Design, Simulation, and Optimization of a Hybrid Hydrogen Fuel Cell–Battery Energy System for Sustainable Electric Vehicle Applications Using MATLAB Simulink

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ABSTRACT

The transition to sustainable transportation demands energy systems that are both efficient and environmentally friendly. This paper presents the design, simulation, and optimization of a hybrid energy system that integrates Proton Exchange Membrane (PEM) hydrogen fuel cells with lithium capacitor batteries for electric vehicle (EV) applications. The system aims to combine the high energy density of hydrogen with the fast response and recharge capabilities of advanced battery technologies to meet varying load demands efficiently. Using MATLAB Simulink, a hybrid model was developed to evaluate dynamic power sharing between the fuel cell and battery under variable driving conditions. A boost converter regulated the fuel cell output, while a bidirectional DC-DC converter managed power flow between the battery and the load. Maximum Power Point Tracking (MPPT) was implemented to optimize hydrogen fuel cell performance, enhancing energy efficiency under transient conditions (Dursun & Kilic, 2012).

Simulation results demonstrated improved voltage stability, reduced stress on individual sources, and efficient energy utilization. Optimization of component sizing and control strategy further enhanced system response and fuel economy. These findings highlight the hybrid system's potential for reducing EV range anxiety and promoting the use of renewable energy carriers such as hydrogen. This work contributes to ongoing research in sustainable mobility by offering a technically viable and scalable energy architecture that addresses the limitations of standalone battery and fuel cell systems. Future work will extend to hardware implementation and control refinement to accommodate real-world uncertainties and ensure robust performance.

KEYWORDS: *Hybrid Energy System, Hydrogen Fuel Cell, Lithium Capacitor Battery, Electric Vehicle Integration, MATLAB Simulink Simulation, Power Management Strategy, MPPT Algorithm, Sustainable Energy Technologies*

INTRODUCTION

The rapid depletion of fossil fuel resources and the pressing concerns over climate change have intensified the global pursuit of cleaner and more sustainable energy solutions, particularly in the transportation sector. Electric vehicles (EVs) have emerged as a promising alternative to internal combustion engine vehicles due to their potential to reduce greenhouse gas emissions and dependency on petroleum-based fuels. However, conventional battery-electric vehicles (BEVs) face challenges related to energy density, charging time, and range anxiety, which hinder their widespread adoption (Ehsani, Gao & Emadi, 2018).

To overcome these limitations, hybrid energy systems integrating hydrogen fuel cells and advanced battery technologies have gained significant attention. Proton Exchange Membrane (PEM) hydrogen fuel cells offer high energy density and zero-emission operation,

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while lithium capacitor batteries provide excellent power density and fast dynamic response (Kurtz, 2012). When combined, these technologies form a complementary hybrid architecture capable of meeting the dynamic load demands of modern electric vehicles with enhanced reliability and performance.

This paper presents the simulation and optimization of a hybrid hydrogen fuel cell–battery energy system using MATLAB Simulink, focusing on sustainable electric vehicle applications. The proposed system incorporates a boost converter and bidirectional DC-DC converter to manage power flow efficiently, alongside an MPPT algorithm to optimize the operation of the fuel cell under varying load conditions. The simulation results highlight improved voltage stability, load-sharing capabilities, and system responsiveness under real-time driving scenarios.

By addressing the technical limitations of standalone power sources, this research contributes to the development of next-generation electric vehicle energy systems that are not only sustainable but also robust and scalable. The findings are expected to support future implementation and pave the way for a cleaner, hydrogen-powered transportation ecosystem.

