International Scientific Journal of Engineering and Management (ISJEM) ISSN: 2583-6129
Volume: 05 Issue: 04 | April – 2026 DOI: 10.55041/ISJEM06687
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

# Hybrid Electric Vehicle Energy System using a Lithium-Ion Battery and Hydrogen Fuel Cell with Smart Energy Management

**snehal gavhalkar**

## ABSTRACT

Hybrid electric propulsion using a battery and a proton exchange membrane (PEM) fuel cell is a practical approach for improving the performance of electric vehicles under varying load conditions. A battery can respond quickly to sudden power demand, but repeated peak-current operation increases thermal stress and accelerates aging. A fuel cell can support longer operation and fast refueling, yet its dynamic response is slower during rapid load transitions. This work presents a prototype hybrid energy system that combines a lithium-ion battery pack and a PEM hydrogen fuel cell through DC–DC power converters and a common DC bus. A smart energy management controller based on the ESP32 monitors battery voltage, current, temperature, hydrogen pressure, and load demand, and then selects the operating mode in real time. The developed controller enables coordinated source sharing during peak load, cruising, charging, and fault conditions. An IoT monitoring interface is also used for remote supervision and fault indication. The prototype is intended to reduce battery stress, maintain DC bus stability, and improve operational safety in hybrid electric vehicle applications.

Keywords—Hybrid electric vehicle, PEM fuel cell, lithium-ion battery, smart energy management, ESP32, DC–DC converter, IoT monitoring

## 1. INTRODUCTION

Electric vehicles are increasingly adopted because they reduce local emissions and improve energy efficiency compared with conventional internal combustion vehicles. In most commercial systems, lithium-ion batteries are the primary onboard energy source because they offer high efficiency and simple electrical integration. However, battery-only vehicles still face challenges such as limited driving range, long charging time, voltage sag at high load, and gradual capacity loss under repeated high-current cycling.

Hydrogen fuel cells provide a complementary solution. A PEM fuel cell can deliver electrical power continuously as long as hydrogen is available, and refueling time is typically shorter than battery charging time. Even so, a fuel cell alone is not ideal for traction systems that experience rapid changes in demand because its transient response is slower than that of a battery. It also requires close supervision of pressure and temperature for safe operation.

A hybrid battery–fuel-cell system can use the strengths of both sources. The battery can handle transient and peak power demands, while the fuel cell can operate near a steady and efficient region to support average load and recharge the battery when required. The effectiveness of such a system depends heavily on the control strategy used to distribute power.

## 2. RELATED WORK

Recent work on fuel-cell/battery hybrid vehicles has shown that energy management strategy strongly affects efficiency, hydrogen consumption, and battery life. Rule-based supervisory methods are widely used in prototype systems because they are simple to implement and computationally light. More advanced methods such as model predictive control and intelligent optimization techniques can improve efficiency further, but they generally require more accurate models and greater processing resources.

Research on fuel cell integration also emphasizes the importance of temperature, pressure, and dynamic voltage characteristics. Likewise, battery studies show that limiting current spikes and maintaining operation within a safe state-of-charge window can improve service life. Several authors have also reported the usefulness of embedded monitoring systems and IoT-based dashboards for real-time diagnostics.

Although many studies discuss hybrid architectures conceptually, prototype papers are often weak in practical implementation details. A clear description of sensing, control logic, operating modes, and measured performance is therefore necessary. The present work focuses on that prototype-level implementation.

# 3. PROPOSED HYBRID ENERGY SYSTEM

The proposed system combines a lithium-ion battery and a PEM fuel cell through a regulated DC bus, as shown conceptually in the architecture below.

## 3.1 Main Subsystems

- Battery subsystem: supplies fast transient power and supports peak load conditions.
- Fuel cell subsystem: provides steady-state power and supports battery charging during low SoC conditions.
- Power conditioning stage: includes a buck–boost converter for the battery and a boost converter for the fuel cell.
- Smart energy management unit: implemented using ESP32 for sensing, decision-making, switching, and protection.
- Monitoring unit: transmits operating data to an IoT dashboard through Wi-Fi.

