

## AN ANALYSIS OF RECENT TRENDS IN FUEL CELL TECHNOLOGY

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**Abstracts:** Fuel cells have been researched as prospective energy alternatives because they are more efficient and environmentally friendly than other alternative energy sources. This report examines the current state of fuel cell innovation as well as some of its global obstacles. In the industrial, corporate, and domestic areas, fuel cells have become a significant innovation for a variety of non-linear loads. To assess how far fuel cell technology has come, 38 publications from the literature were analyzed for this study. The goal of this paper is to thoroughly evaluate and examine the most recent research findings and global energy data in light of these developments.

**Keywords:** Fuel cell, Proton Exchange Membrane Fuel Cells, Health management, Electric vehicles, and Hydrogen fuel cell.

### 1. Introduction

The possible consequences of global warming are grave and irreversible, releasing greenhouse gases (GHGs). Thermal, hydroelectric, nuclear, and solar power plants currently provide for all of the world's energy needs. These aforementioned energy production methods are less efficient but emit more greenhouse gases (GHG), which harm the environment. In essence, fuel cells are accessible thermodynamic devices. They rely on electrochemical activities for the operation and take reactants from an outside supply. For small-scale operations, they are advantageous substitutes for traditional power generation techniques. The "microchip of the hydrogen age," fuel cells are viewed as a pure, sustainable energy source that can replace the fossil fuels now utilized to drive the global economy. In a fuel cell, electric power is converted to chemical power. These cells require a steady supply of fuel and oxidants to power their electricity-generating process. This paper discusses mathematical modeling for fuel cells, the types of fuel cells (FC) compared, existing research trends, market conditions, and potential future applications.

**Table 2(a) - (c)**, discusses recent developments in the literature review which are as follows:

To forecast Proton Exchange Membrane Fuel Cell (PEMFC) depreciation in the frequency response, this work gives a new prototype approach based on the frequency domain Kalman Filter (FDKF) and voltage degradation model (VDM) [1]. This research proposes and investigates a frequency decoupling-based EMS for FCHEV using fuzzy control technique (FCM) to increase fuel cell lifespan [2]. Model-based reinforcement learning (MBRL) is being used for EMS in this work [3]. This article outlines the development of a technological device called the Fuel Cell Technology Readiness Level (FCTRL) that relates only to FC technologies (TECH) [4]. The multi-objective power allocation strategy (PAS) issue in a modular fuel cell vehicle (MFCV) is addressed in the current work using a unique decentralized convex optimization (DCO) approach that relies on the auxiliary problem principle (APP) [5]. In this article, we use the model predictive control (MPC) approach to explore the issue of managing energy flow in charge-sustaining FC electric vehicles (EVs) [6]. This study uses a semi-empirical model (SEM) to construct an online EMS for a multi-stack FCHEV to improve fuel efficiency and FCS lifespan [7]. In this study, a real-time (RT) rule-based EMS integrating multi-objective genetic algorithms (GA) optimization (OPT) capabilities for an FCHEV model is designed [8]. This study suggests a new technique called online systematic management (MNGT) plan (3d map) boosts an EMS's effectiveness in a slow-moving FCHEV [9]. In this study, a novel approach to estimating the linear and nonlinear variables of a well-known PEMFC system is presented. It is focused on the Lyapunov adaptation law (LAL) [10]. The proposed technique carries out the energy dispersal across four PEMFC layers by using the degree of performance degradation (DOPD) of layers and the request energy [11]. The PEMFC gadget layer and the hydrogen supply channel's current hydrogen leakage detection technique (HLDM) are examined in this research. [12]. Relying on the active architecture of the hybrid ESS, this research proposes the hybrid energy storage system (ESS) size for an FC mixed excursion ship [13]. The most recent unidirectional non-isolated DC-DC Multistage Power Converter (MPC) architectures for FC Vehicular Power Train (VPT) applications are covered in this paper [14]. The time-varying constants of a well-known PEMFC SEM are estimated in this work using an online system identification (OSI) technique [15]. This paper suggests a new integrated management technique, or surrogate technique, for integrating FC with polymer electrolytes (PEFC-CGSs) [16]. In this study, an aviation-propulsion system (APS) combining HFC and a superconducting motor (SM) is created, and the system's suitability for use in aircraft is evaluated utilizing detailed power estimates [17]. In this study, Pukurushpan's ninth-order model (PNOM) is used to suggest sliding mode controllers (SMC) for a PEMFC [18]. In this study, a cost minimization (MIN) strategy (CMS) is created to reduce the total running costs of FC hybrid electric vehicles (HEV) while enhancing the longevity of power sources (PS) [19]. Adaptive neuro-fuzzy interference system (ANFIS), a modern control technique, is used to the power converter so that the output is precise

