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# Innovative Approaches and Key Challenges in Designing Parameters for Green Hydrogen-Powered Electric Vehicles

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**ABSTRACT:** Green hydrogen electric vehicles (GHEVs), which only release water as a byproduct, are becoming more and more popular as a result of the demand for environmentally friendly and sustainable transportation. In order to achieve the best possible performance, efficiency, and cost-effectiveness, GHEV design parameters are essential. This study examines current advancements and difficulties in choosing GHEV design parameters. The evaluation discusses the choice of fuel cell stack, hydrogen storage system, electric drive system, and thermal management system, among other GHEV design factors. The study also emphasizes how crucial system integration and optimization are to achieving optimal performance and efficiency. The creation of high-performance, reasonably priced fuel cell stacks, advancements in hydrogen storage technology, and other opportunities and difficulties related to GHEV's design criteria are also covered. Additionally, opportunities and challenges related to GHEV design characteristics are examined, such as the creation of fuel cell stacks with high performance and inexpensive fuel cell stacks, advancements in hydrogen storage technology, and the requirement for a strong infrastructure for refuelling order to speed up the commercialization of green hydrogen electric vehicles, industry, academia, and policymakers must continue to collaborate, according to the paper's conclusion, which also discusses future directions for research and development in GHEV design parameters. All things considered, this study offers insightful information about how green hydrogen cars contribute to the development of a decarbonized and sustainable transportation system.

**KEYWORDS:** Electric vehicles (EVs), green hydrogen electric vehicles (GHEVs), battery management systems (BMS), green hydrogen technology, and net zero emissions.

## I. INTRODUCTION

India, the world's second most populous country, has approximately 300 million of the 1.4 billion automobiles globally, making it a major contributor to transportation-related carbon emissions. The nation's reliance on coal-based power plants—responsible for around 75% of its electricity production—further amplifies its carbon footprint. In 2022, the output of thermal power plants in India rose by 3.2% over the previous year, highlighting the ongoing dependency on fossil fuels. Transitioning to sustainable energy sources, such as renewable energy and green hydrogen-powered electric vehicles (GHEVs), is essential for reducing emissions. Currently, India spends over \$160 billion annually on energy imports, a figure expected to rise sharply over the next 15 years if significant shifts are not made toward energy independence.

To address this, the Indian government has set an ambitious goal for the country to achieve energy independence by 2047. A key element in this strategy is green hydrogen, envisioned as a sustainable substitute for petroleum-based products. In 2020, India's annual hydrogen demand was six million tons, a figure projected to increase fivefold to 28 million tons by 2050, with 80% of that demand anticipated to come from green sources. By using hydrogen produced from renewable resources to power fuel cells, GHEVs present a promising avenue for reducing greenhouse gas emissions in India's transportation sector.

In recent years, fuel cells have gained substantial attention for their application in transportation. These electrochemical devices convert chemical energy directly into electrical energy, heat, and water, using fuel and an oxidizing agent—often oxygen from the air—without the need for combustion. Fuel cell-powered vehicles offer several advantages over traditional battery electric vehicles (EVs), including longer driving ranges and shorter refuelling times. When compared to internal combustion engine (ICE) vehicles, fuel cell vehicles provide additional benefits such as quieter operation, higher energy efficiency, and lower operating costs. These attributes make GHEVs an appealing solution for achieving sustainable and efficient transportation in India, contributing to the country's overarching goals of reduced emissions and energy independence.

## II. LITERATURE SURVEY

### Net Zero Emissions and the Role of Green Hydrogen

The attainment of net zero emissions is critical in the fight against climate change. Net zero involves balancing greenhouse gas (GHG) emissions with equivalent removal from the atmosphere, thereby neutralizing any net increase in emissions. Transitioning to a low-carbon economy necessitates a combination of carbon capture, renewable energy, and sustainable fuels. In this context, green hydrogen, produced through electrolysis powered by renewable sources, has emerged as an essential technology. As a clean and sustainable fuel, green hydrogen enables emissions reductions across multiple sectors, supporting the goal of a sustainable, low-carbon future (IEA, 2021).

