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Fuel Cells Versus Lithium-ion Batteries (LIB) in Transportation: A Comprehensive and Comparative Review

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Abstract. The impacts of modern transportation on climate change have become more and more serious. To offset these impacts, electrification via alternative engines and driving systems has become a concern and a promising method for governments and industries as they implement newer, cleaner technologies. Amongst these new ones, battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) have drawn most attention due to the fact that they are the two most promosing alternatives to the traditional internal combustion engines. This essay gives a comparative and in-depth review of hydrogen fuel cells and lithium-ion batteries in transportation technologies. It examines their theoretical principles, energy efficiency, viability of infrastructure, environmental impact, and feasibility in terms of cost. The finding is that BEVs have higher wheel-to-wheel efficiency, lower costs, and a more mature market, making them suitable for use in passenger fleet and urban applications. FCEVs are advantageous in long-distance, heavy-duty, and commercial use since they possess higher energy density and faster refueling time, resulting in higher mobility. The research concludes that both technologies are indispensable components of the general effort towards green mobility.

1 Introduction

Transportation plays an important role in producing global greenhouse gas emissions. It is responsible for approximately one-quarter of total carbon dioxide output across the world [1]. Most governments, researchers, and industries are facing the urgency of climate change. Reducing emissions from common road vehicles has been a major priority for them to consider. As a result of their effort, alternative solutions, including different kinds of propulsion methods, have been put out to replace the traditional combustion engine. Among these, fuel cell electric vehicles (FCEVs) and battery electric vehicles (BEVs) have emerged to be the promising ones and have bright future applications.

Both BEVs and FCEVs replace traditional combustion engines with electrochemical processes, but they differ in energy storage, delivery, and usage. In BEVs, electricity that is fed to the electric motor directly comes from lithium-ion batteries. In FCEVs, however, the fuel cell uses hydrogen to supply the electricity that the motor needs. In the fuel cell,

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hydrogen reacts with oxygen to create electricity, making water the only emission that comes out of the system. Because of these differences in generating energy, these two technologies have extremely different strengths and weaknesses.

BEVs are growing rapidly owing to the growing performance and range of lithium-ion batteries and the growing availability of charging stations in recent years around the world. FCEVs have some advantages over BEVs, including shorter refueling times and higher energy density. FCEVs are better models for long-distance travel and heavy-duty or commercial vehicles such as buses and trucks. Although there has been immense progress, debates between the academia and industries have also persisted as to which among these technologies offers superior overall sustainability. Scholars have persistently compared BEVs and FCEVs across various aspects such as energy efficiency, environmental footprint, availability of infrastructure, and economy.

This paper undertakes a comparative study of new findings on lithium-ion batteries and fuel cells in transport to provide a basic understanding of their advantages and weaknesses. The goal is to show how each technology is decarbonizing transport and explore the potential cooperation between BEVs and FCEVs as they can supplement each other's functions, that is, BEVs for urban, short-range use and FCEVs for long-haul, heavy-duty, and commercial transport.

2 Fundamental principles of FCEVs and BEVs

In simple words, BEVs run entirely on electricity stored in rechargeable lithium-ion batteries. Direct current electricity is supplied from the battery to an electric-powered motor, which gives power to turn the wheels. The basic energy flow of BEVs can be described in five words: charging, discharge, inverter, electric motor, and regenerative braking. Electricity is charged into the vehicle and stored in the battery pack. The battery delivers this direct current electricity to the inverter, where the direct current is inverted into alternating current. The electric motor converts electrical energy from the inverter to mechanical energy, which rotates the wheels. Regenerative braking allows the motor to work in reversely during braking, sending kinetic energy back into the battery.

FCEVs generate electricity onboard directly using a hydrogen fuel cell instead of getting electricity from a facility, like a charging station. In the fuel cell, hydrogen reacts with oxygen from the air in an electrochemical reaction, producing electricity and water vapor. A proton exchange membrane fuel cell (PEMFC) is most commonly used in transportation. Core component of a PEMFC includes an anode, where hydrogen gas is pumped in and a catalyst facilitates the separation of hydrogen into protons and electrons; a cathode, where oxygen from the air reacts with protons and electrons to form water vapor; an electrolyte, which sits in the middle and conducts protons but blocks electrons and gases; and an external circuit, which is the path for electrons to go into the motor as power delivery. Then, with the hydrogen going into the PEMFC, the energy is transferred into electricity and delivered to the motor through a direct circuit, which powers the wheels. FCEVs also have a small lithium-ion battery for regenerative braking. FCEVs are a little bit less energy-efficient than BEVs, with around 40-60% of the energy from hydrogen to the wheels, due to losses in hydrogen compression. Refueling time for FCEVs is around 3-5 minutes for a tank. There are limitations for FCEVs, because of the small number of hydrogen refueling infrastructure and the expensive hydrogen production.

