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Comparative study of lithium-ion battery and hydrogen fuel cell powered vehicles: Technical, economic, and environmental analysis

Zixi Lin

Canadian International School of Guangzhou, Guangzhou, Guangdong, 511400, China

1811431219@mail.sit.edu.cn

Abstract. The transition to sustainable energy sources in the transportation sector has led to the development and adoption of various alternative propulsion technologies. This document offers an analytical comparison between vehicles powered by lithium-ion batteries (LIBs) and those powered by hydrogen fuel cells (HFCs). It scrutinises the technical, economic, and environmental advantages and disadvantages of each. LIB and HFC vehicles are among the most notable competitors in this sector. On a technical level, LIBs offer higher efficiency and lower weight, while fuel cells provide extended range and rapid refueling capabilities. Economic modelling shows battery electric vehicles currently demonstrate the lowest total cost of ownership, though supportive policies could improve fuel cell competitiveness in heavy-duty applications by 2050. Both technologies provide major greenhouse gas emissions reductions versus conventional vehicles, with battery electric vehicles maintaining an advantage in most scenarios. However, resilient domestic supply chains for critical battery materials and hydrogen infrastructure must be established to enable wide-scale adoption. Safety risks exist but can be mitigated through preventative strategies. Overall, LIBs and HFCs have complementary strengths, positioning them to transform transportation sustainability. However, batteries currently hold advantages in light-duty vehicles, while fuel cells show promise in heavy-duty segments. Continued technology advances, cost reductions, infrastructure build-out, and supportive policies will be instrumental in realising the immense potential.

Keywords: Lithium-ion batteries, electric vehicles, hydrogen fuel cells, cost analysis, environmental impact.

1. Introduction

Green transportation, which includes different types of environmentally friendly transport methods, has become a crucial solution to a variety of environmental problems. This shift is important in reducing climate change, improving air quality, saving resources, and encouraging sustainable development. Two technological advancements, HFCs and LIBs are significant to this change. Green transportation helps lessen climate change by reducing greenhouse gas emissions. This is mainly achieved by moving from gas vehicles to electric vehicles (EVs) and other low-carbon options. This change can greatly reduce carbon dioxide emissions, which helps fight the effects of climate change [1]. Also, green transportation technologies, such as EVs and public transport systems powered by LIBs or HFCs, produce much fewer emissions, leading to better air quality and a lower risk of lung diseases. Another big benefit of green

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transportation is resource conservation. Energy is used more effectively by automobiles with LIBs or HFCs than by those with internal combustion engines. This higher efficiency results in less energy use and less reliance on fossil fuels [2]. Also, a key part of sustainable transportation systems is the use of renewable energy sources, which further help save resources and reduce carbon footprints. Green transportation also helps reduce noise pollution, a common problem with traditional road traffic. LIBs or hydrogen fuel-cell-powered vehicles generate far less noise, which results in quieter urban surroundings. By reducing air and noise pollution, green transportation has a positive impact on public health and well-being, as it improves air quality and decreases exposure to harmful emissions [3]. The development of LIBs and HFCs has been a big step in the history of green transportation technologies. LIBs, first sold in 1991, have seen improvements in energy storage, lifespan, and safety, becoming the standard power source for electric cars. HFCs first thought of in the 19th century, saw big development and sales only in the late 20th century [4]. These cells make electricity by combining hydrogen and oxygen, providing a clean, efficient, and sustainable power source for vehicles. Government policies and rules around the world have been key in promoting green transportation. Standards for fuel efficiency, emissions rules, and incentives for the use of EVs and HFCs vehicles have sped up the development and use of these green technologies [5].

