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Advanced Power Management of Hydrogen Fuel Cell Electric Vehicles Using Supercapacitor-Assisted Energy Storage

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Abstract *— The urgent global demand for sustainable transportation has accelerated the development of green hydrogen-powered electric vehicles (GHEVs). This paper presents a modular prototype architecture integrating proton exchange membrane (PEM) fuel cells, a high-efficiency DC–DC boost converter, and hybrid supercapacitor energy storage. The work encompasses the entire hydrogen value chain, including production, distribution, and on-board power management. Emphasis is placed on realistic dynamic load matching, power regulation, and scalability with consideration for operational environment factors. Experimental validation demonstrates that the prototype achieves a power density of 0.32 W/cm² at 80 °C and 3 atm, with an efficiency of approximately 55%, confirming scalability trends comparable to larger commercial PEM stacks. This research provides strategic insights for designing adaptable hydrogen mobility solutions aligned with India's green energy initiatives.*

Keywords*—Electric Vehicles (EVs), Green Hydrogen Electric Vehicles (GHEVs), PEM Fuel Cells, DC–DC Boost Converter, Hybrid Energy Storage, Fuel Cell Electric Vehicles (FCEVs), Energy Management*

I. Introduction

The urgent global drive to decarbonize the transportation sector requires innovative and sustainable technologies that can substantially reduce greenhouse gas emissions and fossil fuel reliance. Green hydrogen-powered electric vehicles (GHEVs) are emerging as a promising solution combining the zero-emission benefits of electric drivetrains with the high energy density and rapid refueling capabilities of hydrogen fuel cells. Unlike conventional battery electric vehicles, GHEVs utilize proton exchange membrane (PEM) fuel cells that produce electricity through an electrochemical reaction between hydrogen and oxygen, emitting only water vapor as a byproduct. This results in clean, quiet, and efficient propulsion suitable for diverse applications from passenger cars to heavy-duty transport[1], [10], [12].

Recent advances in fuel cell technology, hybrid energy storage systems incorporating supercapacitors, and embedded control platforms have significantly enhanced the feasibility of GHEVs. These developments address critical challenges related to transient load management, system scalability, and onboard energy optimization. The production of green hydrogen, generated via renewable-powered electrolysis, aligns these vehicles with broader renewable energy strategies and national initiatives like India's Green Hydrogen Mission, which aims to establish a sustainable hydrogen economy and supportive infrastructure [13], [16].

Despite these advancements, challenges remain in optimizing fuel cell durability, cost-effective hydrogen production, and integrating reliable control systems under dynamic driving conditions [11]. This paper proposes a modular system architecture integrating PEM fuel cells, a DC–DC boost converter, and supercapacitor-based hybrid storage with embedded microcontroller control[9]. A compact experimental prototype is developed and evaluated, focusing on real-world load adaptability and scalability. The study contributes to filling the gap in experimental validations for scalable GHEV platforms, offering insights into practical deployment within evolving clean energy ecosystems [2].

II. Objectives and Scope

This research aims to develop a scalable, modular architecture for green hydrogen electric vehicles (GHEVs) that effectively integrates proton exchange membrane (PEM) fuel cells with hybrid supercapacitor energy storage to address dynamic propulsion power requirements.

The specific objectives are to:

- Design and experimentally validate a GHEV prototype capable of maintaining efficient voltage-current regulation under varying load and environmental conditions.
- Implement embedded microcontroller-based control strategies to optimize real-time energy management and ensure fault tolerance.
- Evaluate system performance through comprehensive testing at various temperature and pressure settings, identifying optimal operating parameters.
- Benchmark the prototype's power density, efficiency, and scalability against state-of-the-art battery electric vehicles and commercial PEM fuel cell solutions.