3 Findings and analysis

3.1 Efficiency and technical performance

Efficiency plays a major role in differentiating between BEVs and FCEVs. As shown in Fig. 1, BEVs may reach up to "well-to-wheel efficiencies of 70 - 80%" [1], while FCEVs are closer to 30-40% because the energy source is hydrogen, and producing, compressing, and transporting hydrogen usually costs a lot more. This makes BEVs more suitable for passenger cars and city driving. Families consider more on fuel efficiency and BEVs are more suitable in this way. More efficient means less consumption of natural resources as well. BEVs in the cities and being used as passenger transport will save natural resources.

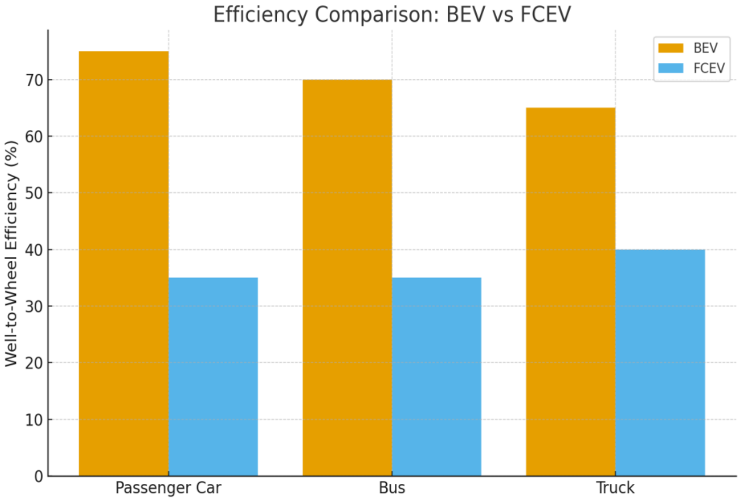

Fig. 1. Wheel-to-wheel efficiency comparison between BEVs and FCEVs for passenger cars, buses, and trucks [1, 2].

However, FCEVs are more fit for long-haul and heavy-duty usages. For example, agricultural tractors were studied in a professional manner and researchers have found that hydrogen fuel cell powertrains could deliver higher operating efficiency than diesel engines in demanding fieldwork [2]. Also, even though BEVs are more energy efficient than FCEVs in the application of heavy trucks, FCEVs are more practical for trucks because hydrogen tanks are lighter than the huge batteries required for similar ranges. This reduces the production costs on materials and workloads. In addition, short refueling time and lower emissions are some other advantages held by FCEVs. By 2050, the TCO (total cost of ownership) for BEVs is expected to reduce by 44.5-45.5% while the reduction for FCEVs reaches 63.8-64.3% [3].

From the statistics' point of view, BEVs seem to be more energy efficient overall, but the application of FCEVs is crucial and irreplaceable in the areas where range, workload, and fast refueling are required.

3.2 Infrastructure and policy support

Infrastructure and policies made by governments usually decide the pace of each technology's expansion. Without proper infrastructure and support from the government, the development of technologies will thus be limited. As of 2023, there were over 1000 hydrogen refueling stations worldwide, while EV charging stations have already had millions of them spreading all over the world [4]. In the U.S., the government is more prone to promote battery charging networks, especially for light-duty cars [5]. Light-duty EVs are making great sales in the whole country. Companies like Tesla and Toyota are favored by Americans due to their fuel efficiency and convenience. Tesla is building more charging stations across the country and reducing the general charging duration at the same time. Hydrogen, on the other hand, has been getting little support and attention. For example, the used Toyota Mirais' market value is dropping rapidly and making fewer deals.

But still, hydrogen is still getting favored by specific niches. Policy reviews highlight that the European Union's "Fit for 55" package includes goals to expand hydrogen stations along major transport routes [4]. It is also well predicted that the gap between charging and hydrogen stations may narrow if governments continue to invest in hydrogen resources for heavy-duty vehicles and public transportations like buses, fleets, and long-distance trucks [6]. In general, infrastructure for BEV is far ahead and more developed than that of FCEV. At the same time, hydrogen infrastructures are getting more policy support in specific industrial areas from many governments, especially in the EU region. It is expected that people will see more FCEV usage on the road and in industrial, public transport areas.

3.3 Environmental impacts (life cycle assessment)

BEVs and FCEVs both sound very clean and must have zero emissions. In reality, however, their impacts on the environment are determined by their entire life cycle instead of just looking at their emission while being used. LIB production creates significant emissions to the environment because cobalt and nickel are often used in the production. About 70-125 kg of carbon dioxide per kWh of battery capacity is emitted [1]. Researchers are working on some cleaner recycling methods to reduce this amount of emission [3]. For FCEVs, the main problem is hydrogen production. As Burchart and Pryzytula state, "hydrogen from fossil fuels can even result in higher emissions compared to diesel" [3]. But if the hydrogen produced comes from some renewable electrolysis, also known as green hydrogen, emissions will be significantly reduced in that way. It can be concluded that the benefits of hydrogen vehicles depend almost entirely on how the hydrogen is produced [7].

