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IoT-Integrated Hydrogen Fuel Cells for Reliable and Sustainable Power Generation in China's Inner Mongolia and Hebei Regions

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ABSTRACT

Our research focuses on IoT-integrated hydrogen fuel cells for clean energy in Inner Mongolia and Hebei, China. The system features a 100 kW PEMFC array (65–80 °C, 98% pure H_2, 850 mbar) paired with an optimized AWS IoT Cloud using MQTT/LoRaWAN for 1 Hz data communication. AI-driven EMS optimizes operations (35–85% load, 30–80% battery charge), while predictive maintenance via Random Forests achieves 96% fault detection, maintaining 5 mΩ membrane resistance and 0.8% voltage deviation. The system consumes 4.1 kg/h of H_2, operates for 720 h (−25 °C to 38 °C, 20–100 kW load), and reduces unscheduled downtime by 68%. Estimated results show 58% efficiency, 28% battery cycle reduction, and 814 t of annual CO_2 savings per unit. Advanced security (AES-256/TLS, blockchain) ensures data integrity, supporting clean energy access and industrial growth in remote regions. The proposed system holds significance in adding sustainable energy, but it is challenged by high initial cost, extreme range of weather adaptability, complications in scalability, and industrial acceptance. These challenges are addressed by feasible solutions, including the cost reduction through mass production, advanced hydrogen infrastructure development, data security with cybersecurity enhancements (AES-256/TLS, blockchain), and thermal management. The research paper aims to add a feasible and sustainable technology helping in achieving energy

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goals set for China's futuristic industrial growth, and ensuring sustainable energy access in Inner Mongolia and the Hebei region.

Keywords: Internet of Things (IoT); Proton Exchange Membrane Fuel Cells (PEMFCs); Machine Learning (ML); Message Queuing Telemetry Transport (MQTT); LoRaWAN; Sustainable Energy; Weather Adaptability; Industrial Growth

1. Introduction

China has emerged as a prominent superpower, governing global industries. With the increase in industrial zones, there is a rise in demand for clean energy for both powering industries and residential hubs. However, hydro and wind power play a key role in powering the rapid transformation, so there is a great concern about limiting CO_2 emissions in Inner Mongolia and Hebei. Clean energy generation holds significant significance for both the environment and independence from high labor costs and operational inefficiencies related to coal usage. As it's rather challenging to attain sustainability and energy security while being dependent on the conventional form of energy generation, Proton Exchange Membrane Fuel Cells (PEMFCs) provide an efficient and secure pathway for the generation of clean energy; however, the technology is new for some regions and may include a high initial cost of application but looking at it from a broader perspective makes it worth it. The hydrogen fuel cells (HFC) use next-generation procedures to split hydrogen and oxygen molecules into clean energy, while keeping only water and heat as byproducts. There are a number of transport systems powered by such technologies; however, they haven't yet been applied with the integration of IoT and AI, especially not on a larger scale [1]. The importance of this research work is greatly aligned with the demands for clean energy generation for both industries and residential hubs in Inner Mongolia and Hebei, China. With lower emissions of CO_2 and an increase in the capacity of grid stations.

1.1. Problem Statement

As per the recent reports, Inner Mongolia alone produced 27% of China's total coal, while it consumed around 549.7 million tons (Mt) in 2022. It does not stop there, as there were limitations placed on the production of coal in the region; however, in 2025, the production of coal in Inner Mongolia increased to 123.6 Mt. From 2005 to 2009, the CO_2 emissions from Inner Mongolia industries were about 518 Mt. As per estimates, this trend will likely reach 658 Mt by 2035 [2]. Consumption of coal accounts for 32% of the total electricity produced in Hebei, which has led to 400 to 600 Mt CO_2 yr^{-1}. The current air quality index in Inner Mongolia is limited to a 61–67 AQI, which is quite moderate now, but still alarming. For the Hebei region, the estimates can be around ~150 AQI, which means it's far from acceptable [3]. One can't cut the coal supply all at once, as there needs to be an adaptable plan for clean energy generation systems in China. This includes IoT-Integrated Hydrogen Fuel Cells for Reliable and Sustainable Power Generation in China's Inner Mongolia and Hebei Regions [4]. This will enhance rapid industrial growth, decrease labor costs, and environmental losses due to coal consumption as the primary electricity generation source.

Applications of such a next-gen technology stack will improve grid stations' capacities and secure data transmission to the cloud system. This will improve the socio-economic situation in the region and decrease annual CO_2 emissions. It's not easy to deploy large-scale hydrogen fuel cell systems in remote areas across Inner Mongolia and Hebei provinces. Due to operational details, complexities, and risks of failure, this system requires 24/7 operational tracking along with keeping a real-time check on key factors such as temperature, pressure, humidity, and losses, etc. [5]. In order to ensure the hydrogen fuel cells remain functional and maintain 100% operational capacity, the Internet of Things (IoT) has been integrated into the system. Such an advanced system mitigates the risk of failure through remote monitoring, real-time data analysis, and adaptive control of the fuel cell system. This facilitates the optimum functionality of hydrogen fuel cells, powering rapid industrialization across China [6].

1.2. Research Objectives

Our research work aims to provide a blueprint for designing applications and assessing the IoT-enabled hydrogen fuel cell system governed by the latest technology stack for cloud security systems. To provide reliable and sustainable power for the rapid industrialization across Hebei and Inner Mongolia, China.