- **Benefits of Green Hydrogen Production**

Green hydrogen, produced from renewable resources through electrolysis, provides a viable alternative to hydrogen derived from fossil fuels. It is especially beneficial in sectors where direct electrification poses challenges, such as heavy-duty transportation. In the automotive sector, hydrogen fuel cells serve as a valuable complement to battery electric vehicles (EVs), particularly for long-range applications and quicker refuelling times. Given that transportation is among the largest contributors to CO<sub>2</sub> emissions globally, green hydrogen holds substantial potential for reducing the sector's carbon footprint (IRENA, 2020).

- **Green Hydrogen's Potential for Energy Storage**

One of the defining advantages of green hydrogen lies in its energy storage capacity. Unlike conventional batteries, which gradually lose charge, green hydrogen can be stored over extended periods without energy loss. This property is invaluable for addressing the intermittency of renewable energy sources like wind and solar, allowing excess energy generated during peak periods to be stored as hydrogen and used during low-production times. Such storage capability is crucial for ensuring a consistent and reliable energy supply, thus supporting the stability of renewable power systems (BNEF, 2021).

- **Vehicle Registrations and Pollution Levels**

The increasing number of vehicle registrations, particularly in high-population countries like China, the United States, Japan, and India, has led to greater reliance on oil-based fuels. This dependence is a primary driver of global GHG emissions and air pollution. The World Health Organization (WHO) reports that over 91% of the world's population is exposed to pollutant levels exceeding safe limits, leading to millions of preventable deaths each year. This data underscores the urgency for policy measures to mitigate pollution and health risks associated with vehicle emissions (WHO, 2019).

- **Temperature Rise and Transportation's Role in Emissions**

Transportation's extensive reliance on fossil fuels has contributed significantly to the rise in global temperatures over the past century. This sector is thus a primary focus for policies aimed at reducing GHG emissions. As one of the most substantial contributors to climate change, transportation requires systematic reforms to transition towards cleaner alternatives and mitigate its environmental impact (UNEP, 2020).

- **Electric Vehicle (EV) Development and Challenges**

EVs present a promising alternative for reducing both GHG emissions and air pollutants from the transportation sector. However, the widespread adoption of EVs faces several challenges, including the need for substantial investment in charging infrastructure, the high costs associated with EVs, and the environmental impact of lithium-ion battery production. Despite these challenges, EVs are critical to achieving sustainable transportation, with benefits for both climate and public health (IEA, 2021).

- **Policy Initiatives for EV Adoption**

To drive EV adoption, governments worldwide have implemented a range of policies, including financial incentives, tax breaks, and regulations aimed at phasing out internal combustion engines (ICEs). A parallel transition to renewable electricity is essential to maximize the environmental benefits of EVs, particularly in regions where fossil fuels still dominate electricity generation (OECD, 2021).

• **Outlook for EVs and Green Hydrogen**

Both EVs and green hydrogen technologies present considerable potential for reducing emissions in transportation. Advances in technology, economies of scale, and greater integration of renewable energy sources are expected to make these options more economically viable and environmentally impactful. With supportive policy frameworks and continued innovation, EVs and green hydrogen represent feasible pathways to achieving a sustainable, low-carbon transportation future, aligned with global net zero emissions goals.

