled ICE vehicles (H_2-ICE). H_2-ICE is selected for the discussion in this category. An overview of an H_2-ICE vehicle is given in Figure 2.



Advantages	Disadvantages	Legend
Renewable energy carrier	Poor hydrogen supply network	H_2 tanks and fuel injection
Product of combustion is water	Low energy content of gaseous hydrogen	Engine, clutch & gearbox
Existing ICE can run on hydrogen	Limited range due to energy content	Drivetrain
Hydrogen tanks can be filled in minutes	Generates NO_x on combustion	Exhaust system

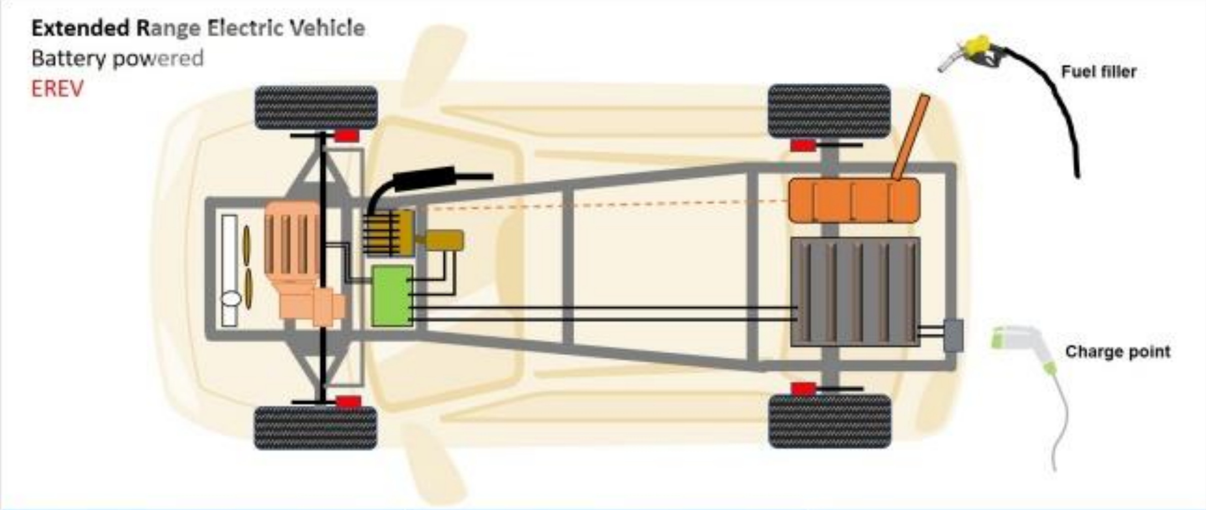
Figure 2: Overview of an H_2-ICE vehicle

The use of hydrogen as an energy carrier for transport applications is mostly associated with fuel cells. However, hydrogen can also be used in an internal combustion engine (ICE) with minor modifications. When converted to or designed for hydrogen operation, an ICE can attain high power output, high efficiency, and ultra-low emissions.

Although the vehicle in Figure 2 uses hydrogen as fuel, the configuration is the same for petrol, diesel, and natural gas. Also shown in Figure 2 are some advantages and disadvantages of a H_2-ICE vehicle.

Battery powered electric vehicles

Battery powered electric vehicles (BEVs) use batteries as the energy carrier and electric motors for motive power. The vehicles are fitted with a charging plug to charge the batteries. BEVs attracted much criticism for the limited range and time required to charge the batteries. This led to the development of the extended-range electric vehicle (EREV). An overview of an EREV is given in Figure 3.



Advantages	Disadvantages	Legend
Extended travel distance over BEVs	Generates CO_2, NO_X & SO_X	Fuel tank and fuel injection
ICE charges battery pack when necessary	Requires both charging and fuel	ICE & generator
Electric motor drives the wheels	More complex than BEVs	Power Control unit
ICE always runs optimally		Electric motor & Gearbox
		Battery pack

Figure 3: Overview of an EREV

The EREV is effectively an all-electric vehicle, with all the motive power provided by an electric motor, but with a small ICE present to generate additional electric power. Alternatively, it may be viewed as a series-coupled hybrid with a much larger battery. When the battery is discharged to a specified level, the ICE switches on to run a generator that, in turn, supplies power to the electric motor and/or recharges the battery. With this arrangement, the range limitation that is inherent in a BEV can be overcome.

