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Environmental Footprint of Battery-Powered Electric vs Hydrogen Fuel-Based Transportation: A Comparative Review

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Abstract- The global demand for clean and sustainable energy solutions is rapidly increasing, with green hydrogen recognized as a key enabler of future carbon-neutral energy systems. This review article focuses on the environmental aspects of two emerging clean transportation technologies: battery-powered electric vehicles (BEVs) and hydrogen fuel cell vehicles (FCEVs). It assesses each technology across lifecycle stages—production, operation, and disposal—focusing on greenhouse gas emissions, energy efficiency, resource usage, and infrastructure requirements. This review accomplishes that while BEVs are currently more environmentally favorable for most passenger transport applications, FCEVs may play a complementary role in decarbonizing sectors requiring high energy density and rapid refueling.

Keywords- Battery, Electric Vehicle, Fuel cell, Hydrogen fuel, Carbon emission, Life cycle

I. INTRODUCTION

Nowadays growing concerns about air pollution, climate change, and the depletion of fossil fuel resources are causing a major shift in the global transportation industry. Among the biggest sources of greenhouse gas (GHG) emissions and the deterioration of urban air quality are conventional internal combustion engine (ICE) automobiles, which mostly run on petroleum-based fuels. Battery-powered electric cars (BEVs) and hydrogen fuel cell vehicles (FCEVs) are two innovative low-emission technologies that have emerged as the front-runners in the search for sustainable alternatives. The diagram as in Figure 1 depicts the progression of vehicle technologies in terms of mileage, fuel source, and vehicle size. Due to their dependency on electricity and excellent efficiency, electric vehicles (EVs), which include personal cars, commuter cars, and small logistics vehicles, are best suited to short-distance applications. Hybrid and plug-in hybrid vehicles are transitional solutions that combine electricity with conventional fuels to power medium-range passenger cars. Long-distance trips and larger vehicles such as delivery trucks, buses, and heavy-duty trucks are prioritizing hydrogen-powered fuel cell vehicles (FCEVs). This demonstrates the complementing roles of EVs, hybrids, and FCEVs in meeting various

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mobility needs.

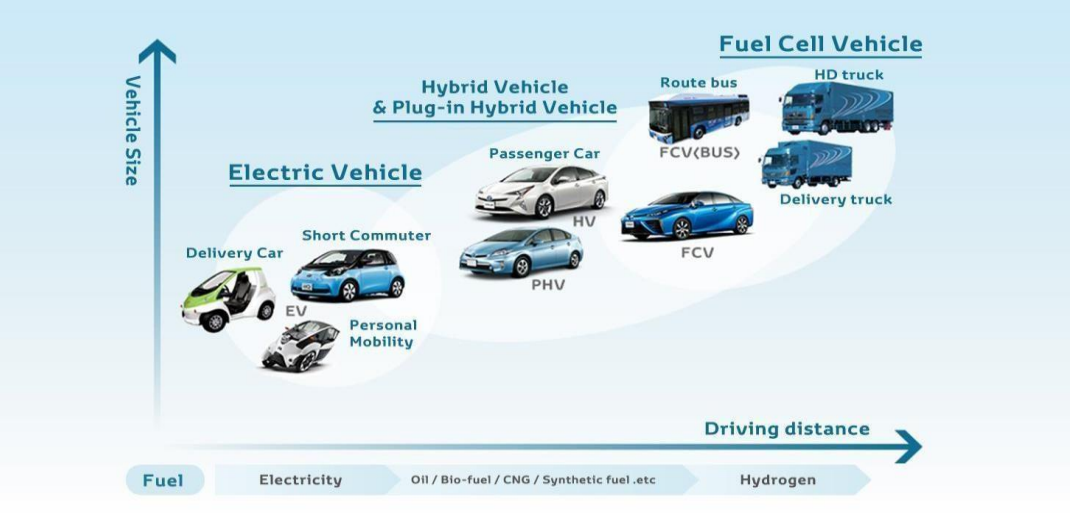


Fig.1. Conversion of vehicle technologies with respect to distance [1]

The diagram (Fig 2) illustrates the difference in range between battery and hydrogen vehicles. Battery vehicles, such as automobiles and vans, are useful to travel short-distance, but their range is restricted. On the opposite hand, Hydrogen cars are ideal for long-distance and heavy-duty applications. Trucks, railroads, and, most notably, ships can travel nearly 7500 kilometers using hydrogen. This indicates hydrogen's benefit in massive mobility, whereas batteries are better suited to smaller, short-range applications.