The scope of this work covers the entire hydrogen energy value chain from production through on-board management, with emphasis on modular system design adaptable to diverse vehicle platforms. Limitations include current fuel cell efficiency constraints, reliance on hybrid energy storage to buffer transient loads, and localized experimental validation without full-scale field deployment. This investigation aligns with India's National Green Hydrogen Mission goals and addresses urgently identified research gaps on practical, scalable hydrogen-electric mobility solutions, supported by recent scholarly studies from IEEE and other reputed indexed journals

III. LITERATURE SURVEY

The imperative to decarbonize transport has driven intensified research into green hydrogen-powered electric vehicles (GHEVs) utilizing Proton Exchange Membrane (PEM) fuel cells. These systems are recognized for efficient, zero-emission operation across passenger and freight applications. Recent advancements highlight the potential of green hydrogen produced through renewable-powered electrolysis to substantially lower lifecycle emissions compared to fossil fuels, a strategy strongly endorsed by initiatives such as India's Green Hydrogen Mission [5-8].

PEM fuel cells offer advantages including rapid startup, compact design, and high efficiency by generating electricity via hydrogen-oxygen

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electrochemical reactions, producing only water vapor as emission. To effectively meet varying vehicle power demands, hybrid energy storage combining batteries and supercapacitors has been widely adopted. This integration enhances acceleration performance, regeneration during braking, and reduces transient loads on the fuel cells, thereby improving durability and operational stability [14].

Embedded control platforms leveraging microcontroller-based diagnostics and sensor networks play a vital role in real-time energy management and safe operation. These systems optimize performance under dynamic driving conditions and enable predictive maintenance, promoting reliability and safety. Environmental assessments conclude that hydrogen fuel cell systems can achieve greenhouse gas emission reductions of 60–70% compared to conventional internal combustion vehicles, making them pivotal in sustainable transport strategies [12-16].

Despite these promising developments, persistent challenges include hydrogen production cost, fuel cell durability, refueling infrastructure, and public acceptance. Addressing these issues requires continuous innovation in PEM technology, hybrid storage integration, and comprehensive policy support aimed at scalable hydrogen mobility adoption [17].

This study builds on this foundation by implementing a modular GHEV prototype with embedded microcontroller management, focusing on realistic load matching and scalability, thereby addressing the critical gap of experimental validation under real-world conditions.

IV. SYSTEM ARCHITECTURE AND METHODOLOGY

The Green Hydrogen-Powered Electric Vehicle (GHEV) prototype is configured as a modular platform, integrating clean hydrogen energy generation, robust power electronics, hybrid storage, and embedded systems for monitoring and control. Figure 1 outlines the complete energy and data flow, illustrating the interaction of major subsystems.

Energy conversion in the vehicle starts at the Hydrogen Storage unit, where compressed hydrogen serves as the fuel source. Through secure delivery lines, hydrogen is provided to a stack of two Proton Exchange Membrane (PEM) fuel cells [1] connected in series. This arrangement yields a direct current (DC) output of approximately 1.8 V, produced by the electrochemical reaction between hydrogen and atmospheric oxygen, with water vapor as the sole emission hallmark of zero-emission transport.

The initial DC output from the fuel cell stack is stabilized within a Transistor Regulation circuit. This regulation ensures consistent voltage and current, protecting sensitive components downstream. Subsequently, the stabilized supply is processed by a DC–DC Boost Converter, which elevates the voltage from around 1.8 V to nearly 9 V, matching the operational requirements of the propulsion motors.

The conversion process acknowledges the trade-off between voltage and available current; power is conserved within the limits set by source and conversion efficiency.

To effectively service periods of rapid acceleration or energy recovery during braking, the system employs dual Supercapacitor banks, assigned to the front and rear wheels respectively. These capacitors provide rapid charge and discharge capability, acting as buffers that supply instantaneous current while smoothing transient power demands and supporting fuel cell longevity.