concerning the controller's capacity for training [20]. For a dual-stack FC hybrid locomotives engine, this study proposes the hierarchical power allocation technique (HPAM) and the forgetting factor recursive least square (FFRLS) method [21]. In this study, a quick electrochemical impedance spectroscopy assessment (FEISM) is used to suggest a health management technique (HMM) for the PEMFC centered on an active fault tolerant control method (FTCS) [22]. In this study, a brand-new control technique for maritime vessels' hybrid FC and battery power systems (PS) is developed [23]. In this study, data packet losses on the stability of Internet-based distributed test platforms (IBDTP) throughout Net data transfer were analyzed theoretically and through modeling [24]. A unique prognostic approach (NPM) has been created to forecast the multi-stack SOFC system's residual usable life (RULs), which will increase the accuracy of the network [25]. This research demonstrates a planned, synchronized, centralized control strategy for SOFC systems with the goal of frequency deviation (FDC) [26]. The optimum functioning of smart hybrid AC-DC microgrids (MG) was presented in this project, taking into account various RESs, like WT and PV, the rapid expansion of PEVs, the realignment method, and the thorough modeling of PEMFC [27]. The implementation of an incremental fuzzy modeling approach (FMM) built on the EKF implemented in real HFC is presented in this research [28]. This study suggests a model predictive control (MPC) method for smart FCHVs that integrates movement and engine modeling and MNGT [29] & [39]. The cost-effective planning and implementation of FCHEVs lorries are suggested in this study, where a chance-constrained optimum is expressed as sequential convex programming (SCP) [30]. This report outlines a revolutionary design for a home solid oxide fuel cell (SOFC) integrated cooling, heating, and power (CCHP) system employing realistic scaling methodologies, the entropy-weighting approach, and grey connection, for the U.K. business [31]. To regulate parallel step-up converters that receive their supply from PEMFCs for DC MG uses, this research suggests a new, reliable control method that was created utilizing the Hamiltonian–Lyapunov energy function (HLEF) (EV, aircraft, etc.) [32]. This research uses a mixed nonlinear programming approach (MINLP) to suggest an OPT strategy of thermal power and electric power dispatch combined with load scheduling (LS) for the local FC CHP system [33]. In this study, a centrifugal air compressor is created to satisfy the needs of Grey Wolf OPT's FC gas supply [34]. This study examines an energy management system (EMS) for FCHCVs associated with multi-objective optimal model predictive control (MOMPC) [35]. For the FC air supply network, this study suggests a fractional order PID (FOPID) control scheme relying on uncertain input nonlinear observers [36]. A unique EMS plan for FCHEVs, developed an approximator for average rewards within a paradigm for partially observable Markov decision processes (POMDP) to minimize the long-term average price [37]. To meet the voltage needs of both the FC and battery network in automobile usage and to offer trustworthy galvanic isolation, a broad voltage-ranging step-up isolated dc/dc converter is presented in this project [38].

### 1.1. Organization of Paper

The primary goal of this brief review-based research is to examine the latest situation in the fuel cell tech sector. These methodologies include artificial intelligence, FDKF, VDM, MPC, FCM, SMC, super twisting algorithm, PNOM, KF, ANFIS, IBDTP, genetic algorithm, artificial neural network, and robust predicted values compensator, among others, to improve the characteristics and attributes of the fuel cell through this evaluation. This paper is divided into four sections. There are four parts to this article. *Section 1*, is the introduction; *Section 2*, is mathematical modeling and comparison; *Section 3*, is the result and discussion in tabular form, along with current market scenarios, and *Section 4*, is the conclusion and future scope.

## 2. Mathematical Formula Problem

By **J. C. Amphlett's** equation [40] for PEMFC output properties, the output voltage of a PEMFC single cell  $V_{cell}$  is in **Eqn. (1)**;

$$V_{cell} = E_{Nernst} - V_{act} - V_{ohm} - V_{con} \quad (1)$$

The voltage,  $V_{stack}$ , for a stack of cells linked in series is in **Eqn. (2)**;

$$V_{stack} = NV_{cell} \quad (2)$$

where  $N$  is the number of PEMFC single cells.

The Nernst equation's derivative, thermodynamics electromotive force ( $E_{Nernst}$ ), is used in the theory in **Eqn. (3)**;

$$E_{Nernst} = \frac{\Delta G}{2F} + \frac{\Delta S}{2F}(T - T_{ref}) + \frac{RT}{2F}[\ln(P_{H_2}) + \frac{1}{2}\ln(P_{O_2})] \quad (3)$$

$\Delta G$  stands for Gibbs's free energy,  $P_{H_2}$  is the portion pressure of hydrogen at the anode, in atm,  $P_{O_2}$  is the partial pressure of oxygen at the cathode, in atm,  $F$  is the faraday constant, in C/mol,  $\Delta S$  is the entropy adjustment, in J/mol;  $T_{ref}$  is the benchmark temperature, K;  $T$  is the operating temperature, K; J/mol K is the ideal gas constant  $R$ .