2. Basic operating principles of lithium-ion batteries and hydrogen fuel cells

The movement of lithium ions between two electrodes—typically made of graphite and a metal oxide compound—is the basis for how LIBs work. During the charging phase, lithium ions are drawn out from the metal oxide compound and traverse through an electrolyte to the graphite electrode, where they are stored. This process is reversible, thus facilitating the battery's capacity to be charged and discharged repeatedly [6]. The discharge process involves the return of the stored lithium ions from the graphite electrode to the metal oxide compound, subsequently releasing electrons. These electrons course through an external circuit, generating an electric current capable of powering various devices. As the lithium ions migrate, the battery's capacity gradually diminishes until a recharge is necessitated [6]. The core elements of LIBs encompass the separator, cathode (positive electrode), anode (negative electrode), and electrolyte; specific materials composing these may vary. On the other hand, an electrochemical reaction between hydrogen and oxygen powers HFCs. The fuel cell is supplied with hydrogen gas (H2) at the anode (negative electrode). The anode and cathode (positive electrode) are partitioned by an electrolyte, which permits ion passage. At the anode, an electrolysis process splits hydrogen molecules into protons (H+) and electrons (e-). The protons traverse through the electrolyte while the electrons journey through an external circuit, creating an electric current that can power devices [7]. Oxygen gas (O2) is concurrently delivered to the cathode of the fuel cell. Here, oxygen is combined with the anode's protons and the external circuit's electrons to produce water (H2O) as a by-product. Hydrogen and oxygen are combined in this overall reaction to produce energy, with water as the only waste. This method establishes HFCs as a reliable and clean energy source [1]. It's significant that there are various fuel cell varieties, including solid oxide fuel cells (SOFC) and proton exchange membrane fuel cells (PEMFC), each having a range of electrolytes and operating temperatures [8].

3. Comparison between Hydrogen Fuel Cell and Lithium-ion Batteries

3.1. Performance comparison: Efficiency, Range, Weight, and volume

In the evaluation of the performance between LIBs and HFCs, numerous factors are considered, such as efficiency, range, weight, and volume. Regarding efficiency, LIBs are recognised for their high efficiency, which typically falls within the range of 90% to 95%. Conversely, the efficiency of HFCs ranges from approximately 40% to 60%. This delineates that a higher proportion of the energy input is transmuted into usable electrical energy by LIBs in comparison to HFCs [9]. From the range perspective, HFCs present an advantage, offering a longer range compared to LIBs. The ability to quickly refuel HFCs allows for an extended range without the necessity of protracted charging times [10]. In the context of weight and volume, LIBs possess a higher energy density compared to HFCs. This implies they can store a greater amount of energy per unit of weight or volume. Being relatively lightweight and compact, LIBs are suitable for portable applications, such as smartphones and electric vehicles. In contrast, HFCs necessitate larger storage tanks for hydrogen gas, which can contribute additional weight and occupy more space [11]. The results may vary between different types of applications.