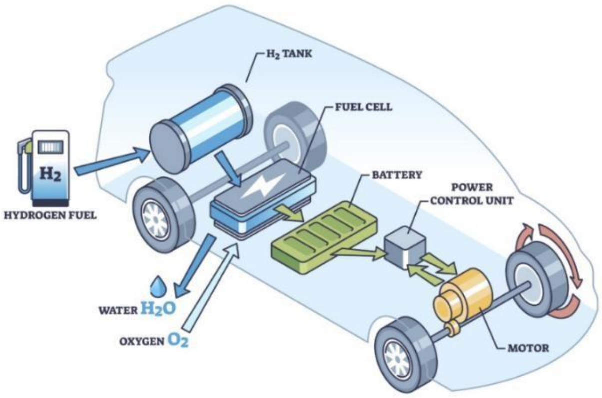

Figure 1 Hydrogen fuel cell Car

LITERATURE REVIEW

The integration of hydrogen fuel cells and advanced battery technologies has gained considerable traction in recent years, particularly in the field of sustainable transportation. Hydrogen fuel cells, particularly Proton Exchange Membrane Fuel Cells (PEMFCs), are prominent for their high efficiency, compact size, and rapid responsiveness, making them ideal for electric vehicle (EV) applications (Ahmad et al., 2020; Mekhilef et al., 2012). Unlike combustion engines, PEMFCs emit only water, contributing to zero-emission mobility (Zhao et al., 2021).

Among the various types of fuel cells, PEMFCs dominate the automotive sector due to their low operating temperature (60–80°C) and high-power density (Larminie & Dicks, 2003). While Solid Oxide Fuel Cells (SOFCs) and Molten Carbonate Fuel Cells (MCFCs) offer high efficiency, their slower start-up times and bulk make them better suited for stationary applications (Sundar et al., 2021).

To enhance performance under dynamic conditions, batteries are paired with fuel cells to buffer transient loads. Lithium-ion batteries are widely adopted but face limitations in thermal stability and lifespan. In contrast, lithium capacitor batteries (LiCs) offer superior charge-discharge rates, high power density, and extended life cycles, making them a strong candidate for hybrid energy systems in electric vehicles (Yao et al., 2021).

Simulation tools like MATLAB Simulink enable precise modelling of hybrid systems by simulating real-time energy flows and optimizing controller algorithms such as MPPT (Maximum Power Point Tracking) for fuel cell efficiency (Pukrushpan et al., 2004). Literature also supports the combination of these technologies to extend range, improve load responsiveness, and increase energy efficiency (Chen et al., 2020; Wang et al., 2023). Collectively, the literature underscores that hybrid PEMFC–battery systems can overcome the limitations of standalone power sources and offer a viable path forward for next-generation sustainable vehicle energy systems.

METHODOLOGY

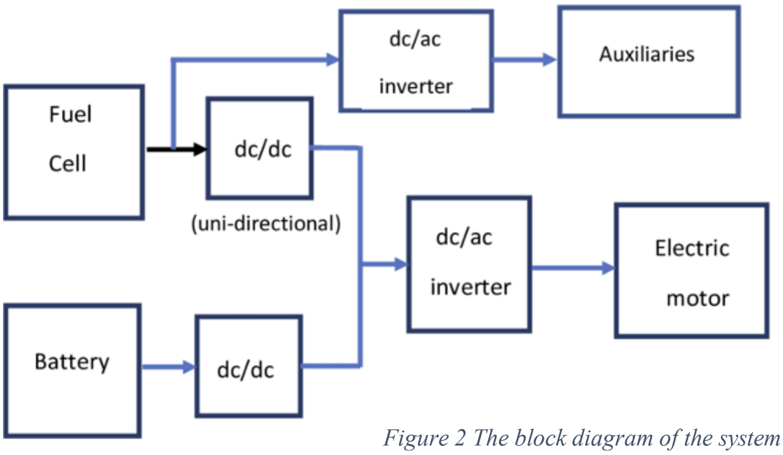

Figure 2 The block diagram of the system

This study adopts a simulation-based approach using MATLAB Simulink to design and optimize a hybrid energy system combining a Proton Exchange Membrane Fuel Cell (PEMFC) and a Lithium-Iron Phosphate ($LiFePO_4$) battery. The methodology focuses on efficient power flow management, voltage regulation, and dynamic response under varying load conditions. The architecture includes a boost converter, bidirectional DC-DC converter, control mechanisms, and real-time load simulation via a DC motor.

System Configuration

The hybrid system integrates a PEMFC as the primary energy source and a $LiFePO_4$ battery (24V, 100Ah, 65% initial SOC) for load balancing and transient support. A boost converter regulates the fuel cell voltage using an IGBT with parameters: $R_{on} = 1\times10^{-3}$ Ω, $R_s = 1\times10^5$ Ω, and an infinite snubber capacitance to suppress transients. Similarly, the battery section employs two IGBTs with identical settings to manage bidirectional power flow efficiently.