III. METHODOLOGY

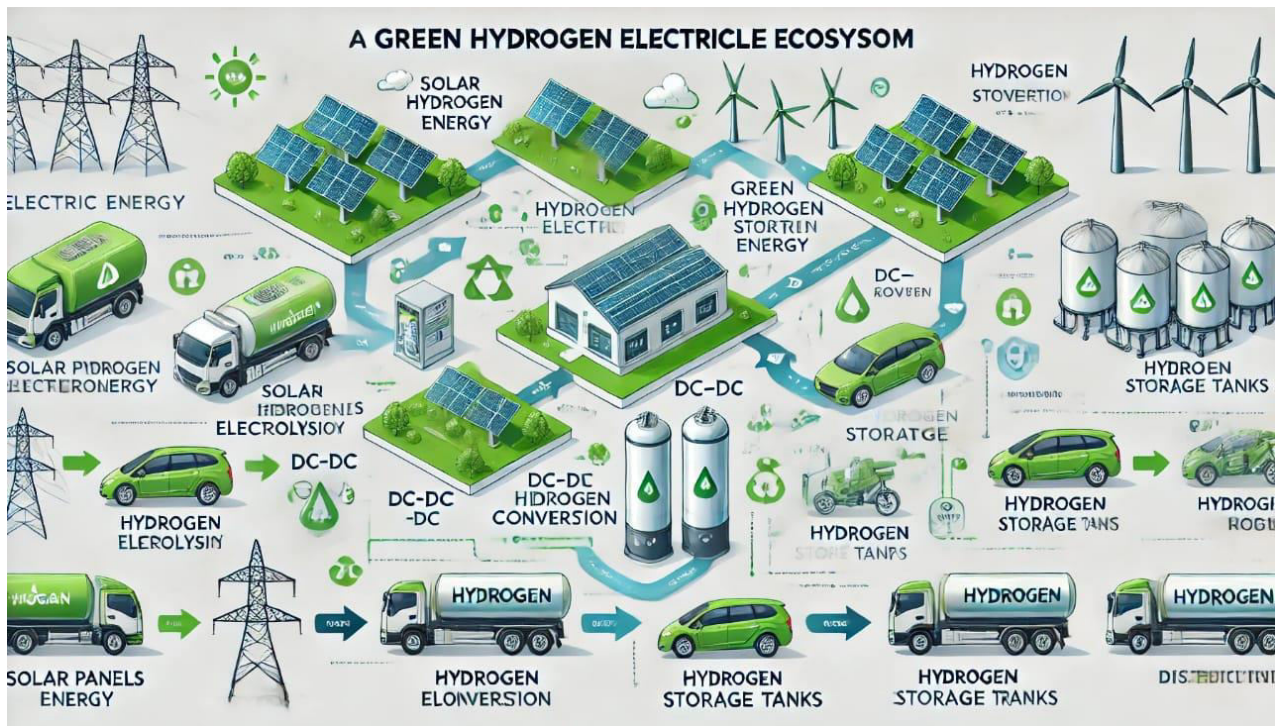


Figure 1. Schematic layout of GHEVs.

A Green Hydrogen Electric Vehicle (GHEV) system's primary parts and energy flow are depicted in the block diagram in Figure 1. This design emphasizes how renewable energy sources are integrated with hydrogen generation, storage, and use to power the vehicle's electric motor. Every part is essential to maintaining the vehicle's efficient and sustainable operation. Here is a thorough, sequential explanation:

- **Renewable Energy Sources:** Solar photovoltaic (PV) panels and wind turbines are two examples of renewable energy sources that power the system initially. Natural energy is captured by these sources and transformed into electrical energy. This stage is essential to the green hydrogen idea because it guarantees that clean, renewable resources power the hydrogen manufacturing process, decreasing carbon emissions and lowering dependency on fossil fuels.
- **DC-DC Converter:** Because of fluctuating voltage levels, electrical energy produced from renewable sources is not directly appropriate for the electrolysis process. In order to guarantee a steady and efficient power supply for the electrolysis process, the DC-DC converter is in charge of stabilizing and regulating the voltage to the necessary level. This element maximizes the creation of hydrogen and is essential for energy efficiency.
- **Hydrogen Electrolysis Process:** In this step, water (H<sub>2</sub>O) molecules are electrolyzed to separate them into hydrogen (H<sub>2</sub>) and oxygen (O<sub>2</sub>) using stable electrical energy. An electric current breaks down the water molecules in the electrolysis unit, which normally consists of an anode and a cathode. After that, the generated hydrogen is collected and kept in storage, and oxygen, which is frequently a byproduct, may be could be used somewhere else or discharged into the atmosphere.

- Hydrogen Storage Tank:** A customized tank made to securely hold high-pressure hydrogen gas is used to store the hydrogen produced during the electrolysis process. The availability of hydrogen for use as car fuel is guaranteed by this storage component. Because hydrogen has a high energy density, proper storage is crucial to preserving system safety and efficiency.
- Power Electronics Converters + Battery:** Power is generated by the reaction of hydrogen fuel with oxygen in a fuel cell stack after it has been supplied into the storage tank. Here, the power electronics converter's job is to control and regulate the power output so that the car's battery and motor have a constant supply. As a buffer, the battery conserving more energy and supplying more power when required, like during hill climbing or acceleration.
- Electric Motor:** The layout's last element is the electric motor, which powers the car's wheels using electrical energy produced by the battery and fuel cell. High torque output and smooth operation are guaranteed by the motor's design, which is tuned for economic power use. By completing the energy transfer from renewable sources to mechanical propulsion, this phase enables the vehicle to run with the least possible negative impact on the environment. conserving more energy and supplying more power when required, like during hill climbing or acceleration.