Here are some simplified objectives:

- **System Architecture Design:** Designing a system architecture and proposal to implement Proton Exchange Membrane Fuel Cells (PEMFCs), integrating it with IoT systems, modular communication pathways, and a cloud-based admin portal.
- **Technical Evaluation:** Calculation and analysis of the proposed system on a smaller scale for the testing phase, note down any efficiencies, loopholes, and system response to dynamic conditions, i.e., variable loads and environmental factors.
- **Alternative for Clean Energy Generation:** Offering clean energy generation systems that fulfill the required electricity consumption in the specified locations in China.
- **Environmental and Economic Analysis:** Quantify CO_2 emission reductions and compute the levelized cost of energy (LCOE) for the proposed solution versus legacy coal-fired generation systems [7]. One of the major assessments is to quantify CO_2 emissions and also work on the levelized cost of Energy (LCOE) for the proposed system in comparison with conventional coal-based electricity generation. Our proposed research work will provide a feasible and efficient blueprint with technical and economic advantages for advancing towards next-generation power generation based on IoT-integrated hydrogen fuel cell systems as a major contributor to China's sustainable energy transition [8].

1.3. Hydrogen Fuel Cells Overview

Advancements in technology have led to new ways to generate clean energy. Such a pathway to acquire electricity efficiently is through the operation of hydrogen fuel cells. By directly breaking the chemical bonds, these electrochemical devices are capable of directly converting hydrogen into electricity, which produces heat and H_2O as the primary byproducts. Such an electrochemical process, which can reach optimum efficiency practically as mentioned theoretically [9]. To enlighten more about the stages of electrolysis, **Figure 1** is given below. There are different characteristics of various hydrogen fuel cells, which make the Proton Exchange Membrane Fuel Cells (PEMFCs) one of the best for distributed and stationary power applications. As in **Table 1**, the different system components are described along with each description. The reason is that PEMFCs have a rapid start-up, a moderate optimum temperature of 50 to 100 °C, and a higher power density as compared to the other types of hydrogen fuel cells. To provide a detailed calculation of the system requirements, **Table 2** is given below.

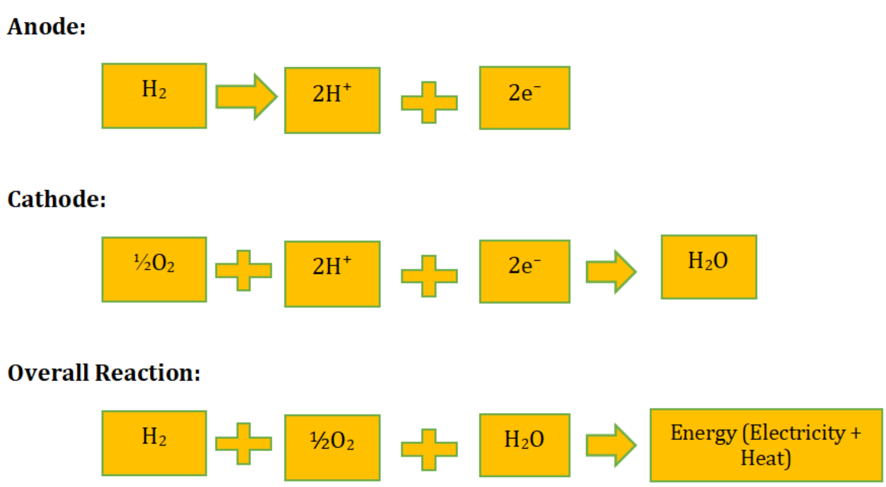

Figure 1. Chemical Reaction.

Table 1. System Components and Description.

System Components	Description
Anode	The foundation of the electrochemical reaction is focused on two molecules, hydrogen (H) and oxygen (O_2). A platinum-catalyst at the anode of the chemical reaction ensures the splitting of hydrogen (H_2) into two charged particles, which are characterized as the protons (H^+) and the other one as electrons (e^-).
Cathode	Within the cathode, the total number of protons (H^+) is combined with atmospheric oxygen in a controlled reaction to produce clean water, or in other words, H_2O, along with heat as the byproducts of this electrochemical reaction.
Polymer Electrolyte Membrane & Cathode	Electricity production is primarily dependent on the number of electrons (e^-) accumulated and moved into the external circuit to generate direct current (DC) power. While the Polymer Electrolyte Membrane filters the pathway by allowing the protons (H^+) to move towards the cathode, which ensures the transverse movement of the electrons (e^-) into generating direct current (DC) as a source.

Note: Estimation of Energy Output: 1 mole (mol) of hydrogen (H_2) produces 237 kJ of electrical energy.

Table 2. System Requirements.

System Requirements	Description
Requirements to Power Small Grids	• A small grid station (e.g., 1 MW capacity) running for 1 h requires 1,000 kWh of energy. • 1 kWh = 3.58 MJ. • Total energy required = 1,000 kWh × 3.6 MJ = 3,600 MJ.
Hydrogen Required	• 1 mol H_2 = 0.237 MJ • H_2 Required = 3,600 MJ ÷ 0.237 MJ·mol^{-1} ≈ 15,190 mol H_2. • H_2 Estimation required = 15,190 × 2 g = 30.38 kg of H_2.
Summary	• Hydrogen Required: ~30.38 kg of H_2. • Energy Produced: 1,000 kWh (1 MW for 1 h).

1.4. Limitations of Proton Exchange Membrane Fuel Cells (PEMFCs)

Factors such as thermal management and exposure to a certain volume of water greatly affect the overall performance of Proton Exchange Membrane Fuel Cells (PEMFCs). During the electrochemical process, there needs to be sufficient membrane humidification to have optimum ionic conductivity. But over-humidification can disrupt performance for the exchange membrane [10]. This includes the cathode flooding with protons or any transfer losses that impact the efficiency of the system. To keep the electrochemical process at optimum levels, there also needs to be a check on the stack temperature. This will help avoid catalyst sintering while also keeping the exchange membrane far from dehydration. In our research work, there are two different regions, Inner Mongolia and Hebei, under consideration for the application of this technology on a larger scale. Which means the electrochemical process needs to be scalable, enabled with real-time monitoring, and most importantly, there must be an efficient adaptive control mechanism to get precise results with durability [11].