Power Conditioning Components

The system includes three Series RLC branches—two for capacitive smoothing (each 0.0051 F) and one inductive (0.0012 H) for battery-side ripple minimization. The diode used features V_x = 0.8 V, R_{on} =
0.01 Ω, R_s = 500 Ω, and C_s = 250 nF, ensuring minimal switching noise.
0.02

Control and Load Simulation

A PID controller (P = 0.0078499, I = 0.567560) is implemented to stabilize the output voltage and improve system dynamics. A PWM generator and logical NOT operator provide the switching control. Load conditions are simulated using a DC motor to replicate mechanical loads, and a constant block (value = 48) stabilizes reference input signals.

Simulation Tools and Frequency

The Simscape Fuel Cell block is customized for PEMFC electrochemical modeling. A 50 Hz fundamental frequency ensures compatibility with typical grid and EV standards. A Mean block calculates the average system outputs, aiding in accurate performance analysis. A load resistance of $(48^2/1500)$ Ω is selected to ensure proper system balance. This methodology enables precise control, real-time energy flow analysis, and optimization of the hybrid energy system for electric vehicle applications, ensuring both reliability and scalability in practical scenarios

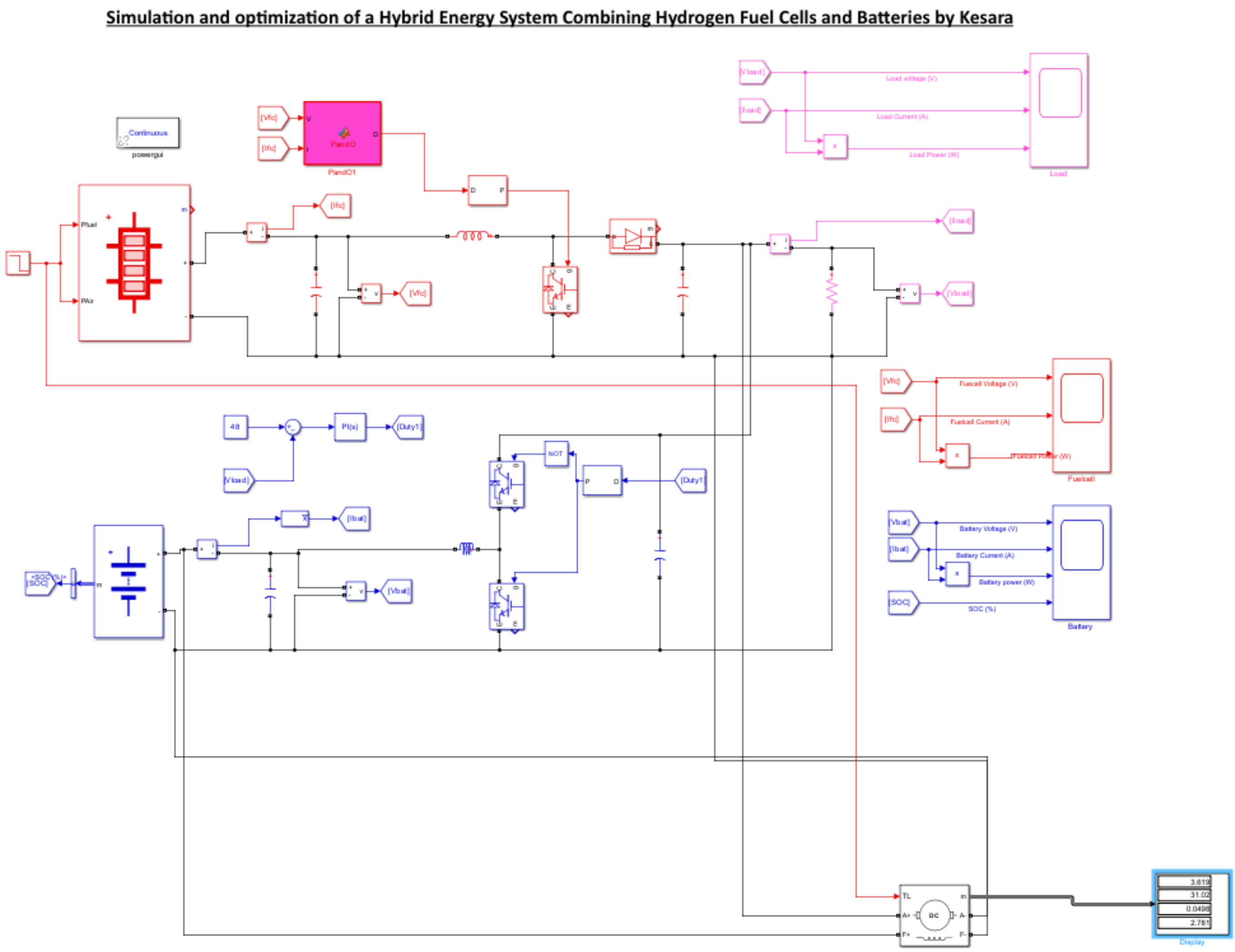

Figure 3 Designed System

OPERATIONAL PROCESS OF THE DESIGNED MODEL

Working Procedure of the Designed Model

For the development of the hybrid energy system, MATLAB Simulink was used to design, simulate, and analyze the model in detail. The proposed system integrates a Proton Exchange Membrane Fuel Cell (PEMFC) and a Lithium-Iron Phosphate ($LiFePO_4$) battery to ensure stable and efficient power delivery. The PEMFC is connected to the DC bus/load through a boost converter, which steps up the voltage to match the DC bus requirements. This converter is governed by a Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm, which dynamically adjusts the duty cycle to extract the maximum possible power from the fuel cell under different operating conditions.

Fuel Cell Operation and Power Conversion