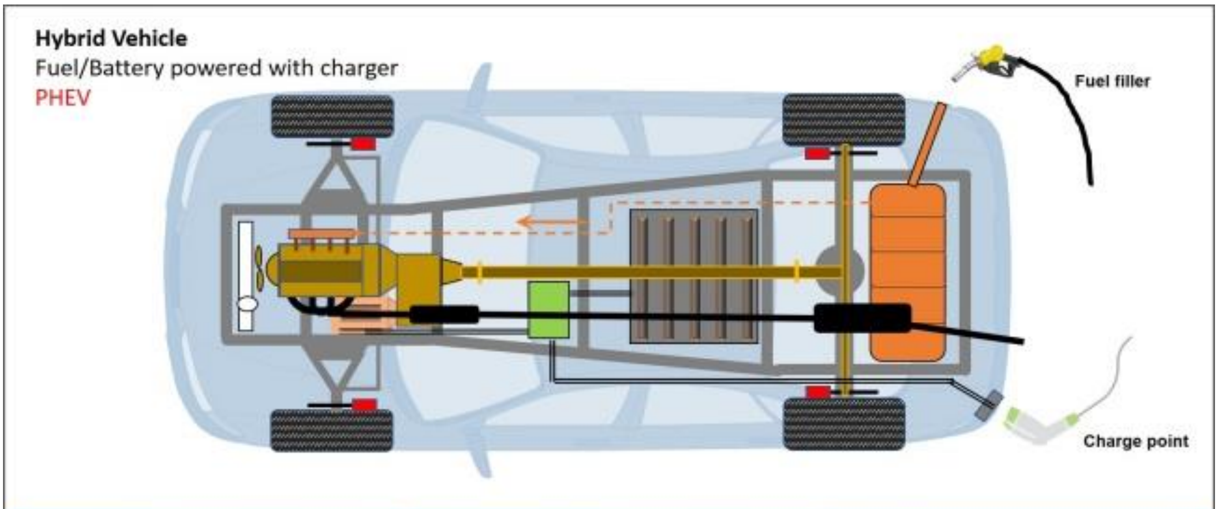
The EREV in Figure 3 is shown with front wheel drive, but it can also be rear wheel drive. Again, the advantages and disadvantages of this technology are highlighted. Although an EREV no longer has range limitations, it will generate carbon dioxide, nitrogen oxides and sulphur compounds when the ICE starts.

Some configurations of battery powered electric vehicles use more than one electric motor. For instance, we see examples with wheel mounted motors on the market.

Hybrid vehicles

A hybrid vehicle drivetrain usually consists of no more than two powertrains. More than two power trains will make the drivetrain overly complicated. One of the powertrains is typically ICE driven and the other is an electric drive.

We have seen that the EREV is essentially a series-coupled hybrid vehicle. However, what is referred to as a hybrid electric vehicle (HEV) is normally one with a parallel-coupled electric motor and an ICE. The ICE is assisted by an electric motor that is mechanically coupled to the driveline. HEVs can run in pure electric mode, in pure ICE mode, or in hybrid mode where both the ICE and electric motor are used. Pure electric mode is used when travelling slowly in stop/start traffic, pure ICE mode is used when the batteries are depleted, and hybrid mode is used when the driver demands more power from the powertrain(s). An overview of an HEV fitted with an external charge point (PHEV) is shown in Figure 4.



Advantages	Disadvantages	Legend
Motive power from ICE and electric motor	ICE generates CO_2, NO_x & SO_x	Fuel tank and fuel injection
ICE only runs when more power is needed	Requires both charging and fuel	ICE, coupler, clutch & gearbox
ICE charges battery pack when running	More complex than BEVs or ICE vehicles	Power Control unit
Can use a smaller ICE		Electric motor
		Battery pack