It is possible to discuss the activating overvoltage  $V_{act}$  is in **Eqn. (4)**;

$$V_{act} = \epsilon_1 + \epsilon_2 T + \epsilon_3 T \ln(C_{O_2}) + \epsilon_4 T \ln I \quad (4)$$

Where:  $I$  is the load current of the FC (A);  $\epsilon_1, \epsilon_2, \epsilon_3, \epsilon_4$  is the empirical variable.

In an FC, the impedance of the electrolytes and electrode often follows Ohm's law, allowing for the expression of ohmic overvoltage  $V_{ohm}$  in **Eqn. (5)**;

$$V_{ohm} = IR_{ohm} = I(R_m + R_c) \quad (5)$$

Where  $R_c$  is contact resistant to electron flow,  $R_m$  is resistant to proton transfer via the barrier, and  $R_{ohm}$  is corresponding ohmic resistance.

The impedance impact of electrons traveling via the membrane can be disregarded since ion electron flow is more challenging than electron charge transport, which significantly affects ohmic resistance.

$$R_m = \frac{r_m L}{A} \quad (6)$$

where  $L$  is the membrane's width in cm,  $A$  is its active surface in  $cm^2$ , and  $r_m$  is its unique resistivity in cm.

FC concentration overvoltage ( $V_{con}$ ) could be represented in **Eqn. (7)**;

$$V_{con} = w \exp(ni) \quad (7)$$

Where,  $i$  are the current densities, measured in  $A/cm^2$ ,  $n$  is the electrolytic reaction's product increase level in the catalytic barrier,  $w$  is the bulk transferring ratio, and  $\mu_f$  is the fuel's accessibility, calculated as 0.95.

The stack's effectiveness  $\eta$  is in **Eqn. (8)**

$$\eta = \mu_f \frac{V_{cell}}{E_{Nernst}} \quad (8)$$

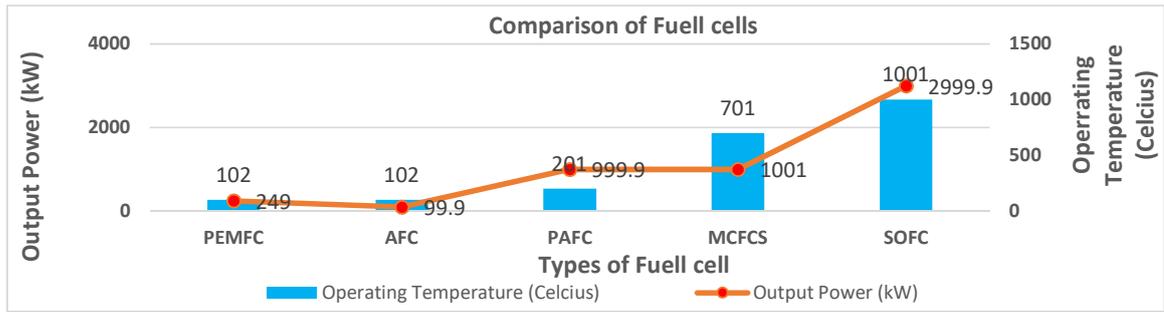
## 2.1. Overview of Several Fuel Cell Techniques

In proton exchange membrane (PEM) fuel cells, a catalyst activates the hydrogen to generate proton ions, which then emit electrons at the anode. While the electron is compelled to move to the external circuitry and create energy, the proton flows via the membrane.

Alkaline (AFC) produces electricity using potassium hydroxide (KOH), an alkaline electrolyte, in a water-based mixture.

Carbon-coated electrodes and fluid phosphoric acid (H<sub>3</sub>PO<sub>4</sub>) electrolytes are used in phosphoric acid fuel cells (PAFC).

In molten carbonate (MCFC), carbonate ions and hydrogen (H) fuel interact at the H electrode to produce carbon dioxide, water, and electrons.