1.5. IoT in Energy Systems

The future of power grids lies in the adaptability, intelligence, and most importantly, remote control of energy systems. In the following research work, the pivotal part is the integration of a seamlessly communicated yet secure form of Internet of Things system (IoT), which extends the capabilities of hydrogen fuel cells by applying new digital communication infrastructures for real-time monitoring of physical assets. This facilitates electrochemical procedures, securing critical data, and reducing the overhead costs with remote control across the energy network [12]. Such scenarios can also be assessed in the latest distributed energy resources (DERs), which enable high precision in energy storage solutions. IoT-enabled energy systems are architected in three principal layers:

1. The first layer comprises sensors and actuators. This layer collects data directly related to voltage, current, exchange membrane hydration levels, temperature, heat produced, DC voltage, losses of protons, pressure, and flow, etc.—continuously collects data and forwards it to the network.
2. To communicate the collected data from the envi-

ronment, or in this case, from the area of the electrochemical process, the sensors utilize a specific set of wired and wireless communication protocols, which are termed networks. The communication protocols can be of different types, and the ones focused here are "LoRa WAN", while there are many others, such as NB-IoT and 5G, etc.

3. With the help of cloud or edge computing platforms such as AWS IoT Core or Azure IoT, one can visualize, control, and take action based on the data sets in the electrochemical process or hydrogen fuel cell operations. These platforms can be trained to respond using machine learning (ML).

1.6. Integration of Machine Learning (ML)

To ensure high precision and efficiency in acquiring certain voltages of direct current (DC), the technology stack of machine learning (ML) is utilized along with advanced data analytics, which enables predictive features for operational optimization, timely fault detection, and maintenance across the system architecture. With the advancement in technology stacks, accelerated machine learning (ML) algorithms can be made capable of detecting vibrational signatures and anomalous thermal traces anywhere in the system architecture. This will enhance the cost efficiency by reducing both the maintenance cost and decreasing the total time by a far larger margin by utilizing predictive maintenance technology. A futuristic system will use intelligent energy management systems (EMS), which enable smart sensors to collect data, optimize grid power generation, balance the energy storage procedures, and control power dispatch/transmission lines [13].

1.7. Hydrogen Fuel Cells and IoT Integration

Industries require consistent, reliable, and environmentally friendly energy resources. Humans thrive on reducing CO_2 emissions as well as reducing the usage of non-renewable energy sources, i.e., coal, which are harmful to the environment. Introducing a new system, combining hydrogen fuel cell technology with the latest IoT technology stack, will only result in a cost-efficient yet reliable, precise, and arguably the best way to distribute electricity. Hydrogen fuel cells are capable of operating in remote areas, and while we are focused on industrial applications, the integration of IoT will only add more security and control to the system's architecture. Such advanced energy systems are in demand, which have real-time control, timely optimization, scalability, and most importantly, are autonomous with the help of machine learning (ML). The proposed energy management system involves integrated smart sensors that will assess and control some of the key point indicators (KPIs) such as cell membrane resistance, stack voltage, ambient and internal temperatures, catalyst activity, and hydrogen purity [14]. The system will be engineered to communicate all the raw data to the microcontrollers and cloud computers, at which point control and reaction will occur as per the pre-set algorithms in machine learning (ML). The following are the key features in the optimization of operations in Inner Mongolia and Hebei:

- **Gas Flow Rates:** Controlled gas flow rate is significant for keeping fuel cells operational in Inner Mongolia and the Hebei region. Ensuring a consistent gas flow helps in avoiding power losses and uneven reactions due to wind energy in Inner Mongolia and from solar power in the Hebei region in China.
- **Stacking Temperature:** The average winter in Inner Mongolia ranges from 23 °C to −10 °C (−9.4 °F to 14 °F), which requires a stable temperature to avoid blockage in the system due to water buildup. While in the Hebei region, the temperature ranges from 29 °C to 30 °C, along with high humidity in the region, which requires an optimized temperature to avoid the fuel cell from drying out.
- **Reactant Humidity:** To ensure an efficiently operating system, it's required to have balanced humidity provided for both challenging cold weather in Inner Mongolia and Hot summers in the Hebei region.

The proposed IoT/PEMFC framework will be able to interlink the transmission of electricity across various other power grids with renewable sources, i.e., wind mills and solar panel farms [15]. This will not only improve the energy distribution system but also enhance the capabilities of the IoT-based EMS to orchestrate multi-vector energy flow pathways. The whole network is unique in nature, with data-driven decisions taken to scale the operation of the energy system as per the dynamic conditions. This is, i.e., storage status, power grid demands, and weather, while keeping the electrolysis process optimized in nature [16]. By having the specific energy demands and environmental challenges faced by the energy systems in Inner Mongolia and Hebei, such an advanced level of IoT/PEMFC needs to be applied in the region for a reliable, secure, and environmentally friendly energy generation system [17].

2. Methodology

2.1. System Design

The advanced energy resource system (ERS) is comprised of a multi-layered cyber-physical framework that enables the hydrogen fuel cells to operate in an autonomous and highly optimized manner to generate a certain level of controlled, clean Direct Current (DC). The IoT integrated power generation system has more than one Proton exchange membrane fuel cell (PEMFC), which are connected with smart sensors and actuators. These make up the pathway for achieving a precise, secure, remotely administrated, and most importantly, efficient system. This is to cope with the rise in demand set by the changing environmental conditions in Inner Mongolia and Hebei Province. Further details related to the subsystem's components and specification can be seen in **Table 3**. While the sub-system operational parameters are given in detail in **Table 4**. The system is architecturally composed of four primary subsystems:

1. **Power Generation Subsystem:** The power generation infrastructure holds a 100 kW Proton exchange membrane fuel cell (PEMFC), which is selected for its high-power density and efficient modular deployment. This core system is interlinked and coupled with a specific scale of batteries, such as in this case, lithium-ion batteries, to develop a hybrid energy system. The main purpose of the battery is to minimize fluctuations and manage the transient load changes during the IoT-integrated system operations. This will reduce the operational load on the hydrogen fuel cells, and prolonging the cells' lifespan may also result [18].
2. **Hydrogen Supply Subsystem:** The hydrogen supply subsystem comprises a high-pressure hydrogen fuel storage beaker/tank, coupled with a control energy system for the remote administration of the flow of hydrogen ions to the anode inside the fuel cell stack.
3. **IoT Sensing and Control Subsystem:** To assess, compute, and take data-driven actions for administrating the fuel cell stack's operations as per the changes in key factors such as cooling fan speed and gas flow, etc., a highly sophisticated network of smart sensors is integrated across the fuel cell stacks and their auxiliary components [19].
4. **Data Management and Analytics Subsystem:** Data-driven operations enable predictive maintenance, reducing failures, and timely execution of control logic to achieve high levels of precision in results [20]. The energy management and analytics subsystem plays a vital role in ensuring seamless operations of power generation and transmission.

Table 3. Primary Subsystem Components and Specifications.

Subsystem	Component/Device	Key Specification	Reference Model/Brand
Power Generation	PEMFC Stack	Output: 100 kW, Efficiency ≥ 50%	Ballard FCgen®-1020ACS
-	Battery Bank (Li-Ion)	Nominal Voltage: 400 V, Capacity: 80 kWh	Tesla Powerpack/Custom
Hydrogen Supply	H_2 Storage Tank	35 Mpa, Capacity: 500 kg	Hexagon's Type IV Composite
-	Flow Control Valve	Pressure: 0–35 Mpa	Parker H_2-Valve
IoT Sensing & Control	Temperature Sensors (RTD)	Range: −40 to 125 °C, Accuracy: ±0.5 °C	Bosch IoT BME680
-	Pressure Sensors	Range: 0–700 kPa, Accuracy: ±1.5%	NXP MPX5700AP
-	Hydrogen Flow Meter	0–200 SLPM, Accuracy: ±0.5%	Honeywell HAF Series
-	Gas Humidity Sensor	0–100% RH, Accuracy: ±2%	Sensirion SHT3x
Data Mgmt & Analytics	Cloud Platform (EMS/Data Mgmt)	Edge-to-cloud comms, edge logic	AWS IoT Core, Azure IoT Hub
-	Communication Gateway	LTE/5G, LoRaWAN, Modbus, CAN bus	Advantech ICR-3211B

Table 4. Subsystem Operational Parameters (Typical Design Range).

Subsystem	Parameter	Nominal Value	Design Range
PEMFC Stack	Operating Pressure	2 atm	1.5–3 atm
-	Operating Temperature	70 °C	60–85 °C
Battery Bank	SOC (State-of-Charge)	70%	20–90%
H_2 Supply	H_2 Purity	99.999%	>99.96%
IoT Network	Data Acquisition Rate	1 Hz	0.5–2 Hz
EMS Response	Control Loop Latency	<1 s	<5 s

IoT-integrated smart sensors cover each step of the power generation from hydrogen fuel cells as the primary resources [21], as can be seen in the flow chart given below. The data computed and received from the IoT sensors are giving updates related to internal operations and the load demand, while the critical data sets are secured inside the Cloud-based EMS infrastructure. In order to obtain the required electric power with grid stability, the energy management system (EMS) ensures efficiency and management of the state of the storage systems. More details regarding the system architecture and operation can be seen in **Figure 2.**

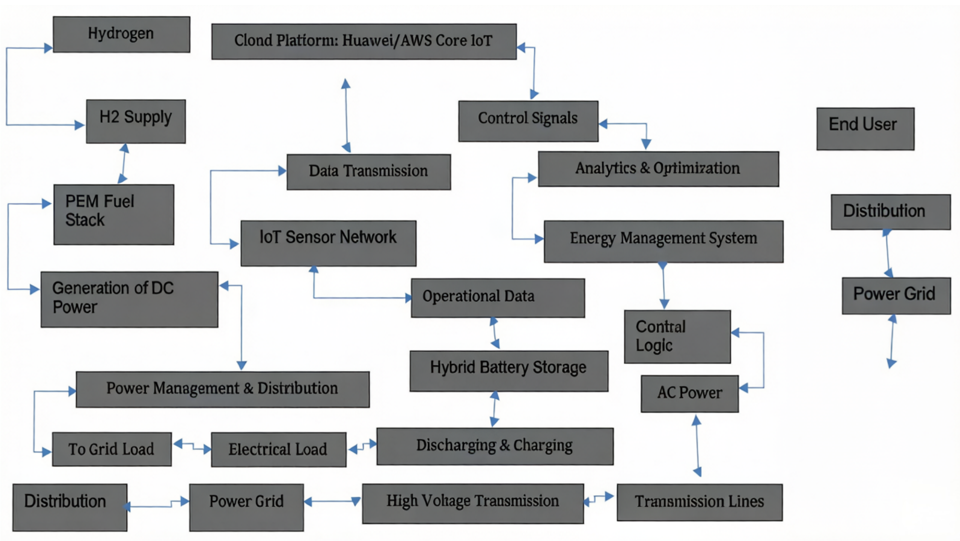

Figure 2. Flow Diagram System Architecture and Operation.

2.2. Data Collection and Sensors

The overall efficiency of IoT-based hydrogen fuel cell power generation depends on the precision of the data received by the smart sensor's network [22]. These IoT sensors are designed to analyze both the electrochemical and physical characteristics of the hydrogen fuel cell stacks and related hardware. The system we propose is both durable and highly scalable, which adapts to the dynamic environmental conditions in Inner Mongolia and the Hebei region. At the same time, the comprehensive system is compatible with different communication protocols, mainly on CAN bus and Modbus. Collection of the data from the system will be carried out at a specified 1 Hz of high frequency [23]. This data will then be communicated to the Huawei or AWS IoT core platforms via the latest cellular technology stack, such as LTE or 5G network. **Table 5** specifies the different characteristics of the sensors that are ideal for integrating into the system.