3.2. Economic Analysis

Recent research examined the total cost of ownership of diesel-powered heavy-duty trucks, HFCs, and LIBs. The study investigated both current costs and future projections to assess the conditions under which emerging technologies could become cost-competitive [12]. The total cost of ownership modelling conducted provides a comprehensive evaluation spanning production costs, maintenance costs, and operating costs across each vehicle's lifetime. This encompasses the upfront vehicle purchase price, energy costs, including projected fuel and electricity prices, infrastructure investments, scheduled and unscheduled maintenance costs, financing costs, battery replacement needs, and residual value at end-of-life [12]. The analysis reveals that today, HFCs electric vehicles (FCEVs) can match or even undercut the total cost of ownership of diesel vehicles for certain applications. For example, the study shows an FCEV city bus having a total cost of ownership of €0.67/km compared to €0.63/km for a diesel bus. However, battery electric vehicles (BEVs) currently demonstrate a lower total cost of ownership than both alternatives, with a BEV bus costing €0.54/km [12]. To accelerate the cost competitiveness of FCEVs, the study highlights the importance of incentives and supportive policies. Applying carbon taxes on diesel fuel could allow FCEV total cost of ownership parity 5-7 years sooner. Reducing hydrogen costs from €10/kg to €5/kg could lower FCEV's total cost of ownership by 18-20%. Higher purchase subsidies of €160,000 compared to €80,000 could reduce lifetime costs by 13-15% [12]. Looking towards 2050, the total cost of ownership modelling projects, FCEVs are emerging as a cost-effective option for certain heavy transport segments. With favourable conditions, FCEV tractor trucks could achieve a TCO 11-21% cheaper than diesel. City buses powered by HFCs are projected to reach total cost of ownership levels below BEV buses with rapid charging. On average, though, BEV's total cost of ownership is forecasted to remain 28% less than FCEV's total cost of ownership in 2050[12]. The competitiveness and acceptance of these technologies are also greatly impacted by existing government subsidies and policies encouraging the use of battery electric trucks (BETs) and fuel cell electric trucks (FCETs). However, the analysis in the ScienceDirect article suggests the policy environment tends to reinforce the economic advantages of BETs over FCETs in Europe. The study notes purchase subsidies are available in many European nations for both truck electrification options. These subsidies reduce upfront costs compared to conventional diesel trucks. However, subsidy amounts are generally larger for BETs, providing a greater incentive for their adoption. For example, Germany offers subsidies of up to €80,000 for BETs but only up to €30,000 for FCETs. Some countries also exclusively provide infrastructure incentives for electric charging stations, preferentially benefiting BET deployment [13]. Carbon pricing policies such as the $100/ton assumed in the analysis improve the cost competitiveness of both alternatives compared to diesel. However, within the electric truck market, the asymmetric subsidy and infrastructure support magnifies the total cost of ownership edge of BETs over FCETs [14]. The research indicates more balanced policy support is needed to catalyse the adoption of FCETs. Increasing purchase incentives and investing in hydrogen refueling infrastructure could accelerate FCET viability and commercialisation. Targeted subsidies and the build-out of refueling stations could allow FCETs to become cost-competitive in long-haul trucking, where their advantage lies.

3.3. Environmental Impact

Electric vehicles (EVs) offer clear greenhouse gas emissions benefits compared to conventional gas-powered cars, despite higher manufacturing impacts from large batteries, according to analysis by MIT experts. While EVs have no tailpipe emissions, producing their LIBs generates high carbon dioxide emissions, up to 16 metric tons for a typical EV battery. Due to the labour-intensive manufacturing process, a new EV initially produces 80% more emissions than a comparable gas vehicle. However, during the course of driving, EVs show significantly lower emissions than cars with internal combustion engines in almost all cases. According to a model that looked at comparable EV and gas vehicles, gas automobiles generate more than 350 grams of CO2 per mile driven on average. EVs, charged on the US energy grid mix, emit around 200 grams per mile - over 40% less. These EV emissions vary based on the carbon intensity of local electricity, from very low figures where renewable energy dominates to slightly higher than gas cars in coal-dependent grids. But under most assumptions, EVs outperform gas counterparts. As electricity grids worldwide add more renewable sources, the emissions from EV charging will decrease significantly. MIT projections estimate EVs dropping from 200 grams per mile today to as low as 50 grams per mile by 2050, while gas cars improve marginally to around 225 grams per mile [15].

3.4. Energy Storage and Supply Chain Issues

Grid-connected energy storage is essential for integrating more renewable energy onto the electric grid and enhancing resilience, but the supply chain for LIBs, the dominant technology, is highly vulnerable. Global energy storage demand is projected to grow over 9 times from around 10 GWh today to over 90 GWh by 2030, with LIBs making up over 95% of short-duration storage. However, the United States currently has only 13% of global lithium-ion cell manufacturing capacity compared to almost 80% for China. The US also lags significantly in producing cathodes, anodes, and other components, with less than 1% of capacity in some cases. In addition, the US produces less than 2% of critical battery minerals like lithium, cobalt, and nickel, which could see 20-40 times more demand by 2040 under climate scenarios [16]. With minimal domestic reserves and refining, the US relies heavily on imports for LIBs. Recycling batteries from electric vehicles could meet around 10% of primary mineral supply needs by 2040, but ramping up collection and processing is challenging. Alternatives like iron flow batteries and compressed air storage using conventional equipment avoid geographic constraints and supply chain risks. But Capital costs are high, with lithium-ion packs at $132/kWh now compared to DOE targets of $80/kWh by 2030[17]. As the US grid storage market grows from around 5 GWh today to over 40 GWh by 2030, developing robust and diverse domestic supply chains will be essential to enable growth and resilience while avoiding critical limitations.

