Analysis of Prospects and Challenges for the Future Development of Hydrogen Vehicles

Zhirong Yao[1,*]

[1] Dover, UWCSEA, 139654 1207 Dover Rd, Singapore

Abstract. In the context of the global transportation industry, which presently combats environmental pollution and resource scarcity, HPV (hydrogen-powered vehicle) technology stands out as a feasible alternative to electric and ICE (internal combustion engine) vehicles. The current article aims to present a review of the benefits that relate to the usage of HPVs, including FCEVs and HICEs, with the focus on efficiency, emissions, and range. The essay also delves into the current limitations of the existing power sources, emphasizing the factors of technology, economy, and society as the main obstacles to hydrogen adoption. This assessment includes a comprehensive study of hydrogen storage, transportation, infrastructure, production, and public perception. Strategies are designed that could enable transportation with hydrogen to become more feasible. The results indicate that, given the current circumstances, HPVs seem not to be in a position for mass adoption. However, both innovative technologies and policy support can serve as important necessary prerequisites to placing HPVs as one of the pillars for sustainable future transportation.

1 Introduction

For decades, the fossil fuel industry has energized the transportation sector, and as such, vehicles with internal combustion engines (ICE) remain the most popular in the world. The depletion of these resources, the rampant environmental pollution, and the ever-increasing oil price instability make the search for non-fossil alternatives a necessity. Alternatives to ICEs, such as Battery Electric Vehicles (BEVs) and Hybrid Electric Vehicles (HEVs), offer a better combination of energy efficiency and fewer emissions. As strong as these technologies are, they are still limited by some factors that inhibit their massive deployment, the biggest of which is long-range travel and the readiness of infrastructure.

Along this avenue, hydrogen-powered vehicles (HPVs), which use hydrogen as a fuel in fuel cells, are more advantageous. HPV runs on hydrogen fuel cells, produces zero emissions, are faster in refueling, offer a longer-range drive distance, and are preferred for heavy-duty and commercial transport. One of the challenges associated with this transport option is that these vehicles are still impeded by several technical, economic, and social obstacles, which make for difficulties in realizing their optimization.

* Corresponding author: yao139548@gapps.uwcsea.edu.sg

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2 Limitations of current power sources

2.1 Internal combustion engines (ICEs)

An ICE Converting the chemical energy of gasoline or diesel into mechanical energy, however ICEs are extremely inefficient as only 20% to 30% of that chemical energy is transformed to engine power; the rest is considered as waste heat [1] movement. Also, close to the pollutions, carbon emissions are the by-products of ICEs. In 2023, the emitted CO_2 that resulted from the use of light-duty cars and trucks alone made up around 3.8 gigatons, which is the major share of road transport emissions (CMP, "Global Status Report on Road Safety," 2023). In a kilometer basis, a mid-size gasoline ICE vehicle emits about 250 gm CO_2 equivalent per kilometer while a BEV (battery electric vehicle) emits 80N/CO_2 per kilometer based on the European electricity mix [2] (Figure 1).