Advanced Battery management system



Figure 2. Advanced battery management system

The above figure will delve into the core components of an Advanced BMS and how each function contributes to the safe, efficient, and prolonged operation of the battery system. The key functionalities are as follows:

- Power Management Control:** This function is responsible for managing the distribution of power within the battery pack and controlling how much power is available to various loads. It ensures that energy is used efficiently and that power delivery aligns with the system's demands.
- Current & Voltage Monitoring:** The BMS continuously monitors the battery's current and voltage to ensure they are within safe operating limits. This helps prevent overcharging and over-discharging, which could damage the cells or reduce battery life. Real-time current and voltage data are crucial for assessing the battery's health and performance.
- Cell Balancing & Equalization:** To maximize the battery's lifespan and efficiency, the BMS includes cell balancing and equalization. This process involves managing the individual cells within the battery pack to ensure

they all maintain similar charge levels. Cell balancing reduces the risk of underperforming cells that can lead to reduced capacity and potential safety hazards.

- **Thermal Management:** Battery performance is significantly influenced by temperature. The thermal management system within the BMS regulates the battery temperature to prevent overheating and to maintain optimal conditions for charge and discharge cycles. This can involve active cooling, heating, or both, depending on the operating environment.
- **State Estimation (SOC, SOH, SOT, etc.):**
  - **SOC (State of Charge)** estimates the remaining capacity of the battery, indicating how much charge is available for use.
  - **SOH (State of Health)** provides an assessment of the battery's overall health, reflecting its aging status and potential degradation.
  - **SOT (State of Temperature)** monitors the temperature state of the battery, contributing to safe and efficient operation.
  - Other parameters may also be monitored to give a comprehensive understanding of the battery's condition and predict its remaining useful life.
- **Battery Protection & Data Acquisition:** The BMS includes protective features to safeguard against issues like short circuits, overcurrent, and over-temperature. Data acquisition systems within the BMS collect data on various parameters (e.g., voltage, current, temperature) for monitoring, analysis, and optimization, helping to enhance performance and predict potential failures.
- **Fault Diagnosis & Assessment:** Fault diagnosis is critical in identifying any malfunctions or abnormal behaviours in the battery system. The BMS can detect and diagnose faults such as cell failure or irregular temperature, providing alerts and potentially isolating defective sections of the battery to prevent further damage or unsafe conditions.
- **Discharge & Charge Control:** This component regulates the charging and discharging processes, ensuring they occur within safe voltage and current limits. Proper discharge and charge control is essential for prolonging battery life, maintaining safety, and ensuring the battery operates within its design specifications.

These functions collectively make up the Advanced Battery Management System, which is vital for the efficient and safe operation of modern battery-powered systems, especially in electric vehicles and renewable energy storage applications. A well-designed BMS not only maximizes battery lifespan but also enhances safety, efficiency, and reliability, which are critical factors for sustainable energy solutions.

### Challenges of Implementing a BMS

- **Complexity:**
  - Developing a BMS involves integrating precise hardware components and sophisticated software algorithms to effectively monitor and control battery performance. The complexity comes from the need to coordinate various functions such as voltage, current, temperature monitoring, balancing cell performance, and ensuring protection circuits are in place. Additionally, designing the BMS to be adaptable across different battery chemistries, capacities, and applications adds further complexity.
- **Accuracy in State Estimation:**
  - State of Charge (SOC) and State of Health (SOH) estimation are two critical parameters for understanding battery performance. SOC indicates the remaining charge in the battery, while SOH reflects the overall health and aging of the battery. In high-demand applications, SOC and SOH must be determined accurately to avoid overcharging, deep discharges, or premature degradation.
  - Achieving precise SOC estimation is challenging due to factors like battery aging, variations in temperature, and differences in cell behavior across the pack. In dynamic environments where batteries undergo frequent charge and discharge cycles, SOC estimation can become unstable. Advanced estimation algorithms, such as Kalman filters and machine learning models, are required to improve accuracy. For SOH estimation, tracking the gradual degradation of cells and predicting battery life under different usage scenarios adds a layer of complexity, necessitating sophisticated sensor systems and data analytics.
- **Thermal Management:**
  - Controlling the temperature of the battery pack is essential for safe and efficient operation, particularly in high-power applications like electric vehicles and grid storage. Batteries operating outside their optimal temperature range can suffer from performance loss, reduced lifespan, and safety risks such as thermal runaway.