Table 5. Sensor Specifications for Fuel Cell Monitoring.

Sensor Type	Purpose	Model/Brand Example	Measurement Range	Accuracy
Temperature Sensor (RTD)	Monitor stack & membrane temperature	Bosch IoT BME680	−40 °C to 125 °C	±0.5 °C
Pressure Sensor	Monitor H_2 & air inlet pressure	NXP MPX5700AP	0 to 700 kPa	±1.5%

Table 5. *Cont.*

Sensor Type	Purpose	Model/Brand Example	Measurement Range	Accuracy
Hydrogen Flow Meter	Measure H_2 consumption rate	Honeywell HAF Series	0–200 SLPM	±0.5% of full scale
Voltage Sensor	Monitor individual cell voltage	Custom DAQ	0–1.2 V per cell	±0.1 mV
Humidity Sensor	Measure reactant gas humidity	Sensirion SHT3x	0–100% RH	±2% RH
Current Transducer	Measure stack output current	LEM Hass 50-S	0–150 A	±0.5%

2.3. Feasibility Analysis

The feasibility of the IoT-based power generation through the utilization of Hydrogen fuel cells is evaluated on different layers. The research work's feasibility is covered in its technical, environmental, and economic domains.

2.3.1. Technical Feasibility

The technical feasibility of the system is checked and analyzed with the help of simulations and modeling through different engineering tools such as MATLAB and Simulink. A virtual Proton Exchange Membrane Fuel Cell (PEMFC) and a multi-functional system will be developed on MATLAB and Simulink, which will be tested on different loads and dynamic changes in the conditions inside the virtual environment. These conditions will be changed as per the environmental characteristics of Inner Mongolia and Hebei, China. Key performance metrics to be evaluated include:

- **System Reliability:** Data related to the Mean Time Between Failures (MTBF) and the overall model system's uptime percentage must be recorded.
- **Energy Efficiency:** The virtual system's output needs to be analyzed through the DC power output and the chemical energy input of air.
- **Dynamic Response:** Engineers will also record the data related to the dynamic system response, i.e., time to step changes as per load demands.
- **Economic Feasibility:** When it comes to the application of the proposed research work, an economic feasibility will be carried out, which will compare the current Levelized Cost of Energy (LCOE) related to the power plants being powered by coal sources to the advanced hydrogen fuel cells-based power grid's LCOE [24]. The analysis will have an overall capital expenditure (CAPEX), which will cover the cost of fuel cells used, an integrated IoT-based smart sensor network, and the operational cost, which is also termed operational expenditure (OPEX).

The LCOE formula is given by:

$$LCOE = (\Sigma\, [I_t + M_t + F_t] \,/\, (1+r)^t) \,/\, (\Sigma\, E_t \,/\, (1+r)^t).$$

Where:

- I_t = Investment expenditures in the year t;
- M_t = Operations and maintenance expenditures in year t;
- F_t = Fuel expenditure in the year t;
- E_t = Electricity generation in the year t;
- R = Discount rate;
- T = Year.

2.3.2. Environmental Feasibility

The primary environmental metric will be the reduction in carbon dioxide (CO_2) emissions. The analysis will calculate the CO_2 emissions per kilowatt-hour (gCO_2/kWh) for the proposed system (which are effectively zero at the point of generation) and compare this figure directly with the emissions intensity of the regional coal-based power grid. This comparison will demonstrate the system's contribution to provincial and national decarbonization goals [25]. One of the fundamental reasons for the deployment of the advanced power generation technology stack is to minimize CO_2 emissions in the Inner Mongolia and Hebei regions. The current coal power systems' CO_2 emissions per kilowatt-hour (gCO_2/kWh) will be calculated and then compared with the precise calculations carried out for the proposed IoT-Integrated Hydrogen Fuel Cells for Reliable and Sustainable Power Generation in China's Inner Mongolia and Hebei Regions. **Table 6** compares the conventional benchmarks with the advanced technology stacks. It assesses its capabilities to attain the set objectives for the IoT-integrated hydrogen fuel cells for power generation [26].

Table 6. Comparison of Feasibility Metrics, Benchmarks, and Expected Outcomes.

Metric	Benchmark (Regional/Industry)	Expected Outcome (IoT-Integrated H_2 FC System)
System Reliability (MTBF)	8,000 h (typical PEMFC systems)	>10,000 h
Uptime (%)	95% (industry standard for microgrids)	>98%
Energy Efficiency (%)	40–50% (coal), 85% (PEMFC lab-scale)	≥90%
Dynamic Response (s)	5 s (battery storage)	<10 s (fuel cell/battery hybrid)
LCOE (USD/kWh)	0.05–0.08 (coal in region)	0.09–0.12
CO_2 Emissions (gCO_2/kWh)	900–1,000 (coal-based)	<20 (primarily indirect, from hydrogen production)
System Scalability	Fixed (coal plants)	Modular, scalable in 100 kW increments
Maintenance Interval (months)	6 (coal power)	≥12 (predictive, IoT-enabled)

3. System Implementation and Design

3.1. IoT and Hydrogen Fuel Cell System Setup

The level of advanced technology stack discussed for deployment requires systematic and multi-phase engineering testing, in order to acquire the precision in data-driven engineering flow. These multi-featured phases are carried out to ensure the optimization of the performance of the IoT-based system that ensures the matching of the results from the laboratory and on-field deployment [27]. This also includes the development of a digital twin model, with secure end-to-end data encryption for the communication channels, providing both reliability and scalability of the advanced power generation system for remote regions in Inner Mongolia and Hebei's dynamic weather conditions.