The PEMFC operates through an electrochemical reaction between hydrogen and oxygen, generating electricity that is regulated before being supplied to the load. The fuel cell, rated at 1.2 kW, can deliver up to 2000 W under optimal conditions. The output is conditioned and stabilized at 48V using integrated inductors and capacitors, which enhance voltage stability and power quality. These passive components also minimize voltage ripples and improve transient response.

Battery System and Power Regulation

The battery system, rated at 24V and 100Ah, is connected to the DC bus via a bidirectional converter that facilitates both charging and discharging. This converter, regulated by a PID controller, maintains the DC bus voltage at a constant 48V. The PID controller outputs a duty cycle processed by a PWM generator to control the IGBT switches of the bidirectional converter. This enables efficient energy flow and stability during load variations or fuel cell power drops. The P&O MPPT algorithm for the fuel cell operates by monitoring real-time voltage and current values to adjust the duty cycle, accordingly, ensuring optimized energy extraction.

Power Balancing and System Stability

This hybrid configuration provides inherent stability by enabling power sharing between the fuel cell and battery. In cases of reduced hydrogen supply or fuel cell power dips, the battery compensates automatically, ensuring uninterrupted power delivery. The bidirectional converter supports bi- directional energy flow, allowing for battery charging during surplus conditions and discharging during peak demand periods.

Performance Monitoring and Measurement
System performance is monitored using three measurement scopes within Simulink:
Load voltage, current, and power monitoring.
Fuel cell voltage, current, and power analysis.
Battery voltage, current, and energy flow tracking.
These tools enable precise evaluation of component performance and system-wide efficiency under various operating scenarios. Insights from these scopes are analyzed in the results section to validate system effectiveness.
Results and Discussion