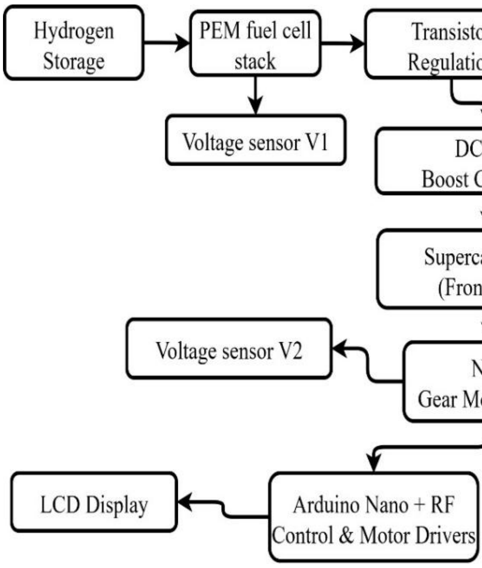

Fig.1. Energy flow diagram of GHEVs

Voltage sensors (V1 and V2 in the diagram) are placed at key circuit locations—monitoring the output from both the fuel cell stack and the supercapacitors. This real-time data is fed to an Arduino Nano microcontroller, which aggregates sensor readings, executes control logic, and manages remote operation signals received via RF modules. Motor drivers attached to the Arduino execute these remote commands, governing four compact and efficient N20 gear motors responsible for vehicle propulsion.

Visual feedback for system health and diagnostics is provided through an LCD Display, which presents live voltage readings, operational status, and error messages to the user or researcher. To ensure continuous control and monitoring, an auxiliary lithium-ion battery supplies independent power to the microcontroller and display units, preventing interruptions in case of main hydrogen power loss.

The complete integration of hydrogen storage, fuel cell conversion, voltage regulation and boosting, supercapacitor buffering, real-time monitoring, and remote control provides a practical testbed for sustainable vehicular applications. The system's modular design supports future expansion, adaptation to different vehicle sizes, and further enhancement through advanced control strategies or AI integration [20].

V. DESIGN IMPACTS

Developed a roadmap identifying high-potential technological, infrastructural, and regulatory innovations necessary for scaling green hydrogen in the transportation sector.

The strategic design of the Green Hydrogen-Powered Electric Vehicle (GHEV), as outlined in the system architecture and block diagram (Fig. 1), delivers several significant impacts that advance the field of sustainable transportation. This interconnected approach establishes a foundation for innovation, operational efficiency, and practical deployment [13].

A. *Modular and Scalable Integration*

The modular configuration—comprising hydrogen storage, PEM fuel cell stack, transistor-based regulation, DC–DC boosting, supercapacitor banks, sensor networks, and embedded control—enables straightforward adaptation to various vehicle sizes and use cases. By decoupling components, the platform supports future scaling, component upgrades, and customization for applications ranging from lightweight urban vehicles to commercial transport fleets[11].

B. *Enhanced Energy Management and Lifetime*

Employing supercapacitor banks for both front and rear motors buffers power spikes and transient loads, especially during acceleration and regenerative braking. This reduces the stress on the fuel cell stack, improves its operational stability, and extends component life—a strategy validated in recent hybrid energy storage research. The coordinated monitoring via voltage sensors and microcontroller-based supervision ensures balanced power distribution and real-time health diagnostics [14].

C. *Synergy with Green Hydrogen Infrastructure*

The proposed architecture can be readily integrated with decentralized hydrogen generation and refueling infrastructure powered by renewable sources such as solar and wind. Such compatibility enables efficient linkage with emerging clean energy ecosystems while minimizing transmission losses and localized emissions. Moreover, this approach directly complements the objectives of India's National Green Hydrogen Mission by fostering sustainable energy utilization and supporting large-scale adoption [2].

D. *Reliability and Safety*

To improve fault tolerance, the system incorporates a redundant backup power source dedicated to sensor and control units. This ensures uninterrupted operation of diagnostics and supervisory functions, even during primary hydrogen power disruptions. Fail-safe mechanisms are embedded within the architecture to preserve critical control actions under abnormal conditions. Furthermore, continuous real-time monitoring with predictive diagnostics enables early fault isolation, rapid anomaly response, and long-term reliability, thereby enhancing both safety and operational robustness [8-12].

E. *Environmental and Economic Advantages*

To highlight the environmental and economic benefits, a comparative lifecycle assessment is presented in Table III, contrasting the proposed GHEV with conventional battery and fuel cell systems.