As shown in Fig. 2, the renewable production of hydrogen and materials for batteries makes a significant drop in carbon dioxide emissions. BEVs produce about 60 tons of carbon dioxide over a lifetime when powered by fossil-dominant grids and about 20 tons of carbon dioxide with renewable electricity, showing that different energy sources could cause a major difference in carbon dioxide emissions. Same for FCEVs, when they are powered by gray hydrogen, the carbon dioxide emission is about 80-90 tons, while those using green hydrogen can drop to about 25 tons of carbon dioxide [1].

In general, BEVs are considered much cleaner today, but FCEVs have a chance to be equally clean or even more sustainable if green hydrogen production becomes more common instead of taking them from fossil fuels.

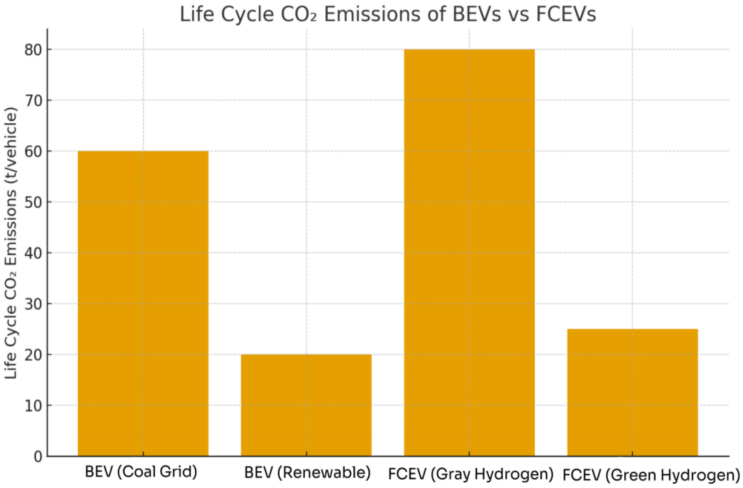

Fig. 2. Lifecycle CO_2 emissions of BEVs and FCEVs under different energy and material sourcing scenarios [1].

3.4 Economic feasibility and market trends

The market value of Lithium-ion batteries has significantly decreased since 2010, for about 85% [8]. BEVs thus became more affordable for consumers, especially for those who live in the cities or common households. It is estimated that the total cost of ownership in Chile was about 1.93-1.95 USD/km for BEVs, compared to 2.32-3.0 USD/km and 1.2-1.5/km for diesel [9]. In consideration of researchers' work and effort in maximizing the usage and application of both FCEVs and BEVs, it is predicted that by 2050, costs for both BEVs and FCEVs are projected to fall enough to catch up with diesel. Hydrogen is expected to decline from around 12 USD/kg today to about 3-4 USD/kg by 2030-2040 [10]. The study also shows that incorporating hydrogen into both gas and power systems could reduce costs by up to 20%.

Fig. 3 illustrates the historical and projected cost decline trends for both lithium-ion batteries and hydrogen fuel between 2010 and 2030. The LIB cost curve shows a dramatic reduction over the years, dropping from USD 1200 per kWh to USD 80 - 100 per kWh by the end of 2030 [8]. This decline is most likely due to better choices of electrode materials, improved manufacturing efficiency, and global production capacity. As a result of these developments, the cost for battery electric vehicles has decreased dramatically, making it more affordable for consumers and more popular in the current automotive market. The hydrogen cost curve follows a similar decrease pattern, falling from USD 12 per kilogram in 2010 to a projected USD 3 - 4 per kilogram by 2030. Integration of power-to-hydrogen systems with smart grids plays a significant role in decreasing the cost of hydrogen fuels. Both declines suggest that hydrogen could achieve low-cost systems with conventional fuels in heavy-duty transport, while LIBs continue to dominate the light-duty and passenger sectors of the market.

In summary, BEVs are considered more affordable and stable today in the market standards, and are more suitable for most of consumers' choices. However, hydrogen and FCEVs are becoming more competitive as the production scale is growing larger and the cost of hydrogen production is dropping fast, especially for heavy-duty transportations where hydrogen-powered vehicles are considered more suitable for long-distance transport and bigger workloads.