**Fig. 1:** Comparison between types of Fuel cells in terms of temperature and output power

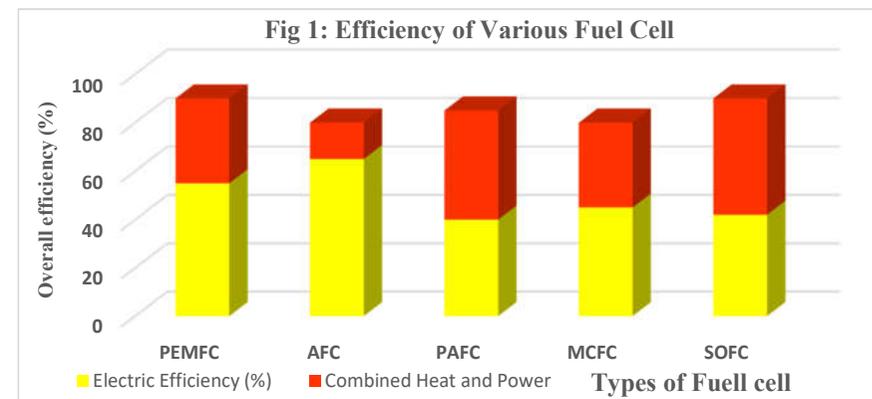
The listed publications collectively focus on energy systems, electric vehicles, smart grids, artificial intelligence, and sustainability, covering energy storage technologies and their recent advancements [42], distributed power generation planning using electric vehicles with associated challenges and opportunities [43], and the global scenario of distributed generation development [44]. A comparative analytical framework for evaluating distributed generations and EVs in distribution systems is presented in [45], while EV integration in super smart grids for enhanced energy management is discussed in [46], and intelligent transformer health monitoring techniques are reviewed in [47]. Applications of cognitive intelligence in smart grid management are examined in [48], along with smart microgrid switching strategies for efficient operation [49], and comprehensive insights into EV charging infrastructure and grid interaction issues are provided in [50]. Optimal scheduling of distributed generators and EVs in distribution networks is analyzed in [51], and broader applications of artificial intelligence in engineering domains are highlighted in [52]. Advanced modeling for EV penetration forecasting using hybrid techniques is developed in [53], and optimization of EV charging systems through machine learning approaches is addressed in [54], while recent advancements in renewable energy technologies are summarized in [55]. Decision tree methods for state-of-charge estimation in hybrid EVs are explored in [56], and automation technologies in IoT and robotics are reviewed in [57]. The role of artificial intelligence in improving fuel cell performance is discussed in [58], grid integration challenges of EVs are detailed in [59], and applications of wireless, 5G/6G, and IoT technologies in smart systems are presented in [60]. Sustainable and energy-efficient Green IoT concepts are covered in [61], blockchain applications in healthcare systems are reviewed in [62], and recent trends in EV planning and design are analyzed in [63]. Research perspectives aligned with Sustainable Development Goals are examined in [64], ecological approaches for biodiversity and habitat restoration are discussed in [65], urban resilience and sustainable infrastructure development are explored in [66], and the strategic role of AI, IoT, and blockchain in advancing sustainability objectives is highlighted in [67], while foundational principles and technical aspects of electric vehicle engineering are comprehensively presented in [68].

**Table 1:** Comparison between different types of Fuel cell

S. No.	Fuel Cell	PEMFC	AFC	PAFC	MCFC	SOFC
	Parameters					
1	<b>Electrolyte Formula</b>	$C_n F_{(2n+1)} SO_3H$	Aq. KOH	$H_3PO_4$	$Li_2CO_3, Na_2CO_3, K_2CO_3$	$Y_2O_3, ZrO_2$ electrolyte, Ni + YSZ and $La_{0.8}Sr_{0.2}MnO_3$
2	<b>Electrolyte</b>	Poly-per-fluoro-sulfonic acid.	Potassium hydroxide.	Phosphoric Acid.	Lithium and potassium carbonate.	Yttria stabilized zirconia Samarium doped ceria.
3	<b>Electrolyte Type</b>	Solid	Liquid	Liquid	Liquid	Solid
	<b>Anode catalyst</b>	$PtNi$	$Pt$	$H_2$	$NiCr$	Ceria, and perovskites.
	<b>Cathode catalyst</b>	$PtCo$	$Pt$	$O_2$	Lithiated $NiO$	$LaSrMn$ oxide perovskite
4	<b>Temperature (°C)</b>	55-85	85-105	145-205	601-702	605-1010
5	<b>Output</b>	1-250KW	10-100KW	50KW-1MW	1KW-1MW	>1KW- 3MW
6	<b>Electrical efficiency</b>	50-62% (Transportation)	61%	>38%	40-45%	30-45%
7	<b>Advantage</b>	Reduce corrosion and quick start-up.	Low-cost component.	High temperature enables.	Fuel adaptability	May make use of a range of catalysts.
8	<b>Disadvantage</b>	Expensive catalyst.	Electrolyte management.	Prolonged starting period.	Minimal power density	Disintegration and rusting at high temperatures.
9	<b>Uses</b>	Transport, standby power, reliable generators, etc.	Aerospace and defense, etc.	Diversified production	A sizable decentralized energy facility, a power utility, etc.	Electrical utilities, huge dispersed generating, supplemental energy, etc.