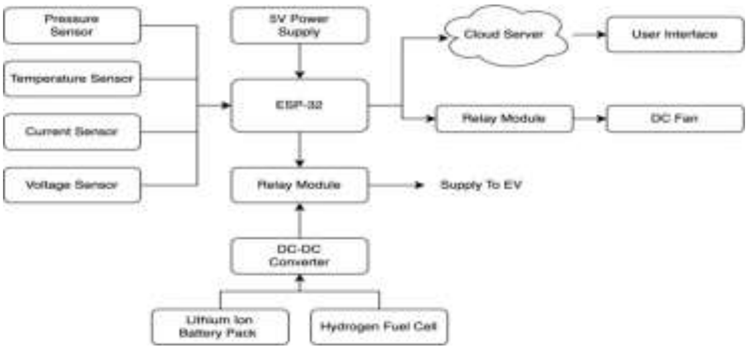


**Fig. 1. System architecture of the proposed hybrid battery–hydrogen fuel cell energy system with smart energy management.**

## 3.2 Operating Modes

The controller selects one of the following operating modes:

1. High-load mode: battery and fuel cell jointly supply the load.
2. Cruising mode: fuel cell provides the main share of load power.
3. Battery-support mode: battery compensates during sudden transients.
4. Charging mode: fuel cell supports charging when battery SoC falls below threshold.
5. Fault mode: unsafe conditions trigger isolation and shutdown.

# 4. MATHEMATICAL MODELING

To describe the hybrid system, basic battery and power balance equations are used.

### 4.1 Battery State of Charge

The battery state of charge is estimated by Coulomb counting:

$$SoC(t) = SoC(t0) - 1/Cbat \int ibat(\tau)\, d\tau$$

where Cbat is battery capacity in ampere-hour equivalent and ibat is battery current. For discrete implementation: $SoC(k+1) = SoC(k) - ibat(k)\Delta t/Cbat$

### 4.2 DC Bus Power Balance

The total load power is supplied by the battery and fuel cell:

$$Pload = Pbat + Pfc - Ploss$$

where Pbat is battery power, Pfc is fuel cell power, and Ploss represents converter and wiring losses.

### 4.3 Source Power

Battery and fuel cell power are expressed as:

Protection Constraints

$Pbat = VbatIbat$ $Pfc = VfcIfc$

The controller maintains operation within safety limits:

$Tbat < Tbat,max$ $Tfc < Tfc,max$ $PH2 > Pmin$

$Iload < Imax$

If any of these conditions are violated, the controller enters fault mode.

## 5. Smart Energy Management Algorithm

The smart energy management algorithm is rule-based and uses sensor inputs in real time.

### 5.1 Decision Variables

- Battery SoC
- Load current or load power
- Fuel cell voltage/current
- Hydrogen pressure
- Battery temperature
- Fuel cell temperature

### 5.2 Control Logic

The algorithm operates using threshold-based decisions:

- If load demand is high and battery SoC is sufficient, battery and fuel cell both supply power.
- If load demand is moderate and fuel cell conditions are normal, the fuel cell supplies the DC bus.
- If battery SoC is below the lower threshold, the fuel cell supplies load and charges the battery.
- If temperature or hydrogen pressure crosses safety limits, the system isolates the affected source and triggers fault protection.

## 6. Hardware Implementation

The prototype hardware consists of a lithium-ion battery pack, a PEM fuel cell stack, DC–DC converters, voltage and current sensors, temperature sensors, a hydrogen pressure sensor, relay or MOSFET switching circuits, and an ESP32 controller board.

### 6.1 Power Stage

- Battery connected through buck–boost converter
- Fuel cell connected through boost converter
- Common DC bus feeding motor load or resistive load
- Controlled switching to enable source selection and fault isolation

### 6.2 Sensing Stage

- Voltage sensors for battery and fuel cell terminals
- Current sensor for bus/load current
- Temperature sensors mounted near battery and fuel cell

### 6.3 Control and Monitoring

ESP32 acquires sensor signals, executes control rules, controls relays or gate drivers, and transmits data to a cloud dashboard using Wi-Fi. A cooling fan is activated when temperature rises beyond a preset threshold.

## 7. Experimental Setup

The system was tested on a laboratory platform under different operating conditions representing typical electric vehicle behavior.

### 7.1 Test Conditions

The following test cases were considered:

- Case 1: Battery-only operation
- Case 2: Fuel-cell-only operation
- Case 3: Hybrid operation under steady load
- Case 4: Hybrid operation under sudden load increase
- Case 5: Low-SoC charging support mode
- Case 6: Simulated fault under low hydrogen pressure or overtemperature

### 7.2 Measured Parameters

- DC bus voltage
- Battery current

- Fuel cell current
- Battery temperature
- Fuel cell temperature
- Hydrogen pressure
- Mode transition response

## 8. Results and Discussion

The hybrid configuration showed better voltage support under changing load than single-source operation. During sudden load increase, the battery responded immediately and reduced the transient burden on the fuel cell. During steady load operation, the fuel cell carried the main power demand, which reduced battery current stress. The DC bus remained more stable in hybrid mode than in battery-only mode during load variations.