3.5. Safety Considerations

Though promising technologies, LIBs and HFCs come with inherent safety risks that must be properly managed. LIBs can experience thermal runaway, ignition, and reignition, potentially leading to fires and explosions if not controlled. Preventative measures include providing emergency responders with practical guidance tailored to specific electric vehicle models and standardising hazard labels and symbols across brands [18]. Similarly, HFCs carry risks like leaks, hydrogen combustion, and explosion during accidents. Hydrogen filling and charging safety strategies are critical to prevent hazards [19].

4. Suggestions on Future Technology Advancements of Lithium-ion Batteries and Hydrogen Fuel Cell

Studies have shown the potential for continued improvement in LIBs and HFCs, two critical technologies for the creation of electric vehicles. Notably, data on LIBs reveals an impressive 13% annual reduction in the cost per unit of energy capacity [4]. This trend may further improve, particularly with innovations such as solid-state battery designs optimized for stationary storage. Meanwhile, HFCs offer advantages like robust power output, highly efficient energy conversion, and proven reliability. Progress in fuel cell technology encompasses enhanced stack durability, improved compressor responsiveness, and increased onboard hydrogen storage density. However, certain areas like membrane materials, catalysts, bipolar plates, and storage system costs still require advancements. In the pursuit of sustainable energy solutions, future developments are paramount. LIBs technology must prioritize increasing energy density to extend EV range and refining fast-charging capabilities for quicker replenishment. Solid-state batteries, despite facing manufacturing and cost challenges, hold promise due to their safety and energy density potential. Sustainability initiatives are also driving innovations in recycling and responsible material sourcing, reducing environmental impact. Safety improvements are essential to mitigate risks such as thermal runaway and dendrite formation. Regarding the HFCs, improving efficiency remains a priority for better hydrogen utilization and reduced emissions. Research into advanced materials, like non-platinum catalysts, seeks to enhance fuel cell cost-effectiveness and sustainability. Developing efficient hydrogen storage solutions, including solid-state materials and advanced tanks, is pivotal for hydrogen's practicality. Infrastructure expansion, including hydrogen refueling stations, is necessary to support widespread fuel cell vehicle adoption. Extending fuel cell lifespan and implementing rigorous safety measures are equally critical for long-term viability. In conclusion, these advancements in LIBs and HFCs underline their transformative potential in the realm of sustainable transportation. Continued research and innovation will drive efficiency gains, cost reductions, and increased environmental responsibility, ultimately promoting the widespread adoption of electric vehicles and contributing to a greener, more sustainable energy landscape.

5. Conclusion

In conclusion, LIBs and HFCs offer tremendous potential as sustainable transportation technologies, yet they also come with unique advantages, limitations, and challenges. LIBs demonstrate higher efficiency and lower weight than fuel cells, making them well-suited for vehicles. However, HFCs provide a superior range and rapid refueling capabilities. Economic analysis reveals battery electric vehicles currently have the lowest total cost of ownership, though with supportive policies, HFC vehicles are emerging as a cost-effective option for certain heavy-duty transport applications by 2050. Both technologies deliver major emissions reductions compared to conventional vehicles, with EVs maintaining an edge. Robust domestic supply chains for LIBs and hydrogen infrastructure must be developed to enable wide-scale adoption. Safety risks exist for both technologies but can be mitigated through preventative measures. Overall, the complementary strengths of LIBs and HFCs position them both to play pivotal roles in enabling the transition to sustainable transportation systems.

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