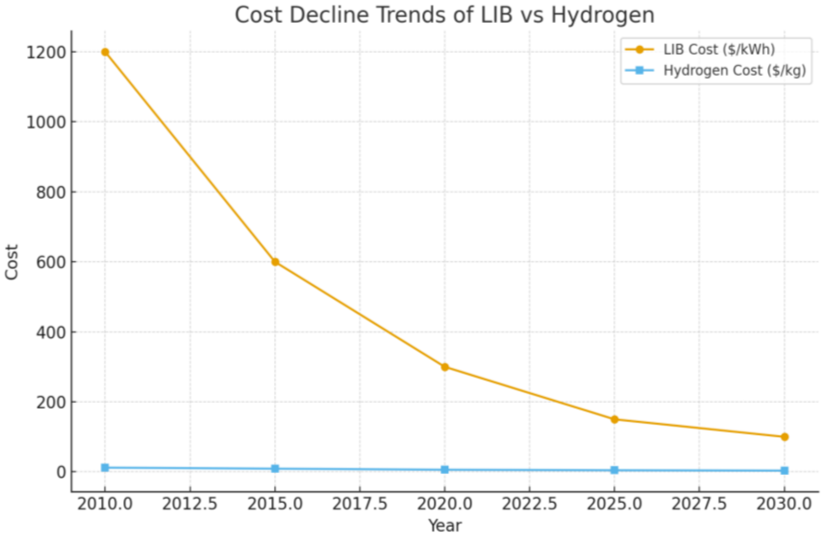

Fig. 3. Historical and projected cost trends of lithium-ion batteries (USD/kWh) and hydrogen (USD/kg) [8].

3.5 Integration and hybrid approaches

With the development of technology, a growing number of studies suggest that BEVs and FCEVs should not be treated as direct competitors against each other but as complementary and mutually beneficial parts of the clean energy system. Studies have demonstrated that coordinated control of lithium batteries and hydrogen storage in microgrids improves stability, reduces wear, and extends system lifespan [11]. Others have proposed adaptive energy management strategies for hybrid vehicles combining batteries and fuel cells [12]. Integrating these two strategies will allow BEVs and FCEVs to fully exhibit their advantages. BEVs seem to be more advantageous in every area in terms of economic feasibility, but with some add-ons from FCEVs, a combined model in the future will probably be the solution of a more environmentally and budget-friendly transportation method. These approaches look into a future where vehicles and energy networks combine both technologies, maximizing efficiency and flexibility. All in all, hybrid systems that combine LIBs and fuel cells can help break off the limitations of each and enlarge both of their strengths.

4 Challenges and perspectives

Although they both seem very promising, both BEVs and FCEVs face technical, economic, and policy obstacles. Issues for BEVs is that LIB manufacturing incurs substantial environmental and resource burdens with 70-135 kg of CO_2 per capacity of kWh [1]. There are also issues with the availability of essential raw materials including nickel and cobalt [8]. While recycling of batteries is on the rise, mass, circular economy options are yet to develop. Fuel cell electric vehicles still rely heavily on hydrogen production processes. Fossil fuel-produced hydrogen often comes with more pollution because “hydrogen produced from fossil fuels can even lead to increased emissions compared to diesel” [4]. Even though utilizing power-to-hydrogen systems with renewable energy can save sexpense and avoid renewable energy waste, the efficiency of hydrogen storage is far lower than that of LIBs (30–40% vs. 85–95%) [10]. Shortages of policy and infrastructure also slow FCEV implementation in most locations, and U.S. policy has historically been favoring BEVs [5]. In the future, hybrid integration presents a feasible path over these challenges. Adaptive energy management systems that combine LIBs and fuel cells have been proposed by researchers to leverage their strengths [12], and coordinated hydrogen and battery storage control has been shown to improve microgrid stability [11]. Such advancements imply that the future of clean motoring shall not be "battery vs. fuel cell" but optimized systems in corporating both technologies. In short, BEVs and FCEVs are supplementing technologies to decarbonize transportation. It will take steady innovation in infrastructure, materials, and policy to get past their specific hurdles, eventually resulting in a more efficient, sustainable, and equitable transportation system.

5 Conclusion

This research has provided a comprehensive comparison between LIBs and fuel cells within the context of modern transportation. Through analysis of efficiency, infrastructure, environmental impact, and economic availability, it demonstrates that these two technologies are not rivals but complementary solutions to vehicle decarbonization. The evidence throughout this review shows that LIBs have become the base for urban and passenger transport electrification, while hydrogen fuel cells offer suitability for long-range. heavy-duty application scenarios.

The significance of this study is to highlight that a sustainable transportation future will depend on balanced integration of both systems rather than reliance on a single technology. The comparative insights of this review highlight not only the current performance boundaries of both technologies but also the shared potential for both technologies to merge and assimilate instead of competing against each other. As innovation continues, improvements in battery performance, hydrogen production, and global energy policy will determine how effectively these technologies can work together to accelerate the transition toward cleaner mobility.

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