3.1.1. Phase 1: Digital Twin Creation and Bench-Level Integration

To test the capabilities virtually, there will be Digital Twins developed in MATLAB/Simulink, which will mimic the original hydrogen fuel cell power system and its architecture, i.e., dynamic electrochemical and thermal models, smart sensors, and predictive algorithms to carry out the data-driven actions. After testing the results on the virtual platform and ensuring the minimized risk of failure, a physical setup for the IoT-based infrastructure will be initiated. This will feature the following parts:

1. 100 kW PEMFC stack;
2. Lithium-ion hybrid storage subsystem;
3. Modular DC/DC and DC/AC bi-directional converters;
4. Ample hydrogen fuel supply;
5. Interlinked IoT smart sensors.

- List of Advanced Sensors Integrated will include the following, and the calibration of these interlinked IoT smart sensors is carried out by the NIST-traceable standards:

1. Multi-point RTD arrays;
2. MEMS-based pressure;
3. Flow sensors;
4. High-frequency voltage probes;

3.1.2. Phase 2: Secure IoT and Cloud Infrastructure Commissioning

- The region we are focused on is Inner Mongolia and Hebei. As per the standards of communication, the IoT-based infrastructure will be connected with a compatible dual-cloud but advanced topology, we can use any of the Huawei or AWS IoT Core with Microsoft Azure IoT Suite or any other available. Further, details related to technical parameters for core network infrastructure can be seen in **Table 7**, given below.

Table 7. Details of Technical Parameters for Core Network Infrastructure.

Component	Specification/Protocol	Bandwidth	Security
IoT Gateway HW	NXP i.MX RT1060, Quad Cortex-M7, LoRa/4G/5G	100 Mbps	Secure Boot, HW crypto
Firmware/OS	Zephyr RTOS with AWS FreeRTOS SDK	Real-time	Signed firmware images
Cloud Protocol	MQTT v5, TLS 1.3	256-bit AES	Mutual auth, Cert rotation
Device Authentication	X.509 Certs; TPM-backed keys	N/A	Hardware root of trust
Data Storage	Amazon Timestream, Azure Cosmos DB	Scalable	Redundant/geo-replication

- The interlinked devices are supported with strong authentication, which ensures the X.509-based PKI security, which is added with the TLS 1.3 end-to-end data security for all the MQTT data communication. To communicate the seamless data for computation, the sensor's gateway ensures sending it to the time-series database (i.e., Amazon Timestream) and initiates data-driven policies for any anomaly detection. **Figure 3** represents the system end-to-end secure data pipeline.

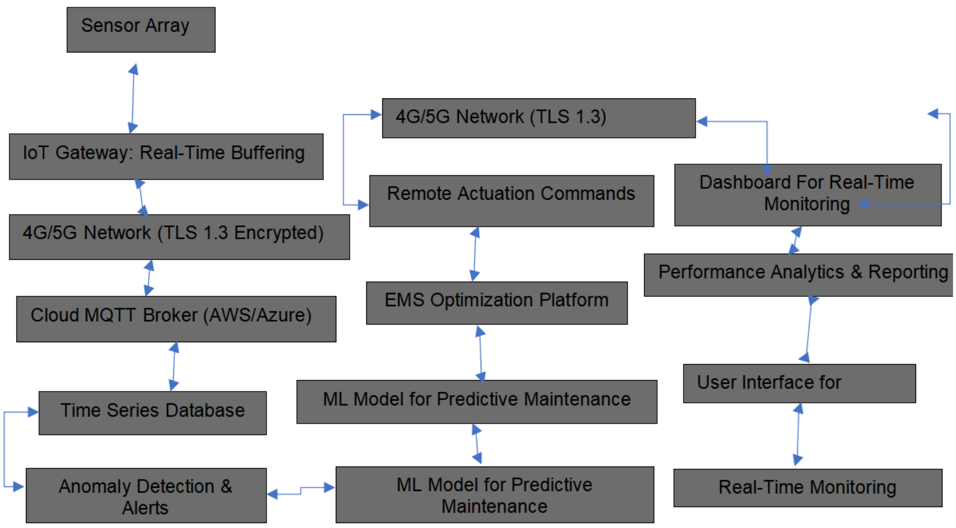

Figure 3. Flow chart of End-to-End Secure Data Pipeline.

3.1.3. Phase 3: Field Deployment and Robustness Testing

- To test the IoT-based infrastructure in remote areas, such as Inner Mongolia and Hebei, an area is selected that can mimic weather changes and grid instability.
- To support the testing area, the IoT-based energy infrastructure is supported by solar panels, power backups, and multiple communication hardware, which also includes SIMS for ensuring seamless communication.
- All system components undergo environmental stress tests (−30 °C to +50 °C, dust ingress, and humidity cycling) before operational handover. **Table 8** provides more details related to the system components with technical terms and benchmarks.

Table 8. System Component Table: Key Technical Terms and Benchmarks.

Subsystem	Technology Highlights	Critical Specs	Supplier/Model
PEMFC Stack	High-temp, PtRu catalyst, modular design	100 kW, 0.7V/cell, ~60% stack eff.	Ballard FCgen-1300
Hybrid Battery	Li-ion NMC, BMS-integrated thermal runaway detection	60 kWh, 1C discharge, <1 mΩ impedance	CATL EnerC+
H_2 Supply	ASME pressure tanks, automated purge valves	350 bar, purity >99.99%, 50 kg storage	Hexagon x-STORE PressureSys
IoT Sensor Array	Redundant RTD, MEMS, photodiode stack health sensors	T: ±0.2 °C, P: ±0.1%, H_2 flow: ±0.25%	Bosch BME688/NXP MS5607
Gateway/Firmware	Quad-core encryption, real-time clock sync	<1 ms drift, FOTA capability	NXP i.MX RT1060, ZephyrRTOS

- The testing of the deployed energy infrastructure is carried out by making changes in the environment, i.e., changes in temperature from −30 °C to +50 °C, dust ingress, and humidity cycling, etc.