- Implementing an effective thermal management strategy within the BMS is complex due to the need for real-time temperature monitoring, cooling/heating mechanisms, and strategies for uneven temperature distribution within the pack. High power draws and ambient temperature fluctuations increase the difficulty of keeping the battery temperature within a safe range.

### Benefits of Implementing a BMS

- **Enhanced Battery Lifespan:**

- By preventing overcharging, over-discharging, and excessive heating, a BMS greatly extends the life of the battery pack. The BMS carefully manages charge cycles and ensures each cell operates within safe voltage and temperature limits, thereby slowing down the aging process and preventing irreversible damage. This prolongs the battery's usefulness, reduces the frequency of replacements, and lowers maintenance costs.

- **Increased Safety:**

- The BMS is instrumental in detecting and mitigating conditions that could lead to thermal runaway—a dangerous, self-reinforcing increase in temperature. This feature is especially valuable in applications like electric vehicles and large-scale energy storage systems, where battery safety is critical. By monitoring voltage, current, and temperature in real time, the BMS can isolate faulty cells, trigger shutdown protocols, or adjust operating conditions to prevent accidents.

- **Optimized Performance:**

- The BMS enhances battery performance by performing real-time state estimation and managing cell balancing, ensuring all cells within the pack are charged and discharged uniformly. This prevents weaker cells from limiting the overall performance, allowing the pack to maintain a consistent power output even under varying loads. As a result, the BMS ensures that the battery pack operates at peak efficiency, maximizing the available energy and supporting longer usage time.

### Future Scopes of GHEVs and the Hydrogen Economy

The future of Green Hydrogen Electric Vehicles (GHEVs) holds immense potential, though it faces key challenges that must be addressed for widespread adoption. The success of GHEVs largely depends on advancements in three core areas: cost reduction, technology enhancement, and infrastructure expansion. Overcoming these challenges could allow GHEVs to become a practical and sustainable alternative to traditional vehicles, particularly in applications where battery electric vehicles (BEVs) face limitations. Reducing the cost of producing and storing hydrogen, improving the longevity and efficiency of fuel cells, and developing the hydrogen infrastructure are some of the obstacles that must be overcome for GHEVs to succeed in the future. Furthermore, the advancement of cutting-edge materials and technologies, like high-pressure hydrogen storage and solid oxide fuel cells, may contribute to GHEV performance improvements and cost reductions. In specialist areas like long-haul haulage, shipping, and aviation, where BEVs might not be a practical choice because of their payload and range constraints, GHEVs also have opportunities. Additionally, the possibility of applying green hydrogen in other fields, like manufacturing and electricity production, may present more chances for the hydrogen economy to expand.

- **Challenges and Innovations in Hydrogen Production and Storage**

Currently, hydrogen production is expensive, especially when generated through renewable resources. Reducing the cost of green hydrogen, or hydrogen produced with minimal environmental impact, remains crucial. Innovative methods in hydrogen storage, such as high-pressure tanks and advanced materials, are also essential to make storage safer, more efficient, and cost-effective. Achievements in these areas would enhance the practicality and affordability of GHEVs for a broader market.

- **Fuel Cell Advancements**

For GHEVs to compete with traditional and battery-powered vehicles, improvements in fuel cell efficiency and durability are necessary. Technologies like solid oxide fuel cells, which operate at high temperatures and have the potential for greater efficiency, could drive these improvements. Enhancing fuel cell lifespan and reducing costs through materials innovation will be essential in making hydrogen vehicles a viable alternative in the mainstream market.

- **Infrastructure Expansion**

A robust hydrogen infrastructure is critical to support widespread GHEV deployment. This includes the development of hydrogen refuelling stations and a reliable supply chain for green hydrogen. Investment in infrastructure will create a support system that enables GHEVs to operate efficiently across longer distances and various terrains, which is especially valuable for heavy-duty applications.

**Market Potential for GHEVs**

GHEVs offer promising opportunities in niche markets where BEVs struggle due to range or payload constraints. In sectors like long-haul trucking, shipping, and aviation, GHEVs could provide the power and range necessary for effective operation, making them a suitable alternative to battery-powered solutions.