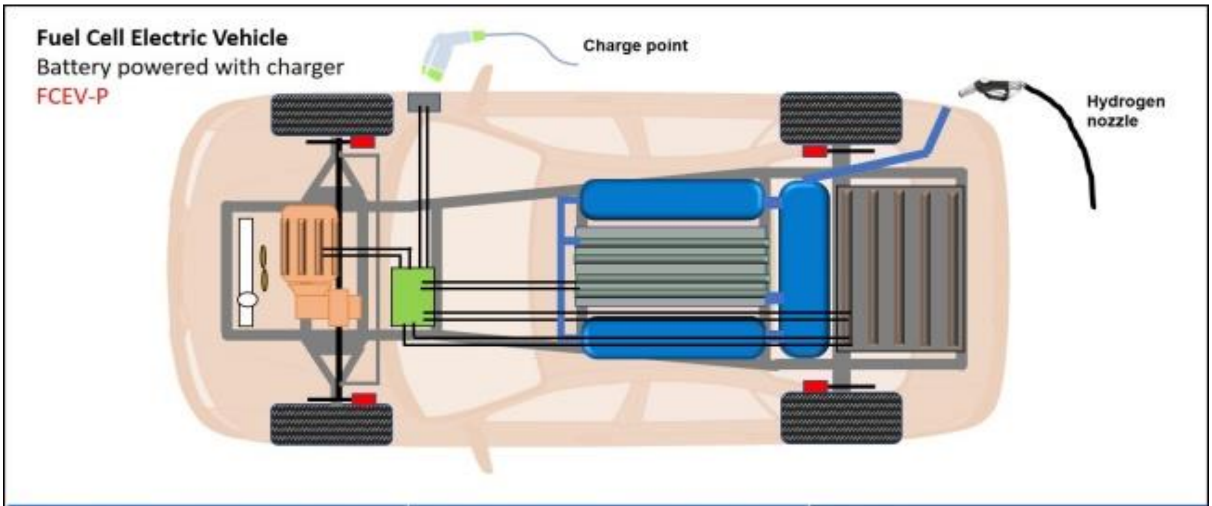
Figure 4: Overview of a PHEV

The battery pack in an PHEV can be charged with the external charge point, by a generator powered by the ICE, or by regenerative braking, where the kinetic or potential energy of the vehicle is recovered through the electric motor functioning as a generator.

Power output of the hybrid drivetrain is taken as the sum of the output of the ICE and the output of the electric motor.

Fuel cell powered vehicles

Hydrogen has long been known as a potential low-carbon transport fuel (blue and green hydrogen), but establishing it in the transport fuel mix has been difficult. However, the fuel cell electric vehicle market is beginning to expand rapidly, with several Japanese and Korean manufacturers bringing out hydrogen powered vehicles. Vehicles using hydrogen as the energy carrier for a fuel cell which generates electricity for charging the battery pack and powering the electric drive motor, is referred to as a fuel cell electric vehicle, or FCEV. An overview of a FCEV fitted with an external charge point (Plug-in FCEV or FCEV-P) is shown in Figure 5.



Advantages	Disadvantages	Legend
Fuel cell generates only water	Limited hydrogen infrastructure in place	Hydrogen tanks
Fuel cell power goes to motor and batteries	Blue or Green hydrogen very expensive	Fuel Cell pack
Electric motor drives the wheels	Fuel cells are expensive	Power Control unit
Filling hydrogen tanks takes minutes.	Low heating value of gaseous hydrogen	Electric motor & Gearbox
		Battery pack

Figure 5: Overview of a FCEV-P

Figure 5 lists some of the pertinent advantages and disadvantages of FCEVs. A concern is the longevity of fuel cells and the price thereof. It is expected that both these issues will be resolved in the near future by focused research. Similarly, the availability and production cost of green hydrogen is currently a concern, but the cost of water hydrolysis is also expected to come down as the market grows. Market growth can be stimulated with appropriate government incentives.

According to the International Energy Agency (IEA, 2020), the global FCEV number nearly doubled to 25 210 units at the end of 2019, with 12 350 new vehicles sold; more than doubling the 5 800 purchased in 2018. At the end of 2019, 470 hydrogen refuelling stations were in operation worldwide, an increase of more than 20% from 2018 (IEA, 2020).

Consumer preference

KPMG's Automotive Institute has been conducting surveys amongst automotive executives and consumers on an annual basis over the past several years. One of the questions for the consumers is: "Which powertrain technology would you choose if you were to buy a car in the next 5 years?" The responses for the past three years are reflected in Figure 6.