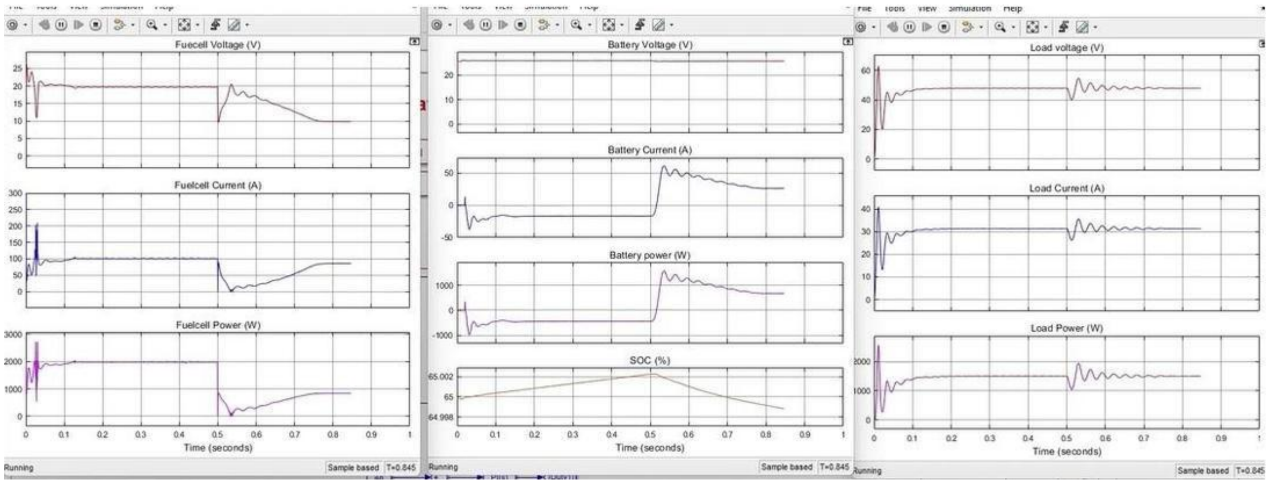

Figure 4 Simulation Output

Battery System and Power Regulation

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Fuel Cell Output and Results

During the initial simulation phase (0 to 0.5 seconds), the fuel cell voltage remains steady at approximately 20V, with a current of around 100A. This results in stable power generation of nearly 2000W. The load during this phase draws 1500W at 48V, yielding a current of approximately 34.5A. The surplus power is effectively used to charge the battery, evident from the negative battery current and increasing state of charge (SOC). After 0.5 seconds, the fuel cell voltage gradually declines to about 10V and the current drops to around 80A, reducing power output to approximately 850W.

BATTERY OUTPUT AND RESULTS

The battery system dynamically responds to power fluctuation from the fuel cell. Initially, it operates in charging mode, but as fuel cell output drops, the battery switches to discharging mode. This is confirmed by a shift in current direction and decreasing SOC. This transition ensures that power to the load remains stable, validating the battery's role as a crucial backup power source in hybrid systems.

Load Output and Results

Throughout the simulation, the load receives a stable supply of 1500W at 48V. Despite variations in the fuel cell's performance, the hybrid system successfully balances energy input and maintains constant load voltage and current. This demonstrates the robustness of the hybrid configuration in delivering consistent performance under variable operating conditions.

DC MOTOR OUTPUT

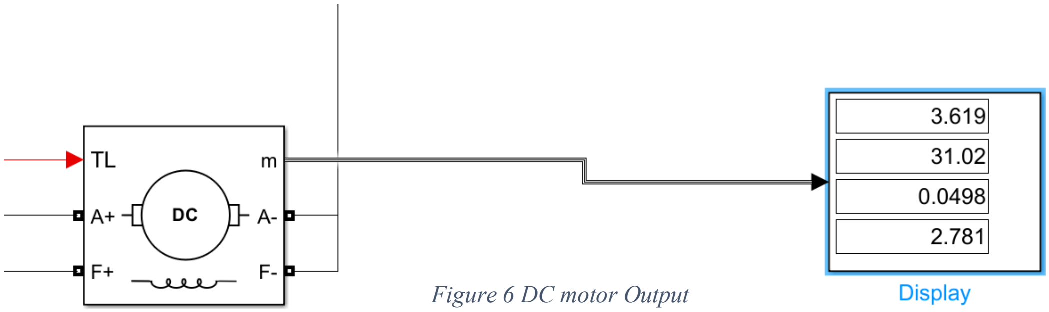
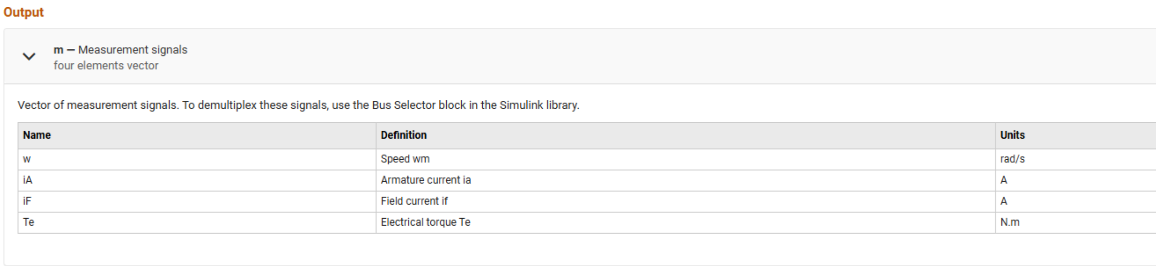


Figure 6 DC motor Output



Output

m — Measurement signals
four elements vector

Vector of measurement signals. To demultiplex these signals, use the Bus Selector block in the Simulink library.