In **Table 1**, Proton exchange membrane FC (PEMFC), alkaline FC (AFC), phosphoric acid FC (PAFC), molten carbonate FC (MCFC), and solid oxide FC are all compared (SOFC) [41].

In **Figure 2**, Different fuel cell variants have been compared in terms of their overall efficiency, that is a sum of electricity efficiency and combined heat and power efficiency.



**Fig. 2:** Efficiency comparison of different fuel cell

### 3. RESULTS AND DISCUSSION

#### 3.1. Latest Developments in Fuel Cell Engineering

**Table 2(a):** Technological assessment for fuel cells

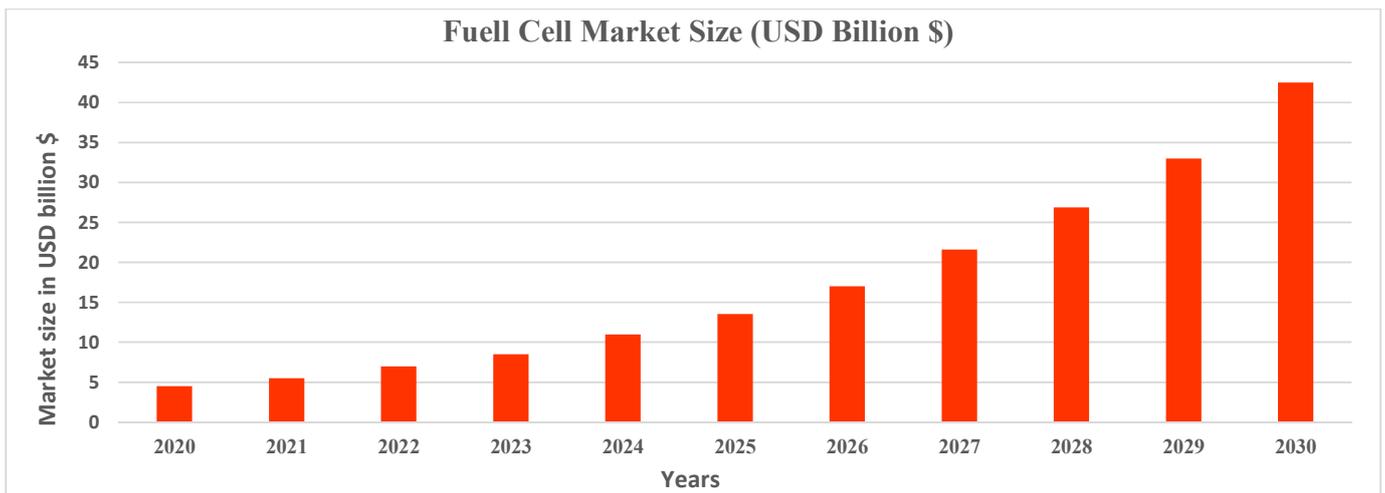
S. No.	Topics	Objective	Component	Limitation	Performance parameter	Method Utility	Future Scope	ROC
1	PEMFC prognosis based on FDKF.	Better precision and takes much less time to calculate.	PEMFC.	Expensive Catalyst.	For PEMFC1 and PEMFC2, the relative inaccuracy of VDM is consistently less than 1.8 percent and less than 3 percent, respectively.	FDKF, and VDM.	Proposed FDKF method with EMS.	5
2	Frequency Decoupling-Based EMS for FC/ Battery/UC HEV using FCM.	FC's lifetime will be increased and power surges will be less damaging.	FCHEV.	Less accurate.	7.94% lessens the amount of fuel used.	FCM.	AI-based strategy.	6
3	FCHEV EMS includes data-driven model updates utilizing MBRL.	The learning process is very stable and reduces fuel consumption.	FCHEV.	A genuine EV's electrically controlled unit is incapable of managing MBRL.	The amount of fuel used dropped by 5.7%.	MBRL.	When various behavioral verifications, different simulations are conducted to enhance MBRL efficiency.	5
4	Creation of a cutting-edge instrument for FC TECH to evaluate technical preparedness.	Replace conventional energy TECH.	FC.	Low manufacturing readiness.	While utilizing hydrogen as the fuel, breadboard efficiency is greater than 40%; when utilizing different fuels, it is just 25%.	FCTRL.	Improvements to the FCTRL tool.	3
5	PAS is based on decentralized convex OPT in MFCV applications.	Accelerating the CT of solving the complex problem.	MFCV.	Less accurate.	About 3 times less CT than the previous one and also provides less sensitivity.	PAS, DCO, and APP.		5
6	FCM-based control for EMS OPT in FCEV.	Fuel cost MIN, and stability MAX.	FCEV.	Lab-scaled FC prototype analysis is missing.	MAX CT elapsed is 0.4388 s.	MPC, FCM, and KF.	Machine learning techniques are used.	6
7	An EMS for multi-stack FCHEVs relying on an adaptable state machine.	System effectiveness at its MAX.	FCHEVs.	The sizing of the battery pack is not included.	Fair Dispersion and Daisy Chain methods consume 25.8% and 14.90% of the minimum amount of hydrogen, respectively.	Daisy Chain, Uniform Dispersion, and SEM of FCS.	Either restricting mobility or adding another DC/DC converter for the battery.	16
8	A FCHEVs with a multi-objective OPT RT rule-based EMS.	Ensures the stability of the gadgets that are linked after it.	FCHEVs.	Lacks online PG for an unknown driving pattern.	FC power change rate is 14.8314 W/s.	GA.	Further work on pattern recognition (PG).	1
9	Efficiency upgrade of FCHEVs EMS by online systemic MNGT of FC.	Increase the use of hydrogen in the economy by 3.7%.	FCHEVs.	Expensive.	3.7% efficiency enhancement can be reached.	EMS, and online 3D map systemic MNGT scheme.	Systemic MNFT to the PEMFC stack's water MNGT.	5
10	Analysis of an FC's adaptive parameters for EMS applications that prioritize health.	Compared to EKF and KF, the suggested methodology may be more than twice as accurate.	PEMFC.	RT analysis has been missing.	LAL gives a MAX current is 27.74 A, and a MAX power is 2701.1 W.	EKF, health assessment, and LAL.	Several FCsSeverald to verify the RT parameter predictor.	2
11	A PAM taking FC efficiency constancy into account for a multi-stack PEMFC platform.	The MFCS can continue to run after failures of one unit.	PEMFC.	Less accurate.	Working stresses are 18.5086, 18.5278, 15.1428, and 14.3872 respectively.	PAM, and DOPD.	Utilization of a multi-stack FC hybrid PS in the rail transport sector.	6
12	HLDM for PEMFC: methods and suggestions on its use in FCEV.	Diagnosis of HL in the stack.	PEMFC.	High flow rate.	Reduce hydrogen leakage.	HLDM.	Evaluate HL at a lower flow rate.	2