When battery SoC dropped below the lower threshold, the controller shifted the system into charging support mode and the fuel cell supplied both the load and charging current within safe limits. Safety shutdown was also verified by creating abnormal conditions such as low hydrogen pressure and elevated temperature. In these cases, the controller successfully isolated the affected subsystem and transmitted an alert to the monitoring interface.

**Table 1. Example format for experimental results**

| **Test condition** | **DC bus voltage (V)** | **Battery current (A)** | **Fuel cell current (A)** | **Battery SoC (%)** | **Battery temperature (°C)** | **Fuel cell temperature (°C)** | **Hydrogen pressure (bar)** | **Observed mode** |
|---|---|---|---|---|---|---|---|---|
| Battery only, steady load | 24.1 | 2.8 | 0.0 | 82 | 31 | 29 | 0.0 | Battery mode |
| Fuel cell only, steady load | 24.3 | 0.0 | 2.4 | 81 | 30 | 36 | 1.6 | Fuel cell mode |
| Hybrid mode, normal cruising | 24.5 | 0.9 | 1.8 | 80 | 31 | 38 | 1.5 | Shared power mode |
| Hybrid mode, high load / acceleration | 24.2 | 3.6 | 2.7 | 78 | 34 | 41 | 1.5 | Dual-source mode |
| Sudden load increase | 23.9 | 4.1 | 2.2 | 77 | 35 | 42 | 1.4 | Battery assist mode |
| Low battery SoC condition | 24.4 | -1.2 | 2.9 | 24 | 32 | 40 | 1.5 | Fuel cell charging mode |
| Battery charging support with light load | 24.6 | -1.8 | 2.5 | 26 | 31 | 39 | 1.5 | Charge + supply mode |
| Low-load operation | 24.7 | 0.2 | 1.0 | 79 | 30 | 35 | 1.6 | Fuel cell dominant mode |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Overtemperature condition | 0 / protected | 0.0 | 0.0 | 76 | 48 | 57 | 1.4 | Fault shutdown |
| Low hydrogen pressure condition | 0 / protected | 0.0 | 0.0 | 75 | 32 | 37 | 0.5 | Fault shutdown |