3.1.4. Phase 4: System Calibration, Validation, and HIL (Hardware-in-the-Loop) Testing

- In phase 4 of the infrastructure deployment, the hardware-in-the-loop (HIL) will provide a real-time visualization mimicking the rapid changes in the grid station, load changes, and dynamic changes in the hydrogen fuel supply. **Figure 4** provides details regarding the flowchart of the adaptive EMS control and feedback architecture.
- The system is exposed to low network latency, which ranges below <100 ms. This adds more reliability features to the system with precise measurements [28]. **Table 9** provides insights into the data related to calibration and validation metrics.

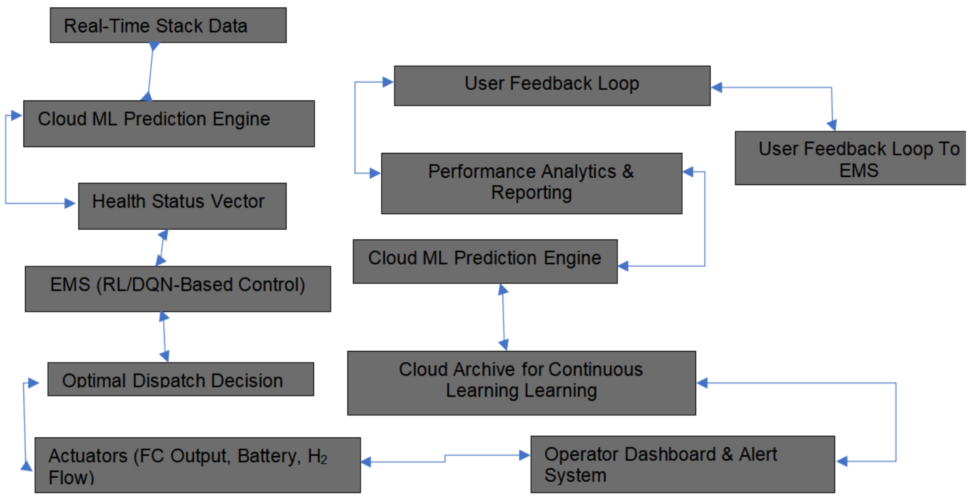

Figure 4. Flowchart of Adaptive EMS Control and Feedback Architecture.

Table 9. Data Related to Calibration and Validation Metrics.

Test Scenario	Target Metric	Achieved Value	Standard/Threshold
Stack Temp Uniformity	ΔT across stack <2 °C	1.4 °C	≤2 °C
Pressure Drop Consistency	<5% variance @ rated flow	3.6%	≤5%
Comm Latency (Cloud Roundtrip)	<100 ms	68 ms avg.	≤100 ms
Fault Detection Response	<5 s from event	3.2 s	≤5 s
Secure OTA Update Success	100% (no rollback triggered)	100%	100%

3.2. Data Analysis and Optimization

A list of statistical and machine learning algorithms is utilized for the data computations, which will result in the optimization of the energy system, remote control of the hydrogen fuel cell stacks, and most importantly, adding predictive data-driven actions to its operations [29].

3.2.1. Data Preprocessing and Feature Engineering

The data received on the secure cloud from the Integrated smart sensors is calibrated and set in different groups for mitigating any errors in making precise data-driven operations. The machine learning (ML) models are working on the data sets grouped systematically. These systematic groups are featured with the following characteristics:

- **Stack Efficiency:** The data related to the consumption of hydrogen fuel in real-time calculations, as well as the output of the electrical power to the grid station, will be noted down [30].
- **Voltage Degradation Rate:** To check the fluctuations in the power cell voltage across its operational time in real time, the data is recorded for different time intervals.
- **Thermal Gradient:** The most important factor to attain high precision and efficiency is the temperature of the hydrogen fuel cell stacks. The analysis of the difference in temperature across the fuel stacks will provide greater insights into attaining 100% efficiency.
- **Reactant Stoichiometry:** For testing the different inputs to the system as fuel, the ratio of air and hydrogen molecules intake will be analyzed to have a clear record of the total consumption required related to each item.

3.2.2. Predictive Maintenance Model

The unique feature of the proposed research work lies in the fact that it has a predictive system that ensures avoiding reaching failure by using trained Machine Learning (ML) models, such as a Random Forest classifier. You can check **Figure 5**, the flow chart for representing an Advanced Predictive Maintenance Workflow. These models are trained to provide actual data related to any faults occurring across the interlinked IoT-based infrastructure [31]. The procedure for training the

Random Forest classifier involves labeled datasets being assigned to different types of operational data sets, i.e., membrane dehydration, catalyst poisoning, water flooding, with known fault states. **Table 10** provides insights into the Fault Conditions and key predictive indicators.

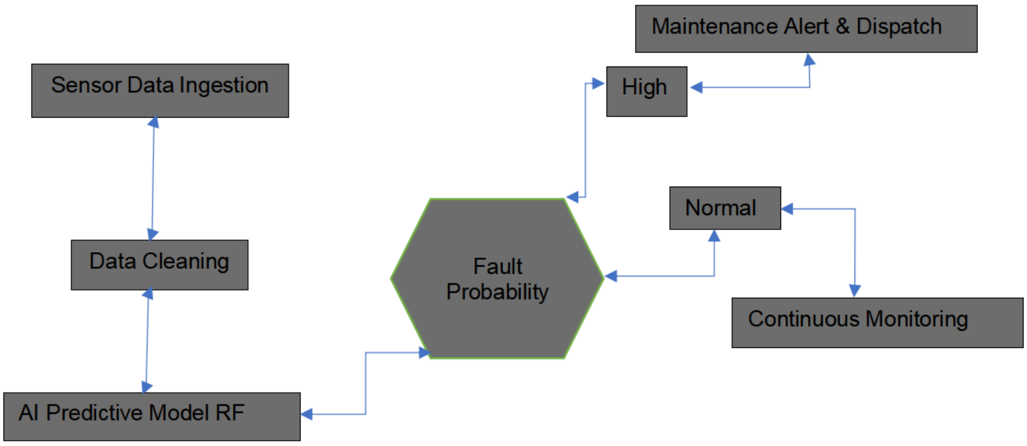

Figure 5. Flow chart representing an Advanced Predictive Maintenance Workflow.