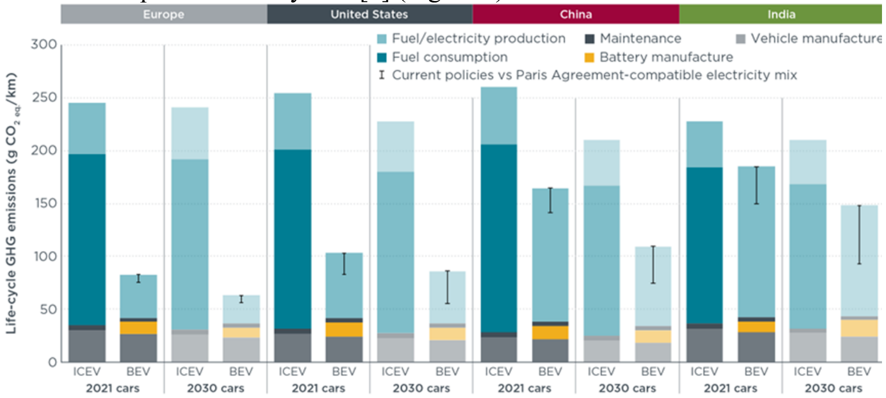

Fig. 1. Lifecycle GHG emissions of average medium-size gasoline internal combustion engine (ICEVs) and battery electric vehicles (BEVs) registered in Europe, the United States, China, and India in 2021 and projected to be registered in 2030. The error bars indicate the difference between the development of the electricity mix according to stated policies (the higher values) and what is required to align with the Paris Agreement [3]

2.2 Battery electric vehicles (BEVs)

Unlike ICEs, BEVs are propelled by lithium-ion batteries in combination with electric motors, as such they produce no tailpipe emissions, and they have an energy efficiency of upto 70% to 80% [1]. In this sense, they are superior environmentally wise over ICE and HEV, but there are still limitations. The time on-the-road to fully charge a cell is around a few hours at home and 30 to 60 minutes at fast-charging stations. This could sometimes make driver range anxiety, especially in areas lacking charging infrastructure.

Manufacture causes environmental and geopolitics issues. Because BEVs depends on the lithium, the cobalt and the nickel -the vital elements of the batteries, both of them are scarce and environmental heavy extraction -which are the major sources of metal. In addition to problems with average battery lifespan, it may be necessary to change the vehicle constantly to sustain the vehicle's production of lifecycle. BEVs have a better performance in urban environment and moderate distance travel, nevertheless, improvement in battery technology and charging facilities is still necessary to maintain their viability.

2.3 Hybrid electric vehicles (HEVs)

Hybrid electric vehicles (HEVs) in their elementary design merge an ICE with electric motor for shots reduction of fuel consumption and emissions. There are two options in the design of HEVs: to either run on gasoline or a mixture of electricity plus gasoline, differing based on driving requirements for efficiency.

Bearing this in mind, hybrids still ruefully place on fossil fuels as they are used to release some greenhouse gases, but they do so in a more diluted form compared to ICE vehicles. Conversely, despite this, there remain avenues for enhancing the efficiency levels, hence much work remains ahead. HEVs are highly electrified in their energy circulation compared to ICE and have more degrees of geek energy efficiency than HEV or BEV. Moreover, HEV is mostly external involution-wise [4].

In the table presented in IPCC's AR6 WG3 report, the data presented are as follows: ICE is at 2.5 MJ/km, HEV is at 1.8 MJ/km, while those of the BEV are the lowest at 0.8MJ/km [4]. Therefore, the usefulness of these statistics is undoubtedly profound. It rocks the notion that HEVs are temporary. Technologically more advanced than ICEs, in that both can no longer compete with BEVs in the production and use of clean energy efficiency.

Regardless of the fact that HEVs promise better mechanical performance through the adoption of additional systems that perk up the repair needs, they might prove too complex. Their transportation remains current vehicles instead of long-distance sustainable options. In 2022 alone, the International Energy Agency reports that carbon intensity from transport increased by 137 million tons of carbon emissions, a calculated figure 2 indicating that HEVs can't cut down the impact of climate change [5].