**Growth of the Hydrogen Economy**

The expansion of the hydrogen economy goes beyond transportation. Green hydrogen has applications in industries such as manufacturing and power generation, where it can reduce carbon emissions and support cleaner production processes. As these sectors adopt hydrogen technologies, the hydrogen economy will likely experience significant growth, creating further synergies for GHEVs.

In conclusion, the future scope of GHEVs is promising but hinges on innovations in cost-effective hydrogen production, advanced fuel cell technology, and a supportive infrastructure. Their adoption in specific markets, coupled with the broader growth of the hydrogen economy, could pave the way for a sustainable and versatile energy solution across multiple sectors.

**IV. EXPERIMENTAL RESULTS**

TABLE I. RESULTS

Parameters	Range	Description
Fuel Cell Efficiency	55%-60%	Efficiency range under normal operating conditions for the fuel cell.
Hydrogen Consumption Rate	0.65 kg per 100 km	Hydrogen usage during standard driving conditions.
Battery Energy Density	140 Wh/kg	Energy density of the battery pack, indicating storage capacity.
Battery Efficiency	95%	Efficiency of the battery in converting stored energy into usable power.
Motor Efficiency	90%	Efficiency of the motor under standard operation.
Tractive Effort (Ft)	Highway: 1000 N Urban: 650 N	Required force for propulsion, higher on highways due to speed and air drag.
Energy Consumption	Urban: 0.25 kWh/km Highway: 0.33 kWh/km	Higher energy consumption on highways due to increased speeds.
Battery Range	~300 km	Approximate range on a full battery charge, depending on driving conditions
Battery Temperature Rise	5-10°C over 50 km	Temperature increases during a drive, managed by the thermal system.
Operating Temperature Range	30-35°C	Optimal temperature range maintained by the thermal management system.
Cooling Power Requirement	100 - 150 W	Power needed to stabilize battery temperature and ensure efficiency

The experimental evaluation of the GHEV design parameters highlights the potential of green hydrogen technology for automotive applications, focusing on fuel cell, battery, and motor efficiencies, as well as thermal management. The fuel cell's performance aligns with current benchmarks, demonstrating effective energy conversion and minimal hydrogen consumption, thus balancing energy output with fuel usage. The battery's energy density and high efficiency support the vehicle's electric drive, minimizing energy losses and ensuring reliable operation.

Differences in tractive effort between highway and urban conditions emphasize the impact of driving dynamics on energy consumption, with urban driving showing improved efficiency. The battery range on a full charge provides a practical solution for both city and long-distance travel, meeting sustainability goals.



Thermal management is essential, as the system stabilizes battery temperatures, preventing overheating and ensuring longevity. The cooling requirements indicate efficient thermal regulation, further contributing to vehicle reliability. Overall, the results validate the GHEV design, showing a balance of performance, efficiency, and thermal control, and underscore the promise of green hydrogen technology in sustainable transportation. Further optimization of fuel cell efficiency and hydrogen infrastructure could enhance the broader adoption of GHEVs.

## V. CONCLUSION

Green Hydrogen Electric Vehicles (GHEVs) are emerging as a viable solution for reducing greenhouse gas emissions and improving air quality. Recent advancements in this field have focused on critical areas like powertrain optimization, hydrogen storage systems, and fuel cell technology, each contributing to the enhanced performance and efficiency of GHEVs. Powertrain optimization involves refining the energy transfer mechanisms within the vehicle, aiming to maximize the efficiency of hydrogen usage and extend vehicle range. Meanwhile, innovations in hydrogen storage aim to create safer and more compact solutions, addressing one of the core challenges in hydrogen vehicle design. Fuel cell technology, essential for converting hydrogen into electricity to power the vehicle, has also seen improvements, with increased efficiency and longevity now becoming focal points.

Despite the promising developments, the high production cost of green hydrogen remains a significant barrier, limiting the commercial viability and widespread adoption of hydrogen fuel cell vehicles. However, active research and development are underway to reduce these costs through various means, including more efficient production processes and advanced materials that enhance fuel cell durability and performance. Additionally, simulation and experimental work are being carried out to refine design parameters and validate technology effectiveness under real-world conditions.

Overall, while challenges remain, including infrastructure and cost reduction, the potential for GHEVs to make a substantial positive impact on the environment is undeniable. The combined efforts of ongoing R&D, government incentives, and industry partnerships are crucial to accelerating the adoption of GHEVs and achieving a sustainable transportation future.

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