S. No.	Topics	Objective	Component	Limitation	Performance parameter	Method Utility	Future Scope	ROC
13	RT OPT EMS for FC hybrid ships considering power sources degradation.	Excellent robustness, and can MIN the fuel cost.	FC.	Short lifetime.	ECMS filter EMS gives 24.28 (10 <sup>3</sup> ) kJ.	RT OPT control strategy, and EMS.	RT hardware implementation.	2
14	Analyze DC-DC non-isolated architectures for FCEVs' one-way power flow.	The switch capacitor-based converter family is best suited for DC-DC converter.	FCEVs.	Poor voltage regulation.	Small size, and low weight.	MPC methods.	Layouts for hybrid DC-DC and multi-port converters for HV exchange rates.	19
15	OSI of FC stack with guaranteed stability for EM uses.	Stability enhancement.	FC.	Less accurate.	20 degrees Celsius and 60% relative humidity are the ambient conditions.	OSI method, and LAL.	RT hardware base analysis.	3
16	MIN estimated operating expenses for a domestic FC system are planned operationally using a surrogate approach.	Incredibly effective domestic FC that aids with the transition to a low-carbon world.	FC.	Low voltage analysis.	30% of the extra operating expenses are reduced.	PEFC-CGSSs, and Surrogate model.	High voltage system analysis takes place.	1
17	HFC and SM are used in the conceptual design of an APS.	Thermal load management, and enhanced efficiency.	HFC.	Not yet adequate to be used with aircraft.	The suggested APS's battery and liquid hydrogen solution have energy densities of 8.0 kWh/kg and 3.7 kWh/kg, respectively.	APS, and 3D finite element method program.	Design future-oriented electric APS.	3
18	Operational efficiency improvement of PEMFC—A SMC Approach.	Minimal chattering can be seen in an algorithm that twists excessively.	PEMFC.	Expensive catalyst.	Extends the stack lifetime of the FC and increases system performance overall.	SMC, super twisting algorithm, and PNOM.	GA.	4
19	CMS for FCHEVs considering PS degradation.	Cost MIN.	FCHEVs.	Less accurate.	The yearly price declines for batteries, FCs, and hydrogen are 11%, 5%, and 11%, respectively.	Predictive models, empirical deterioration prototype, and CMS.	Sophisticated model for forecasting the driving cycle and price assessment	3
20	Design and implementation of MLI for FC energy conversion system.	MIN of switching loss, THD, gadget stress, and power switching elements.	PEMFC.	THD is less accurate.	94.76 percent, 94.26 percent, and 93.87 percent are determined as the efficiencies of the five, seven, and fifteen-level MLI, respectively.	ANFIS.	Advanced GA.	12
21	For a train with two PEMFCs and batteries, HPAM is focused on an online extremum-seeking algorithm.	Enhance the productivity and effectiveness of PEMFC systems while lowering fuel usage.	PEMFC.	Expensive.	Relative to the 27.17 %, the dual-stack system's mean performance is better at 37.46 %.	FFRLS, and HPAM.	Create and use multi-stack technology in low-floor light rail cars.	4
22	HMM for PEMFC based on an active FTCS.	Enhancing the PEMFC's dependability.	PEMFC.	Large computational time.	Reduces the purge period to 10 s, eliminating the consequences of flooding.	HMM, FTCS, and FEISM.	Modifying the HMS to accommodate more PEMFC faults.	2
23	Enhanced flexible DC method to reduce FC marine PS powertrain loss.	MIN energy losses.	FC.	Less accurate.	In the buck, freewheel, and boost modes, the MAX LF peak-to-peak ripple values are 7.5, 5.5, and 5.8 A, respectively.	Variable DC approach, and real industrial PC controllers.	Forecasting loads to monitor optimum performance across various vessel data sets.	3
24	Effects of packet loss and their OPT upon that IBDTP for FCEVs' drivetrain components.	The state's reliability has significantly increased.	FCEVs.	Sophisticated.	A 2 km/h MAX optimum amplitude was achieved.	IBDTP, and robust model prediction compensator.	GA.	2
25	RUL prediction for an MSOFC system with degradation interactions.	Higher prediction accuracy for MSOFC.	MSOFC.	Longer start-up time.	The MSOFC state's MAX absolute RUL estimation loss is 7.7%.	NPM, and copula function.	HFCs.	1