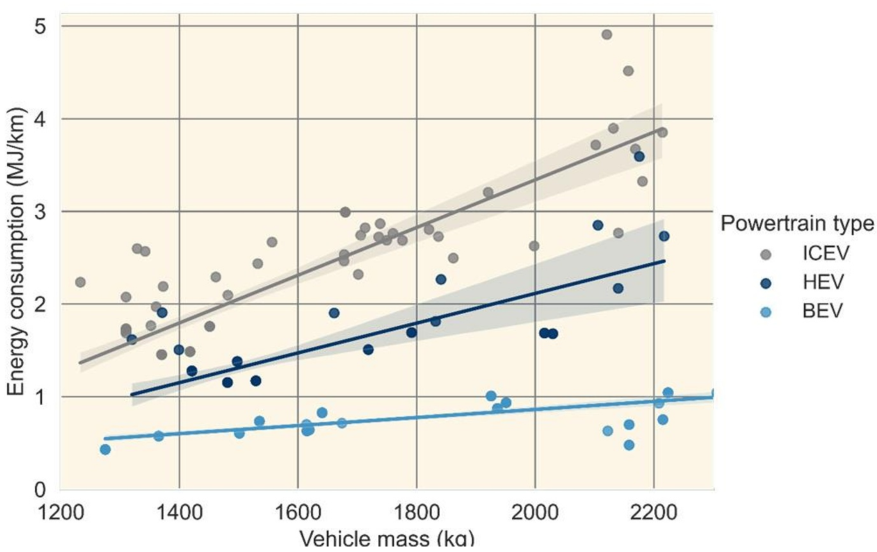

Fig. 2. Energy consumption of vehicles by mass and powertrain type (ICEV, HEV, and BEV), showing BEVs consistently use the least energy per kilometer regardless of vehicle mass. Adapted from the IPCC AR6 WG3 report [4].

2.4 Hydrogen-powered vehicles

Hydrogen-Powered Vehicles: The subject of this article concerns the vehicles running on hydrogen (HPVs). Such vehicles emerged as a potent instrument of the XXI century. Such HPVs components consist of fuel cell electric vehicles (FCEVs) and hydrogen internal combustion engines (HICE). The second one is ICE, much well-known nowadays, with the major difference being that this type of car use hydrogen to make the engine spin. At first, HICE gas is used in combustion with gasoline only. Noteworthy, respective byproduct of HICE is oxygen from water, as in BEVs, so no add-stuffs of carbon to the atmosphere. Nevertheless, HICE does not turn in the highly economic performance, and thus the residence time of this particle builds like that of FCEVs.

Unlike BEVs, FCEVs are deprived of such a crucial energy efficiency advantage. Still, internally combustion engine vehicles including ICEs are less preferable than FCEVs in respect to their lifetime emissions because these emissions also contain emissions from the power source, whether it is the renewable source like green hydrogen or the non-renewable ones. Among the studies carried out regarding the difference of life cycle emissions between matrix FCEVs with grey hydrogen and those with green hydrogen, a greater number of emissions is observed in grey cases as compared to those in green. A percentage of such difference depends on the type of hydrogen production methods and kind of the vehicle; however, the overall findings in that gray scenarios show much emissions than die-offs of the diesel patrol vehicles [3,6]. While in the case of green hydrogen the emissions can be raised up to nearly zero due to its electrolyzation of water using renewable energy [6].

H2 is a chemical that exists in the gaseous form and is stored and ignited in HICEs. Hydrogen is common in the other means as well, traveling with HICEs. Unlike FCEVs, HICEs are less efficient and produce NO_x as a result of the combustion of hydrogen. Vehicles powered with HICEs do have an emission control system not only on itself but also on the entire system. Depending on the process of hydrogen production, HICE emissions may in fact be higher than those of the other systems.

The main problems associated with hydrogen fuel stem from four factors such as infrastructure, sources of energy, cost of procurement and energy loss on processing hydrogen. Worryingly, the statistically significant indicator concerning that the overwhelming proportion of hydrogen is actually derived from the reformation of natural gas, which will significantly boost carbon emissions. Apart from that, what is even more disappointing to hear is the fact that the worldwide supply of green hydrogen is indeed abysmally low. In terms of proportion, green hydrogen uptake today stands at a whooping 0.1% of the total global hydrogen production [7].

It turned out that these three releases of HPVs modifications do have many advantages for emission reduction during the whole distance and within 24 hours. However, further development in the HPV component is needed, because current HPV technology lacks detail, cost and diversity.