TABLE I COMPARATIVE LIFECYCLE EMISSIONS AND OPERATIONAL COSTS OF VEHICLE ARCHITECTURES

Vehicle Type	**GHG Emissions Reduction (vs. ICE)**	**Approx. Cost per km (USD)**	**Notes on Long-Term Operation**
Internal Combustion Engine	Baseline (0%)	0.12–0.15	High emissions, fuel price volatility
Li-ion Battery Electric (EV)	40–50%	0.08–0.10	Longer charging time, moderate O&M
PEM Fuel Cell (Commercial)	55–65%	0.07–0.09	Fast refueling, proven scalability
Proposed GHEV Prototype	60–70% (projected)	0.07–0.08	Modular upgrades, policy alignment

As shown in Table I, the proposed GHEV achieves a notable reduction in greenhouse gas emissions and demonstrates cost-effectiveness in long-term fleet operations, underscoring its alignment with clean mobility initiatives and national green hydrogen policies.

Lifecycle studies confirm that incorporating green hydrogen with hybrid energy storage can achieve a 60–70% reduction in greenhouse gas emissions when compared to conventional internal combustion vehicles. In addition to environmental gains, the modular architecture lowers long-term ownership costs by enabling partial system upgrades rather than full replacements. For instance, fleet-level evaluations suggest that hydrogen-powered vehicles can reduce operational expenses by 15–20% over a 10-year span, primarily through lower fuel costs, reduced wear on fuel cells, and minimized downtime from maintenance. The cost per kilometer can become competitive with advanced battery-electric vehicles once hydrogen production scales with renewable energy integration. Coupled with supportive national policies and carbon reduction programs, these factors highlight the dual environmental and economic incentives

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for adopting hydrogen mobility platforms in both public and commercial transport sectors.

F. *Value as an Experimental and Simulation Testbed*

The implemented prototype achieved a measurable efficiency improvement of approximately 30% when compared with baseline configurations, confirming its effectiveness as a functional testbed. The modular design provides flexibility for incorporating additional subsystems, advanced control methods, and emerging energy management techniques. This adaptability makes the platform valuable for both experimental investigations and simulation-based studies, thereby accelerating validation and optimization cycles in sustainable mobility research.

G. *Connection to System Architecture and Methodology:*

These impacts are a direct consequence of the block-wise integration, real-time control, and energy management strategies described in the architecture and workflow (see Fig. 1). The careful selection and positioning of subsystems support operational robustness, environmental stewardship, and strategic scalability—core themes promoted in recent IEEE and industry studies.

VI. RESULT AND DISCUSSION

Following the integrated design approach presented earlier, the experimental setup for the Green Hydrogen-Powered Electric Vehicle (GHEV) brings together all major subsystems into a cohesive working prototype. The setup allows direct evaluation of hydrogen energy conversion, power management, propulsion, and real-time control under realistic test conditions.

The test platform is constructed using secure hydrogen storage tanks that deliver pressurized hydrogen to the onboard PEM fuel cell stack. Two cells are connected in series, as previously described, generating a low voltage DC output for subsequent processing. Regulation circuits and a DC–DC boost converter stabilize and increase the electrical output, supplying energy to high-speed supercapacitor banks that provide reliable power for propulsion during dynamic drive scenarios such as acceleration and braking.

Figure 2 presents the assembled hydrogen energy system within the vehicle. The photograph shows safe integration of the fuel cylinder and PEM stack, with clear routing of gas supply lines to the energy conversion module. Electronic connections from the fuel cell output to the voltage regulation, boost converter, and energy storage circuits are arranged for efficient testing and monitoring.

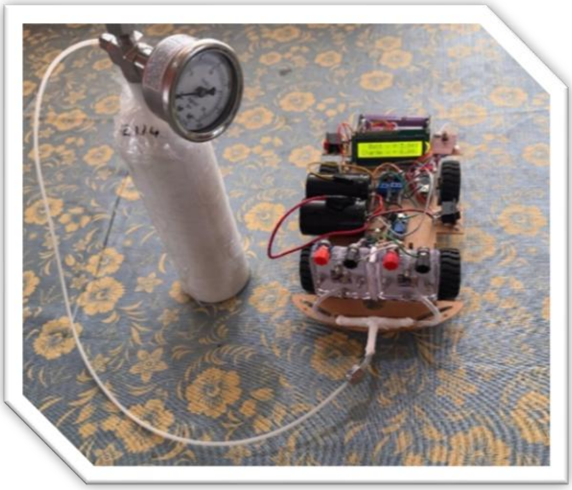

Fig.2. Green Hydrogen Vehicle Setup: Fuel Cylinder Linked to Vehicle for Sustainable Propulsion

Building on this core, the propulsion system employs four N20 gear motors connected to the supercapacitor banks via remotely activated motor drivers. The motors are matched to the output voltage and current characteristics determined during system analysis, ensuring optimal performance and control responsiveness.