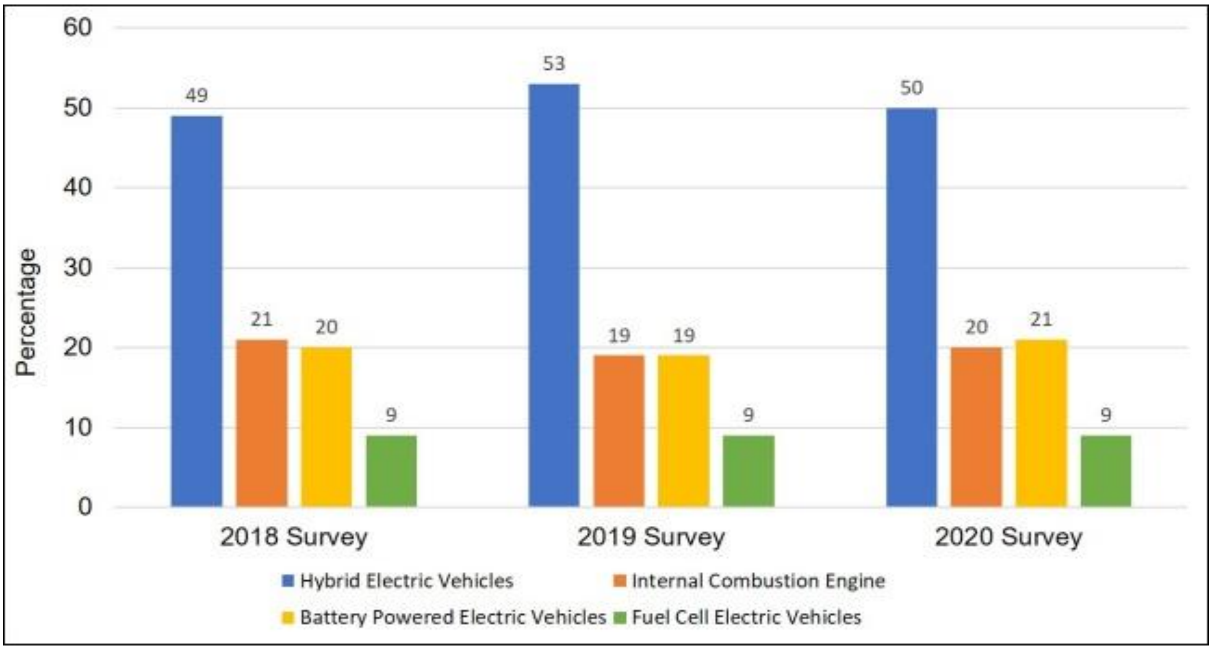


Figure 6: Consumers' preference of powertrain technology (KPMG, 2020)

The clear preference over the recent past is the hybrid electric vehicle, probably because the technology is proven and offers the best of both worlds. Battery powered electric vehicles are on par with conventional internal combustion engines but seem to be slowly edging ahead. Interest in fuel cell electric vehicles remains low throughout at 9%, due to the concerns mentioned in the previous section. This percentage is expected to rise as fuel cell vehicles prove their worth, and support infrastructure becomes available. If I had to make this choice now, I would also pick the hybrid option.

Automotive executives predict that by 2040, approximately 22% of vehicles on our roads will have internal combustion engines, 25% will be hybrid vehicles, 29% will be battery powered, and 24% will be hydrogen fuel cell powered (KPMG, 2020). I believe that by 2040, fuel cell vehicles will outnumber battery powered vehicles.

Concluding Remarks

According to the International Energy Agency (IEA, 2020), the political momentum for hydrogen use continued to gather strength during the past 18 months. This is fundamental for the advancement of hydrogen technologies and markets, since climate change ambitions remain the main impetus for widespread use of blue and especially green hydrogen. This also holds true for South Africa where interest in hydrogen is growing rapidly from all sectors.

KPMG's Automotive Institute (KPMG, 2020) believes that there will be long-term effects from Covid-19 on public transport. They posit that people will move away from public transport and are willing to spend more money to feel safe. This implies an increase in the sales of small BEVs. On the other hand, a loss of income during the past several months could mean that non-essential purchases are delayed.

According to the Hydrogen Council (2020), green hydrogen has already become 60% more affordable, as renewable electricity prices have dropped, and electrolysis capex has fallen. The cost of solar and wind power, the largest driver of renewable hydrogen production costs, has seen an 80% decrease over the past decade.

I believe that our long-term future and prosperity will rely on a fully functioning hydrogen economy. Green hydrogen's cost competitiveness can only be realised with appropriate policy support and investment to accelerate its scale-up.

References

Dickel, R. (2020) *OIES Paper: NG 159 - Blue hydrogen as an enabler of green hydrogen: the case of Germany.* Oxford institute for Energy Studies.

Hydrogen Council. (2020) *Path to hydrogen competitiveness: a cost perspective.* Available from https://hydrogencouncil.com/en/path-to-hydrogen-competitiveness-a-cost-perspective/. Accessed on 4 August 2020.

IEA (International Energy Agency) (2020) *Hydrogen*. Available from https://www.iea.org/reports/hydrogen. Accessed on 25 July 2020.

KPMG. (2020) *Global automotive executive survey 2020*. Available from https://automotive-institute.kpmg.de/GAES2020/. Accessed on 5 August 2020.

Offer, G.J., Howey, D., Contestabile, M., Clague, R. & Brandon, M.P. (2010) Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system, *Energy Policy* 2010, 38, 24–29.

Parnell, J. (2020) *Europe's green hydrogen revolution is turning blue*. Available from https://www.greentechmedia.com/articles/read/europes-green-hydrogen-revolution-is-turning-blue. Accessed on 4 August 2020.

Steyn, J.W. & Render, C.L. (2020) *Hydrogen as energy carrier*. Available from https://www.ownerteamconsult.com/hydrogen-as-energy-carrier/. Accessed on 31 July 2020.