3 Hydrogen vehicle technologies

Hydrogen-powered vehicles are typically divided into two categories: fuel cell electric vehicles (FCEVs) and hydrogen internal combustion engine vehicles (H_2ICEs). Both leverage hydrogen as a primary energy carrier but differ significantly in operation, efficiency, and environmental impact

3.1 Fuel cell electric vehicles (FCEVs)

A FCEV is an electric vehicle that works through a complex electrochemical reaction of hydrogen and oxygen molecules which can be sourced from the surrounding environment. In the course of such a reaction, water is produced, which contains no harmful elements because it lacks SOx, NOx, and PM. Such components are mainly composed of diesel engines. However, these FCEVs and BEVs or battery electric vehicles have a quite similar pattern of an automobile design apart from the use of hydrogen as fuel by replacing the battery packs with hydrogen. One of the key characteristics of FCEVs is that they incorporate all the BEVs advantages, including short period of time up to complete charging (3-5 minutes) and unparalleled driving range of over 500 km per charge. It can be said that these features, accompanied by low emissions, FCEVs are a good alternative to keep urban air clean and reduce pollution in big cities. In addition, a FCEV's relatively silent operation make it much advantageous than ICE-powered vehicles and can operate in varieties of weather. Although FCEVs make their travel in whatever climate condition, there is no effect on their performance in cold climate.

The first problem encountered is the cost side, however any deliberation of it would be faced with concision. The additional spare parts like platinum make the final price of the vehicle become highly expensive. The availability of the fueling infrastructure is one of the important customer selection factors for Fuel Cell Electric Vehicles. Hydrogen refuelling infrastructure has been difficult to grow and therefore now FCEVs are only available in a few countries. Additionally, the efficiency of fuel cell electric vehicles begins to germinate due to the higher energy consumption that happens when the process of extraction, storage and conversion of hydrogen, which therefore results into lower overall WtW efficiency than BEVs.

3.2 Hydrogen internal combustion engines (H_2ICEs)

Hydrogen is a fuel that is used in ICEs (Internal Combustion Engines). HICE is utilized instead of gasoline combustion, whereby hydrogen is vaporized in the engine. According to estimates, HICE is compatible with ICE units and it is possible to integrate it with such technologies easily due to this fact.

ICE and HICE have a quite similar configuration and therefore hydrogen technology can be easily integrated to s existing fleet to allow the business to continue with the same engine, spare part and repair shop infrastructure. Almost without exception, hydrogen combustion emits way lower levels of CO than gasoline engines, even none at all in some cases. However, it has an advantage of quick refueling making it an ideal source for long distance transport.

For now, however, the market position of both FCEVs and HICEs is going down a lot. In the end, HICE is inferior to FCEVs with their respective efficiencies, and they do emit NO_x. As a result, there is a need to introduce the emission control system on H2ICE transports. Considering HICE, which is obtained from either production or other H2 sources, it can reduce emission such as CO_2 compared to other systems. On top of that, the regenerative braking and energy recovery systems are not available on HICEs and that varies with the H2 source. It should be noted that even though HICEs can change their driving mode, they cannot also improve their efficiency.

4 Key challenges in hydrogen vehicle

4.1 Hydrogen storage

The large molecular size and low molecular density of hydrogen impose a significant technical issue for storage. Industrial processes in hydrogen auto manufacturing normally require 700 bar of compression or −250°C liquefaction to ensure the fuel for long distances [7]. These approaches involve energy systems that are energy demanding, with the risk of high-pressure containment. Additionally, hydrogen has an energy density of about 3 kWh/L, which is slightly lower than that of gasoline, which has an energy density of 8.8 kWh/L. This makes it inevitable to manufacture compact storage tanks, which hinders vehicle design [7]. Solid-state storage methods with metal hydride utilization have great potential for compactness and increased security, even though the methods are expensive and under study at the moment [6].