S. No.	Topics	Objective	Component	Limitation	Performance parameter	Method Utility	Future Scope	ROC
26	FDC of distributed systems with FCS in low-inertia electric systems.	Better frequency response.	FC.	Voltage improvement avoids	Frequency matrices are 3728.3 MW/Hz.	Ex-ante analysis, and centralized coordinated control.	GA.	1
27	A secured EMS for smart hybrid MG considering PEMFC and EVs.	Raise the efficiency of data and energy transfers' safety.	PEMFC.	Here, the estimates for WT and PV effectiveness are disregarded.	Total generation is 336 KW.	PEM.	WT and PV efficiency were discussed.	27
28	Iterative FMM of HFC by the EKF.	Design an efficient fuel cell control system.	HFC.	EKF is not an optimal estimator.	The mean absolute error through the Kalman filter is 0.345.	EKF, Takagi-Sugeno type fuzzy model, and FMM.	AI-based method.	3
29	Smart FC/BHEVs with combined motion and drivetrain MPC.	Application of the hierarchy control strategy.	FC, and HEVs.	The environmental factor is missing.	OPT can generally be solved within 20ms.	MPC.	Take into account external elements like road gradients and traffic movement.	5
30	Regarding FCHEVs trucks, joint component sizing, and EMS.	The EM's power rating has significantly decreased.	FCHEVs.	Sophisticated.	The three energy buffers' recovered energy varies between 73 and 78 percent.	SCP.	Particle swarm OPT.	3
31	A creative layout for a household CCHP network in the UK.	Whenever this technology is marketed to several households, the investment cost can be reduced.	MSOFC.	Longer start-up time.	On the coldest and warmest days, the system's effectiveness is 90.96 percent and 87.71 percent, respectively.	Method using entropy weighting and grey relationships.	The increase in power quality should be further planned.	3
32	Robust HLEF for a parallel four-phase FC boost converter utilized in DC MG usage.	Equalize the inductor current.	FC.	-	Stabilize the DC bus voltage.	HLEF.	Featuring multiphase interleaved buck converters and an electrolyzer in the DC MG.	3
33	OPT of local FC-based CHP power dispatching via LS.	OPT places the cost of electricity for both buying and selling energy.	FC.	RT analysis is missing.	CT is 240 sec at cloudy while 413 sec at sunny.	MINLP.	Predictions of solar energy production and hot water usage profiles that are accurate and current.	2
34	Oil-free centrifugal air compressor layout and essential TECH for HFC.	Create a centrifugal air compressor with the least potential power usage.	HFC.	Expensive.	The same law holds for the results of 60 kr/min, 70 kr/min, and 80 kr/min, demonstrating practicality.	Gray Wolf OPT.	Whale OPT method.	1
35	MOMPC EMS for FCHEVs.	Saving money and extending battery life.	FCHEVs.	Less accurate.	Expenses are decreased by 2.75 percent and hydrogen usage is decreased by 2.83 percent.	MOMPC, and FLA.	OPT solution for the MOMPC of FCHEVs.	4
36	A nonlinear observer-oriented FOPID management of the FC ventilation system with uncertain input.	Good convergence property.	PEMFC.	Expensive catalyst.	The MIN steady-state inaccuracy for FOPID is 131 Pa.	FOPID.	GA.	.
37	EMS of FCHEVs based on POMDP.	Achieve high performance.	FCHEVs.	Less accurate.	Reduce CT by 37%.	POMPD, and MPC.	Improvement of the current EMS.	9
38	A standalone DC converter with a broad operating range for FCEVs	Overall efficiency enhancement.	FCEVs.	Expensive.	Whenever the input current is greater than 7 A, the single Ultra-Iso-Boost converter's total effect is greater than 94 percent under various circumstances.	Semi-dual active bridge, and triangular current control.	Buck-boost converter.	9