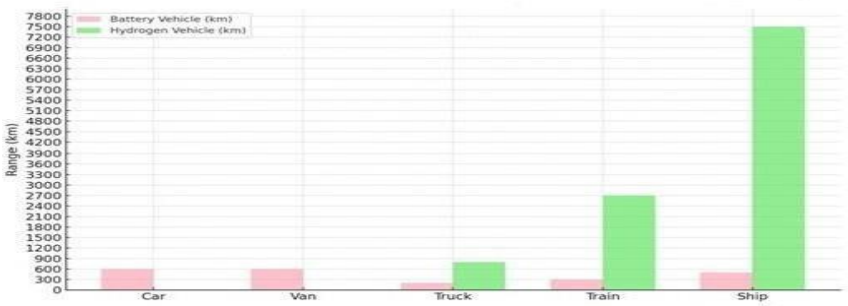


Fig.2**.** Comparison of battery electric and hydrogen vehicle range by transport mode

II. LIFE-TIME CARBON FOOTPRINT

A. Battery-Electric Vehicles:

Higher upfront emissions during production, mostly from the mining and processing of lithium, cobalt, and nickel used to make batteries. As electrical grids decarbonize, operating emissions are significantly lower than those of internal combustion vehicles. Recovering valuable materials through recycling and second-life batteries can further reduce lifetime impacts. Generally 50–70% fewer lifetime GHG emissions than gasoline/diesel vehicles, and generally lower than FCEVs in the current climate.

B. Fuel-Cell Vehicles that run on Hydrogen:

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Moderate emissions up front from carbon-fiber hydrogen tanks and fuel-cell stack generation[2].Natural gas, or grey H_2, can have a longer lifespan than BEVs and occasionally even internal combustion engines [3].Although Blue H_2 (with CCS) lowers emissions, most studies still show that it outperforms Bevs. Green H_2 (renewables) can reduce emissions over time.

The diagrams in Figure 3 show that electric cars (EVs) are far more energy efficient than hydrogen vehicles, with 87% vs 40% overall efficiency. While electric vehicles have zero exhaust emissions, their entire carbon footprint is determined by the grid's source of energy, which differs by country.

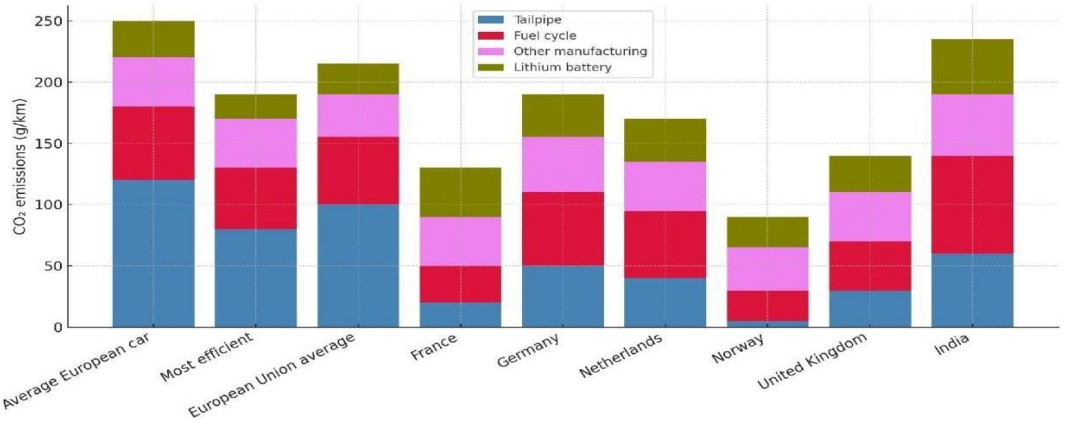


Fig .3. Global life-cycle emissions of BEVs and FCEVs

According to the Figure 4, electric cars (EVs) are significantly more energy efficient than hydrogen vehicles. EVs maintains a high 87% energy utilization rate from source to wheel, but hydrogen vehicles waste substantial resources over many conversion phases, resulting in a significantly lower 40% effectiveness.