4.2 Transportation and distribution

Compared to other fuels, these problems are less significant regarding hydrogen. Hydrogen has been excreted as a contributory factor in the embrittlement of metals; and because of the small size of the molecules, he has also been eliminated as leaking. The specially designed pipelines and materials are, therefore, necessary [7]. A global infrastructure for hydrogen pipelines was there up to 2021, but it was only 4,300 km, with most of it in Europe and North America [8]. The transportation of cryogenic type gas and liquid is costly and inefficient, notably over long distances. Liquid Organic Hydrogen Carriers (LOHCs), such as methylcyclohexane, are considered the most promising alternative because they bind hydrogen chemically to the carrying liquid and don't need special conditions to attract it later. Nonetheless, there are several questions with LOHCs that need to be studied, notably transformation of the chemical bond and melting point, recycling, and scaling problems [6].

4.3 Refueling infrastructure

There are fewer than 1,100 hydrogen stations globally, mostly located in Japan, South Korea, Germany and California [8]. This cost is roughly $1-2 million USD to establish each station, as the hydrogen compressors, storage tanks, and safety measures are so expensive [7]. This incompetent infrastructure creates a feedback system, which involves two parts: FCEVs consumers would rather not own them without the availability of the stations, and investors are reluctant to finance stations when there is limited demand for FCEVs among consumers, which is the described "chicken-and-egg" problem of hydrogen adoption [7].

4.4 Hydrogen production

The environmental effects of hydrogen depend on the production technique. Now, it is estimated that the most common approach to produce hydrogen, i.e., steam methane reforming (SMR), generates large numbers of CO_2. The meaning of hydrogen, therefore, may be described as "grey hydrogen" [7]. The production of blue hydrogen, to the contrary, happens through carbon capture and storage (CCS); therefore, venting of the hydrogen emissions into the atmosphere is possible. Another case is green hydrogen, created from renewable energy through electrolysis. Compared with grey hydrogen, green hydrogen is about three times more costly, with costs ranging from $3-$7 per kilogram, versus $1-$2 for grey hydrogen [7]. Approximately 9 liters of water are consumed in the process of electrolysis to produce one kilogram of hydrogen. The amount could increase demand and add pressure on water supply in the regions with limited resources [8].

These costs, in addition to supply problems, limit the scaling of green hydrogen, especially in the continents with insufficient renewable energy and underground water resources.

4.5 Public perception and market readiness

The availability of hydrogen cars, as well as their public awareness, are not very pronounced. An investigation conducted in 2005 in London demonstrated that the result was only 47% of the surveyed who knew about the existence of hydrogen vehicles, and only 33% of the examined population was prepared to accept the new technologies [9]. Apart from this, the

2023 Bosch global mobility survey has recently reported the recognition and acceptation of hydrogen as a crucial part of the future of clean transport by 41% of the respondents, indicating a better perception among the public [10]. Yet, those safety concerns are not merely hypothetical but belong to the actual present and material somewhere. Hydrogen, a gas with a high risk of explosion, as opposed to the common part of the population, has high pressure on tanks despite the fact that the modern ones go through numerous tests. Nevertheless, the cost of high-quality hydrogen (e.g., the cost of $50,000 of the Toyota Mirai in the US) is so that the gas is reflected as a luxury rather than as a mass transportation. Furthermore, there is a lack of hydrogen models and, with the BEVs having the advantage of a greater market and policy support, hydrogen cars are tightly sanctioned as a specialty machine than as a common vehicle, which could easily be used for fleet, commercial, or heavy-duty jobs.

5 Solutions & suggestions

5.1 Hydrogen storage

Common hydrogen storage methods, such as retrying of gas to 700 bar or cooling to -253°C, are dangerous and expensive. The development of a solid-state storage technology, for example, that consists of hydrogen stored in metal hydrides (e.g., magnesium hydride or alanates) or nanoporous materials, is a safer way to store hydrogen since low pressure and high volumetric density is applied in this method. The performance of the materials is becoming increasingly important; it radically influences the distance between an ideal situation and the real-world commercial approach, and this process, as it currently stands, is not yet finished [11].