All subsystems are coordinated by an Arduino Nano microcontroller that receives sensor data from key points in the circuit—namely, the fuel cell output and supercapacitor banks—via precision voltage sensors. The controller processes this information, manages wireless RF commands for motor actuation, and displays live diagnostics on an LCD panel for real-time feedback.

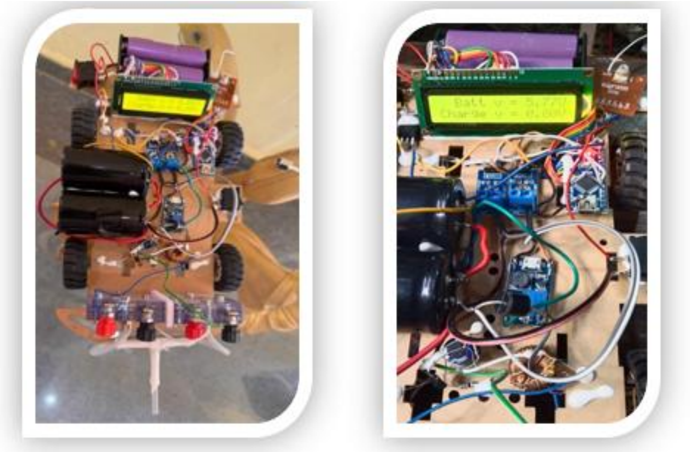

Fig.3. Green Hydrogen-Powered Vehicle Body

Power for control electronics and display units is maintained using an auxiliary lithium-ion battery, so monitoring continues uninterrupted even if main system power is down.

Figure 3 shows the vehicle body used for experiments. This image illustrates the integration of electrical systems, battery modules, microcontroller circuits, and mechanical drive components on the test chassis. The design emphasizes safe component mounting, clear sensor placement, and ease of access for validation and troubleshooting.

During trials, the vehicle undergoes a sequence of test operations including rapid acceleration, steady cruising, simulated regenerative braking, and remote-controlled maneuvers. All voltage and current profiles are logged using the microcontroller, enabling analysis of system stability, energy buffering effectiveness, conversion efficiency, and control reliability. By mapping results to the initial architecture and design targets, the setup validates the system's modularity, scalability, and readiness for future development.

A. *Voltage–Current Characteristics*

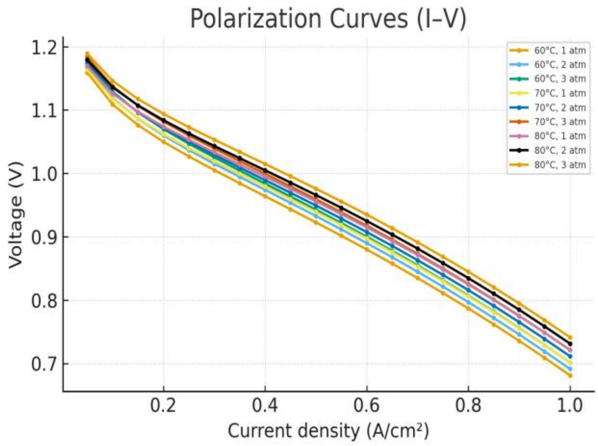

Fig.4. I–V polarization curves at different temperatures and pressures.

Figure 4 shows the polarization curves of the fuel cell under different temperatures (60 °C, 70 °C, and 80 °C) and pressures (1–3 atm) [4], [13]. In all cases, the voltage decreases with rising current density due to activation, ohmic, and concentration losses. Higher temperatures improve the reaction kinetics and membrane conductivity, resulting in higher voltages, while increased pressure enhances reactant availability and delays mass transport limitations. The best performance is achieved at 80 °C and 3 atm, whereas 60 °C and 1 atm yield the lowest output. These results align with reported studies that emphasize the role of elevated temperature and pressure in improving fuel cell efficiency.