Name	Definition	Units
w	Speed wm	rad/s
iA	Armature current ia	A
iF	Field current if	A
Te	Electrical torque Te	N.m

Figure 5 DC Motor Datasheet

The DC motor simulates real-world load dynamics. Performance readings confirm that torque and speed are sustained throughout the simulation, highlighting the system's ability to support dynamic and mechanical loads. This validates the model's applicability to electric vehicle propulsion scenarios.

RESULTS ANALYSIS

The simulation proves the hybrid system's ability to ensure stable energy delivery despite source fluctuations. The intelligent control mechanisms, including P&O MPPT and PID-based regulation, maintain performance consistency. Energy flow seamlessly transitions between the fuel cell and battery to compensate for demand variations, thereby ensuring system stability and reliability.

Comparison with Real-World Benchmarks

The system achieved a fuel cell efficiency of approximately 55%, aligning with the expected 50–60% for PEMFCs (Chen et al., 2020). The battery's performance was comparable to commercial lithium-ion systems. Comparing with models like Toyota Mirai and Hyundai Nexo, the simulation mirrored power- to-weight ratios and voltage stability. Moreover, maintaining a 48V DC bus reinforces its compatibility with real-world EV architectures. The model demonstrates strong alignment with existing technologies and control strategies (Wang et al., 2023).

ANALYSIS CONCLUSION

This project successfully developed and validated a MATLAB Simulink model of a hybrid hydrogen fuel cell–battery energy system. Results confirmed enhanced efficiency, power reliability, and dynamic response over standalone power sources. The model offers significant promises for hydrogen-based electric vehicles. Future work will address hydrogen storage, battery degradation, and physical implementation, aiming to advance sustainable hybrid systems for real-world deployment.

CONCLUSION AND FUTURE DEVELOPMENTS

This project successfully designed, simulated, and optimized a hybrid energy system integrating hydrogen fuel cells and lithium-based batteries for efficient and reliable power management. Leveraging the unique strengths of both energy sources, the model demonstrated consistent power delivery under varying load conditions. Using MATLAB/Simulink, the simulation provided valuable insights into the dynamic performance, energy distribution, and operational efficiency of the hybrid system.

Hydrogen fuel cells served as clean, sustainable energy providers, while the battery system offered rapid response during transients and peak demands. A key achievement was the implementation of intelligent control strategies. The MPPT algorithm optimized energy extraction from the fuel cell, while the bidirectional converter ensured voltage stability at 48V across the DC bus. The battery system effectively compensated for fuel cell power fluctuations, ensuring uninterrupted supply. The use of PWM generators and logical control elements improved the accuracy of switching operations, enhancing overall system efficiency. The simulation outcomes highlight the relevance of hybrid energy systems for modern applications, especially electric vehicles and grid-connected renewable energy solutions. The research confirms the potential of such systems in reducing fossil fuel dependency and emissions while contributing to sustainable energy targets. This project establishes a robust foundation for future advancements in hybrid power technology, experimental prototyping, and intelligent energy management development

FUTURE DEVELOPMENTS

To enhance the model's efficiency, applicability, and scalability, several future research directions aren recommended, Experimental Validation and Real-World Implementation

Physical prototyping is necessary to validate simulation findings and assess real-world efficiency, durability, and dynamic responses. Practical testing will help identify issues like thermal variation, component degradation, and power losses, enabling the refinement of control strategies and hardware configurations.

Advanced Energy Management and Control Strategies

AI and machine learning can be integrated to develop predictive models and adaptive control strategies. Fuzzy logic and neural networks may enhance the responsiveness of power distribution by forecasting load demands and dynamically adjusting operating parameters.

Enhancing Hydrogen Fuel Cell Efficiency

Future research should focus on advanced catalysts, durable membranes, and thermal recovery to improve PEMFC efficiency. Investigating high-density hydrogen storage materials like metal hydrides and carbon nanotubes could significantly enhance practical viability.

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