5.2 Transportation

Concerned hydrogen transportation is the case due to the fact that hydrogen worsens the deterioration of the structure itself, due to a low density and high risk of embrittlement. Liquid Organic Hydrogen Carriers (LOHCs), like methylcyclohexane, are the kinds of carriers that bear hydrogen in a chemically bound state to a liquid carrier over normal atmosphere pressure of gas and liquids. Addressing this matter, it is possible to exploit the existing fuel transportation process. The demand for further progress is in the fields of efficiency in energy consumption and cost of the catalyst [12]. Additionally, the retrofit of hydrogen blending to read gas pipelines is applied in a number of nations. However, in the case when the materials are reinforced, it is possible that savings may be made on distribution costs, and that the transportation may be sped up [7].

5.3 Reducing hydrogen costs

The green hydrogen produced from water electrolysis using renewable energy is three to six times more expensive than grey hydrogen for one kilogram, at about three to six dollars, in contrast to one or two dollars, respectively. This data is taken from the International Renewable Energy Agency (IRENA), which has reported a decrease in the value of green hydrogen. Yet, it is expected that the green hydrogen price should be down, with 60% decrease in 2030 [13]. This reduction can be attributed to mass manufacturing of electrolyzers and improving efficiency as well as the dropping renewable prices.

For these purposes, government toolkits must be structured in order to stand up for the green hydrogen production, i.e., through subsidies, carbon pricing, or incentives for renewables. The implementation of such policy will provide the costs of green hydrogen, compared to other alternatives, with a relative reduction in their value; that will, in turn, promote the private sector involvement in this field.

5.4 Refueling infrastructure expansion

As of 2023, the total number of public hydrogen stations across the world was slightly under 1,100, with most of them located in Japan, South Korea, and Germany [13]. The station construction is considered very capital intense, as the estimated costs are approximately $1 million to $2 million per site. This factor itself is a barrier to investments as they heavily depend on the demand guarantee.

Public-private partnerships (PPPs) are presented as a necessary measure in order to promote efforts for improving hydrogen station infrastructure. The government is expected to speed up the implementation of hydrogen pumps by integrating them into existing gas stations and further by fixing the permit and land planning process. Delivering such cooperation for the sake of all the nations, there is an example of effective multi-stakeholder approach seen in Germany through H2 Mobility and California Hydrogen Highway [14].

5.5 Market adoption and public engagement

As mentioned earlier, the image of hydrogen technology is not where it needs to be. A survey carried out in London showed that less than half of respondents had heard about hydrogen vehicles, and only a third were in favor of their use [9].

The communication balance of potential risks and safety concerns, costs, accessibility, and hydrogen's advantages represents a considerable challenge. Supporting demonstration projects like safe educational programs help early normalization and is particularly important for municipal services, buses, and trucks. These measures should be supplemented with purchase grants and tax incentivization, which significantly increases public backing [15].

6 Conclusion

The analysis indicates that hydrogen-powered vehicles can be the next breakthrough in the transport industry by providing a viable solution for its environmental and energy issues. On the other hand, the HPV (FCEV) often comes out on top in terms of range, refueling duration, and emissions compared to ICEs and BEVs. At the same time, this advantage should be considered in conjunction with the crucial roadblocks, including the high production costs, limited infrastructure, the imperfect energy efficiency cycle, and public refusal. In this regard, the mass passage to HPVs can only be achieved with technologies improvement in hydrogen storage and transport, cost reduction with economies of scale, and strong government support in policymaking and infrastructure development. When green hydrogen becomes more affordable, and trust in hydrogen safety increases, HPVs can assume the lead in the decarbonization of the global transport sector.

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