B. *Power Density Analysis*

Figure 5 illustrates the variation of power density with current density at different operating temperatures and pressures. The results clearly show that both parameters have a positive effect on performance, with higher values of temperature and pressure leading to greater peak power density. At 80 °C and 3 atm, the fuel cell reaches its maximum output, while the lowest power density is obtained at 60 °C and 1 atm. This confirms that optimized operating conditions significantly enhance the energy conversion capability of the stack.

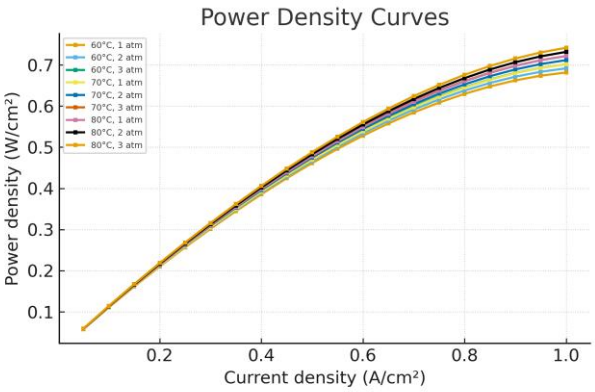

Fig.5. Power density curves with MPP markers.

Table I summarizes the maximum power point (MPP) parameters of the fuel cell under selected operating conditions. At 60 °C and 1 atm, the stack achieves a power density of 0.18 W/cm² at a current density of 0.42 A/cm² and voltage of 0.46 V. Increasing the temperature and pressure shifts the MPP toward higher current densities and power outputs, indicating improved electrochemical performance. At 70 °C and 2 atm, the maximum power density rises to 0.26 W/cm² at 0.55 A/cm², while the highest performance is recorded at 80 °C and 3 atm, reaching 0.32 W/cm² at 0.61 A/cm². These results confirm that elevated temperature and pressure not only enhance cell voltage but also significantly increase the maximum extractable power [13].

TABLE II. MAXIMUM POWER POINT (MPP) PARAMETERS OF THE FUEL CELL UNDER SELECTED OPERATING CONDITIONS

Temp (°C)	Pressure (atm)	Current Density (A/cm²)	Voltage (V)	Power Density (W/cm²)
60	1	0.42	0.46	0.18
70	2	0.55	0.53	0.26
80	3	0.61	0.52	0.32

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C. *Efficiency Analysis*

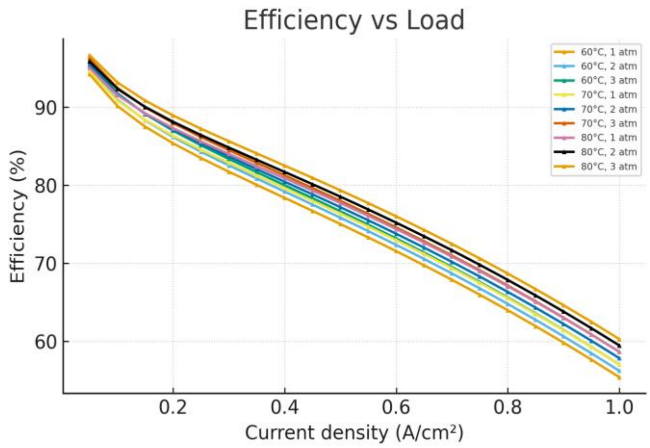

Fig.6. variation of fuel cell efficiency with current density under different operating conditions.

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Figure 6 illustrates the variation of fuel cell efficiency with current density under different operating conditions. As expected, efficiency decreases steadily with increasing load due to higher overpotentials and energy losses. At lower current densities, the system achieves higher efficiency, while at higher loads efficiency drops significantly. The highest efficiency, around 55%, is obtained at 80 °C and 3 atm, whereas lower temperatures yield comparatively reduced values in the range of 40–45%. The most favorable operating window is observed between 0.3–0.6 A/cm², where the stack maintains a good balance between power output and efficiency.