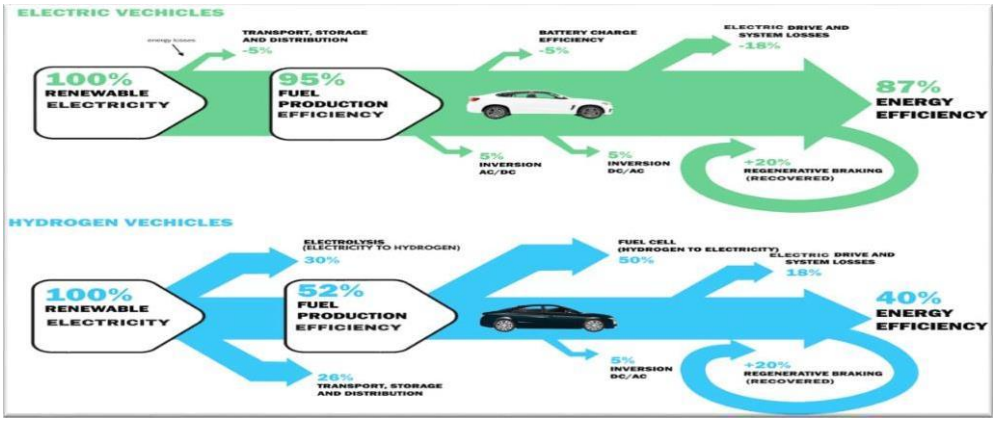


Fig 4. Comparison of energy efficiency in electric vehicles and hydrogen vehicles

This graph contrasts automobiles' life-cycle CO_2 emissions, taking into account the manufacture, lithium battery, fuel cycle, and tailpipe. Electric vehicles reduce emissions from their tailpipes, but they still produce emissions from batteries and electricity generation. France and Norway have the lowest

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emissions from nuclear or clean energy, which makes EVs very sustainable there [4]. Emissions are higher in Germany, the Netherlands, and India due to power that is primarily derived from fossil fuels. According to the table, EVs are not entirely emission-free, and the advantages they offer vary depending on the energy mix of each nation.

This Table 1 compares hydrogen and battery electric vehicles, showing the significant characteristics. Hydrogen FCEVs provide quick recharging and great mileage; however they have limited infrastructure and inferior performance. BEVs have improved efficiency and a developing network, with lengthier charging periods.

Table.1. Comparison between Hydrogen and Electric vehicle

Aspect	*Hydrogen FCEV*	*Battery EV (BEV)*
Energy Source	Hydrogen stored in high-pressure tanks, converted to electricity via a fuel cell.	Electricity stored in a large battery pack.
Refueling / Charging Time	3–5 minutes (like gasoline).	30 min – several hours (depending on charger speed).
Range	300–400 miles (500–650 km) typical.	200–400+ miles depending on battery size.
Efficiency (well-to-wheel)	25–35% (hydrogen production, transport, conversion losses).	70–80% (grid-to-wheel, more direct use of electricity).
Infrastructure	Very limited hydrogen stations (mostly in CA, Japan, South Korea, Germany).	Rapidly growing global charging network.
Environmental Impact	Zero tailpipe emissions (only water vapor). But depends on how hydrogen is produced (most today is fossil-based).	Zero tailpipe emissions. Environmental footprint depends on grid mix and battery manufacturing.
Vehicle Cost	High (fuel cells and tanks are expensive, small market).	Falling costs due to mass adoption and battery improvements.
Operating Cost	Hydrogen is often more expensive per mile than electricity.	Generally cheaper to “fuel” with electricity.
Best Use Cases	Heavy-duty trucks, buses, trains, ships, long-haul transport (where quick refueling and range matter).	Personal cars, city buses, light trucks, urban transport (where charging is practical).
Maturity & Adoption	Still niche, with few models and limited sales.	Mass adoption, wide model variety, strong momentum globally.

III. FUEL PRODUCTION EFFICIENCY FOR HYDROGEN AND ELECTRIC VEHICLES

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Challenges:

In Hydrogen-powered cars it requires multiple transformations to make Electricity from H_2 and a lot of energy [5] being wasted at every step. Net efficiency is approximately 25-35%, compared to 70-80% for BEVs. Hydrogen must be stored under extremely high pressure (700 bar) instead of as a liquid at -253°C. Both processes require considerable amounts of energy. They produce waste heat that cannot be completely reused. Durability concerns (membrane deterioration, catalyst contamination) affect operational efficiency. Hydrogen refueling facilities itself require energy (compression, cooling, and pumping), which contributes to ineffectiveness.