**Fig. 1. DC bus voltage under different operating conditions**

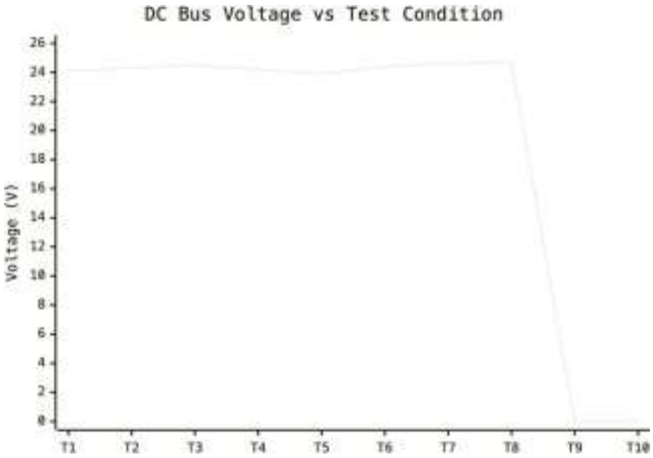


**Fig. 2. Battery current response for different operating modes**

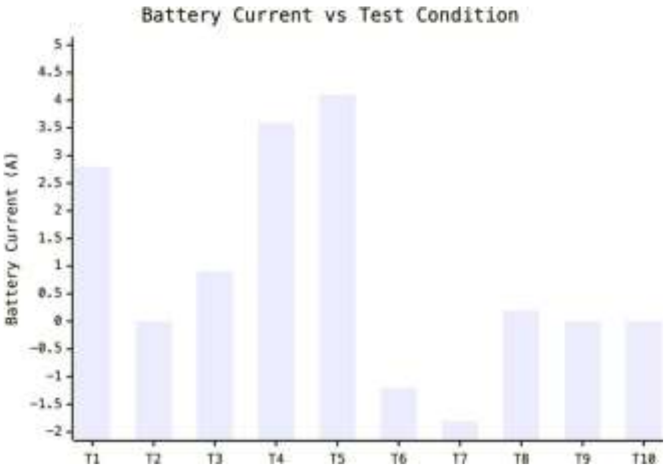


**Fig. 3. Fuel cell current contribution under different test conditions**

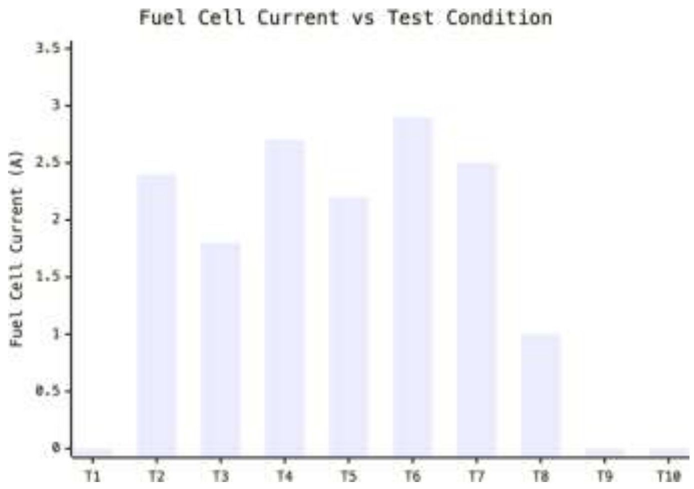
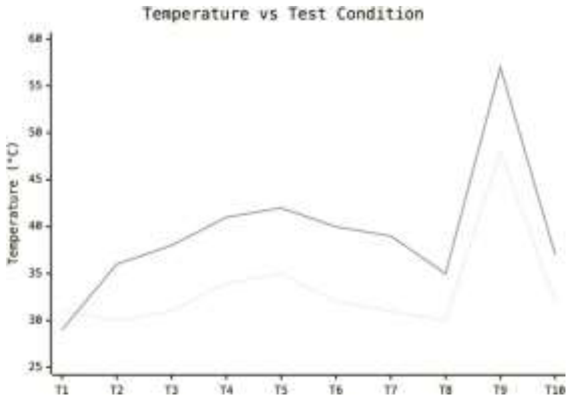


**Fig. 4. Battery and fuel cell temperature variation**



## 9. Conclusion

A hybrid electric vehicle energy system using a lithium-ion battery and a PEM fuel cell was designed as a prototype platform with smart supervisory control. The proposed rule-based energy management method enabled real-time source coordination using load demand, battery state of charge, temperature, and hydrogen pressure. The developed approach improved power sharing behavior, supported stable DC bus operation, and reduced battery loading during steady-state conditions. The monitoring and protection features also improved system safety by enabling timely detection of abnormal events. The work demonstrates that an ESP32-based supervisory controller can be used effectively for low-cost implementation of hybrid energy management in electric vehicle applications. Future work may include predictive control, improved SoC estimation, and regenerative braking integration.

[1] J. Shi, Z. Jiang, D. Zhao, and X. Hu, “Online Energy Management System for a Fuel Cell/Battery Hybrid System with Multiple Fuel Cell Stacks,” *arXiv preprint arXiv:2303.00245*, 2023.
[2] D. T. Machacek, “Energy Management of Hydrogen Hybrid Electric Vehicles,” *arXiv preprint arXiv:2308.11291*, 2023.
[3] H. J. El-Khozondar et al., “A Smart Energy Monitoring System Using ESP32 Microcontroller,” *Elsevier Open Access*, 2024.
[4] G. Fandi, “Review and Modeling on Hydrogen Fuel Cells Electric Vehicles,” *Journal of Energy Systems*, 2024.
[5] M. Essoufi et al., “Advancing Energy Management Strategies for Hybrid Fuel Systems,” *MDPI Energies*, 2025.
[6] S. Liu et al., “Model Predictive Control for Fuel Cell–Battery Hybrid Propulsion Systems,” *ScienceDirect*, 2025.
[7] A. Nazemian et al., “Simulation of Hybrid Fuel Cell–Battery Propulsion System,” *Springer*, 2024.
[8] F. Yu et al., “Deep Reinforcement Learning-Based Energy Management for Hybrid EVs,” *MDPI Electronics*, 2025.
[9] P. Sundarraj et al., “Hybrid Electric Vehicles: Fuel Cell and Battery Integration Techniques,” *IEEE Access*, 2024.
[10] R. Patel and A. Kumar, “Energy Management Strategies for Electric Vehicles: A Comprehensive Review,” *Renewable & Sustainable Energy Reviews*, 2023.