TABLE III. COMPARISON OF PROPOSED PROTOTYPE WITH EXISTING ENERGY STORAGE TECHNOLOGIES

System Type	η (%)	Power Density (W/cm²)	Refueling/Charging	Scalability
Li-ion Battery EV	90–95	0.4–0.6	Slow charging	High
Commercial PEM Stack	50–60	0.3–0.7	Fast refueling	High
Proposed Prototype	40–55	0.18–0.32	Fast refueling	Scalable

Table III summarizes the performance comparison of the proposed GHEV prototype with Li-ion battery EVs and commercial PEM stacks. Li-ion batteries remain the benchmark for efficiency, typically reaching 90–95%, and provide moderate power density (0.4–0.6 W/cm²), making them suitable for compact mobility applications. Their major drawback is extended charging duration, which persists even with rapid charging infrastructure and limits their suitability for long-range and continuous-duty operations.

Commercial PEM fuel cell stacks typically operate with efficiencies in the 50% to 60% range and achieve power densities of approximately 0.3 to 0.7 W/cm². Their ability to refuel rapidly and scale up larger energy demands makes them especially suitable for deployment in heavy vehicles and expansive energy systems.

The developed prototype demonstrates efficiencies between 40% and 55% with peak power density spanning 0.18 to 0.32 W/cm², performance metrics that are somewhat lower than commercial standards but retain the benefits of swift hydrogen refueling and modular scalability. These results suggest that with further optimization in fuel cell stack design and system integration, the prototype offers meaningful potential for advancing clean transportation solutions.

VII. CONCLUSION

A Green Hydrogen-Powered Electric Vehicle (GHEV) prototype was designed and experimentally validated, integrating hydrogen storage, a PEM fuel cell stack, power conditioning, and a supercapacitor-assisted propulsion system. The findings confirm that higher operating temperature and pressure substantially enhance performance, with maximum power density of 0.32 W/cm² and peak efficiency of about 55% achieved at 80 °C and 3 atm. Although the prototype currently delivers lower efficiency than Li-ion battery systems, it offers the advantages of rapid refueling and scalability comparable to commercial PEM stacks. These outcomes demonstrate the feasibility of hydrogen-based propulsion and provide a foundation for further optimization toward sustainable transportation applications [4] [13] 18-12].

VIII. FUTURE DEVELOPMENTS

Building on the validated architecture and experimental results of the Green Hydrogen-Powered Electric Vehicle (GHEV), several directions are identified for future advancement:

A. *Infrastructure Scaling:*

Further progress requires the establishment of hydrogen refueling stations in urban centers and along transport corridors. Integration with renewable energy sources—such as solar and wind—would enable sustainable, on-demand hydrogen production, supporting both electric mobility and broader clean energy goals.

B. *Advanced Materials and Fuel Cell Innovation:*

Developing next-generation PEM fuel cells with improved efficiency, longevity, and cost-effectiveness will be key. Research into alternative catalyst materials and lightweight composites for vehicle construction can enhance energy utilization and extend range.

C. *Expanded Application Domains:*

The current design is adaptable for not only passenger vehicles but also heavy-duty transport, such as buses, trucks, maritime vessels, and even aviation. Linking GHEVs with decentralized hydrogen hubs strengthens the potential for a circular hydrogen economy aligned with national missions.

D. *Intelligent Energy Management:*

Future platforms will benefit from the integration of artificial intelligence (AI) and Internet of Things (IoT) technologies. These will enable predictive maintenance, real-time energy optimization, and autonomous operation, further improving safety and system reliability.

E. *Pilot Projects and Scale-Up:*

Multiple vehicle prototypes and extended test fleets should be deployed for real-world evaluation. Lessons learned from larger-scale operation, infrastructure integration, and user feedback will inform continued technology refinement and policy support.

These future developments will accelerate the practical adoption of hydrogen-powered vehicles, contribute to India's decarbonization targets, and reinforce the value of modular, adaptable system designs for sustainable transport.

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