Solutions:

Green hydrogen via electrolysis powered by renewable energy (solar, wind, hydro). Develop high-efficiency electrolysis (like solid oxide electrolysis, around80–90% potential efficiency).Create next-generation fuel cells with a high ratio of conversion (65-70%).Increase longevity (longer lifetime, less catalyst degradation).Hydrogen can be used to store excess renewable energy. Combine hydrogen with smart grids and renewable energy to equalize car performance. Concentrate on heavy-duty vehicles, buses, trains, ships, and airplanes (where batteries are too large). Industrial processes (steel, ammonia, cement) where direct electrification is challenging.

Solar power is utilized for electrolysis of water, producing hydrogen that is then turned into electrical energy to operate the electrical motors in vehicles, offering a clean, environmentally friendly alternative to fossil fuels for transportation, as explained in the Figure 5.

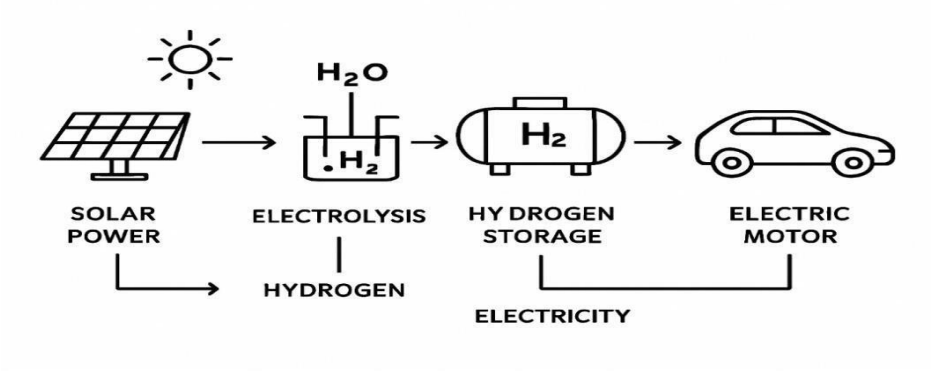


Fig 5. Solar-Powered Hydrogen Fuel Cycle

According to the Table 2, India is rapidly growing its green hydrogen sector through both government and commercial initiatives, with major projects underway and proposed to increase its manufacturing capacity.

Table 2. Recent Hydrogen projects carried by Industry and Government

Project / Commitment	Sector	Capacity / Scale
GAIL (government PSU)	Government / PSU	10 MW electrolyser plant at Vijaipur, Madhya Pradesh
State oil/gas PSUs	Government / PSU	Combined ~ 279 MW electrolyser

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(Hindustan Petroleum, Indian Oil, GAIL, etc.)		capacity targeted by 2024-25; ~ 38,000 tones/year hydrogen production
Adani New Industries (private industry)	Industry	5 MW off-grid pilot plant in Kutch, Gujarat
Make-in-India / Kandla Port Authority	Government / possibly partly industry / local govt	1 MW plant commissioned, planning expansion to 10 MW
Tender awards under National Green Hydrogen Mission	Industry / Private companies	862,000 tones/year capacity allotted across 19 companies; also 3,000 MW/year of electrolyser manufacturing capacity contracts awarded

IV. REFUELING / RECHARGING, ACCESSIBILITY

i. *Vehicles powered by batteries (BEVs):*

Recharging: Although convenient, charging at home or at work is slow (6–12) hours for full charge on ordinary AC). 80% charge time is reduced to about 30 to 45 minutes by fast/ultra-fast chargers (DC), although it is still slower than refueling with gasoline.

Accessibility: Charging networks are using the current electrical infrastructures to grow quickly There are still gaps in some regions' long-distance highway lines, but urban areas are more accessible than rural ones.

ii. *Hydrogen Fuel-Cell Vehicles:*

i. Refueling: Similar to gasoline or diesel (about 3 to 5 minutes for a full tank).Eliminates lengthy wait periods and offers a greater driving range (400–600 km).

ii. Accessibility: Stations for hydrogen refueling are extremely few and confined to a small number of areas (such as California, Japan, and portions of Europe).Infrastructure is expensive and complicated (it needs to be produced, compressed, transported, and stored).

V. CONCLUSION AND FUTURE OUTLOOK

Despite higher manufacturing emissions, battery electric vehicles (BEVs) are now the most feasible and ecologically friendly option for light-duty transportation due to improving efficiency and expanding fast-charging networks. Despite their greater mileage and faster refilling, hydrogen fuel-cell cars (FCEVs) have limitations, including carbon-intensive hydrogen and limited infrastructure. BEVs will keep taking over the market due to innovations in recycling, charging, and battery chemistry, but FCEVs could become viable for heavy-duty transportation, shipping, and aircraft around 2035 thanks to affordable green hydrogen.

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