### 3.2. Market Scenario of Fuel Cell Technology

- The primary factor expected to drive the global fuel cell business is the growing usage of renewable energy alternatives like fuel cells to reduce emissions of GHGs in the atmosphere.
- The business for hydrogen fuel cell vehicles in India is predicted to generate \$820.12 million in revenue in 2022 and \$1340.14 million by 2027, rising at a CAGR of 10.32 percent.
- To reduce its reliance on imported energy and transition the business away from fossil fuels in terms of meeting climate goals, the Indian government is proposing a significant increase in the generation of green hydrogen.
- According to those familiar with the plans, New Delhi wants to reach a 25 million tonne production capacity annually by 2047, according to Bloomberg.
- Asia Pacific, North America, Europe, the Middle East, and Africa, as well as Latin America, have all been designated as different areas within the market. **Figure 5** depicts how the Asia-Pacific region currently controls the world economy.
- The worldwide fuel cell market was valued at US \$4.29 billion in 2022. From 2023 to 2028, the business is expected to increase at a cumulative yearly development (CAGR) of 24.89 percent, IMARC Group predicts, hitting US\$ 16.499 billion.
- From USD 2.89 billion in 2022 to USD 9.05 billion in 2027, the worldwide FC market is anticipated to expand at a yearly expansion rate (CAGR) of 26.0 percent. The increased need for energy production with minimal or no pollutants is one of the primary factors driving business expansion.
- Some of the firms in the global fuel cell industry include Ballard Energy Systems Inc., Bloom Energy Corporate entity, Toshiba Fuel Cell Power System design Company, Fuel Cell Energy Inc., Plug Power Inc., Nuvera Fuel Cells Inc., AFC Energy plc., SFC Energy AG., Panasonic Company., Smart Energy Limited., and Doosan Fuel Cell America Inc.



**Fig. 3:** Size of the global fuel cell market from 2020 to 2030 (in USD)



**Fig. 4:** Share of the market by type of fuel cell in 2022.



**Fig. 5:** World region shares in the total fuel cell market in 2022.

**Figure 3**, discusses the magnitude of the worldwide fuel cell market, while **Figure 4**, discusses the various fuel cell contributions.

#### 4. CONCLUSION AND FUTURE SCOPE

Fuel cells may end up being the most efficient alternative for internal combustion engines and furnaces, enabling carbon-free green affluence and perhaps even a green economic uprising. This article addresses fuel cells, including the mathematical modeling of PEMFC, comparisons of different fuel cell types, recent trends, and the present market environment for fuel cell technology around the globe. A review of 38 research articles is also covered in this article. The conclusion of the research from the preceding discussion is stated below:

- The most effective type of fuel cell is the AFC.
- PEMFC dominates the market in terms of global share.
- Studies have recently shifted from PEMFC to SOFC and are currently progressing toward hydrogen fuel cells.
- Highest total efficiency is seen in SOFC.
- In the worldwide fuel cell market, North America holds the highest share.
- Among all fuel cell kinds, hydrogen fuel cell technology is the one with the greatest growth.

Designers work to hasten the design, manufacture, and marketing of hydrogen fuel cell technologies because they can be fundamental to the future of transportation infrastructure.

In the fight for diverse applications of fuel cell UAVs and taking into consideration each difficult work related to the design of fuel cell electric drivetrain technology, several significant problems and possible possibilities are also enumerated as follows.

- To reduce the total take-off mass of fuel cell unmanned aircraft by providing a high-power density, high-reliability converter.
- To reach internationally best outcomes, complex online EMSs for fuel cell UAVs are being developed while considering various uses into consideration.
- To provide more powerful computation platforms or more effective algorithm designs to enable the real-time implementation of sophisticated EMS techniques.
- Future discussions about FC with EVs will involve hardware experiments.
- Future FC and DG interactions have been discussed.
- Opportunities for FC business in the context of the power sector.
- The most practical approach to handling power and environmental challenges will be developed by cooperation between FC, DGs, and EVs.

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