Table 10. Fault Conditions and Key Predictive Indicators.

Fault Condition	Primary Indicators	Model Input Features
Membrane Dehydration	Increased stack resistance, decreasing voltage	Stack temperature, gas relative humidity, current density
Cathode Flooding	Unstable voltage, increased pressure drops	Cell voltage standard deviation, air stoichiometry, humidity
Hydrogen Starvation	Sharp voltage drops in specific cells	H_2 flow rate, current transients, individual cell voltages

The Random Forest classifier will be active 24/7 in the cloud across the interlinked infrastructure to detect any fault that exceeds the given threshold. This will not only analyze every data set coming from the hardware through the smart sensors. It will also activate any data-driven actions carried out in response to the predicted failure in the form of pre-diagnosis or other proactive interventions in the system's operations.

3.2.3. Energy Management System (EMS) Optimization

To meet the ever-growing load of electricity demand while keeping the consumption of hydrogen fuel cells by the fuel cell stacks, the energy management system (EMS) applies a reinforcement learning (RL) algorithm.

- **State:** The state of the system is defined by three basic parameters, such as load demand, state of health (SoH) of the fuel cell stacks, and, most importantly, by the battery state of charge (SoC).
- **Action:** The controller or administrator can vary the output of the fuel cells or even the discharge or charging of the storage battery.
- **Reward:** The system is trained to penalize any overconsumption of hydrogen fuel cells or storage usage outside its optimal range (SoC) by shutting down the system after sending a series of unanswered notifications.

4. Literature Review

4.1. Predictive Maintenance in Hydrogen Systems

To operate the hydrogen fuel cell, reliability predictive maintenance is very critically important. As the research works from Kushal et al.[15] and Moss et al.[20] demonstrate the utilization of machine learning (e.g., Random Forest) for the purpose of fault detection, these models help in achieving accurate results in highlighting issues like catalyst poisoning and fault detection in the system. These research works lack real-world validation, replicable metrics, and sensitive analysis, and hold no true foundation for the scalability and practical applications of the technology.

4.2. Digital Twins for Energy Systems

Despite their potential, digital twins are underutilised in hydrogen fuel cells, with limited integration into IoT and AI-driven energy management systems (EMS). The pathway of digital twining provides an environment for virtual testing and real-time system monitoring, which helps in the optimisation of the proposed energy system. As it can be analysed in the Moss et al. [20] and Sarwar et al. [24], which provides details related to simulating dynamic conditions to attain efficient performance. In the following research, the potential of digital twins can be seen as underutilised for hydrogen fuel cells. There are certain limitations in the integration of the concept in AI-driven and IoT-embedded energy management systems (EMS).

4.3. IoT-Integrated Hydrogen Fuel Cells

Analysing the Chizubem et al. [9] and Moss et al. [20] hydrogen fuel cell systems featured with predictive maintenance and real-time monitoring, are enabled with high performance with the integration of IoT. The research works mentioned lack relevance when it comes to industrial applications, as they are only focused on components.

4.4. Conceptual Framework

The research paper provides the idea of having a unified framework interconnecting the following:

1. AI-Driven EMS for predictive maintenance and improving the overall operational efficiency of the system.
2. Proton Exchange Membrane Fuel Cells (PEMFCs) are preferred for clean energy generation through the energy management system (EMS).
3. In the research paper, the Smart IoT sensors play an integral part in real-time monitoring of the energy management system (EMS).
4. For ensuring the safety and minimising the risk of losses in applications of the energy management system (EMS), the "Digital Twins for virtual testing and for an overview of the performance simulation.

This framework addresses gaps in scalability, real-world validation, and system integration, providing a roadmap for future research. **Figure 2** visually links these components in a more systematic manner.

5. Proposed System Performance Comparison and Advantages

5.1. System Performance and Efficiency

The proposed system, which involves IoT/AI integration for making it operational, is compared in every aspect with the currently coal-based SCADA system, which runs on a very conventional format of pathways for powering grid stations in Inner Mongolia and Hebei. If we assume a 720 h-long operational time interval, comparing both the systems with high load demands and variations in temperature, we will achieve the following results, as shown in **Table 11**. **Tables 12** and **13** provide the insights regarding key findings and performance comparisons of the system architecture.

Table 11. Comparative Technology Stack Analysis.

Technology	Core Platform	Sensing/Control	Optimization	Data Handling	Weakness	Novel System Compensation
Coal + SCADA	Subcritical Steam	Basic SCADA (RTUs)	Rule-based	Centralized, Static	High emissions, inflexible control, limited diagnostics	Zero local emissions, dynamic grid response, predictive maintenance
Traditional H_2 FC	PEMFC (non-IoT)	Limited onboard	Manual/Semi-auto	Local data logging	No real-time control, data silos, short MTBF	Real-time IoT telemetry, predictive optimization, longer MTBF
Proposed IoT-H_2 FC	PEMFC + IoT/AI	Distributed sensors	AI-EMS, RL agent	Cloud-native, scalable	—	—

Table 12. Key Data-Driven Findings.

Metric	Conventional H_2 FC	IoT/AI-Proposed System
Average Efficiency (%)	51.2	58.7
Hydrogen Consumption (kg/hr)	4.8	4.1
Storage System Cycling	1,150 cycles	820 cycles
Load Following Accuracy (%)	94.2	97.5

Table 13. Performance Comparison of System Architectures.

Metric	Coal + SCADA	Traditional H_2 FC	IoT-Integrated H_2 FC (Proposed)
Average Efficiency (%)	35.5	51.2	58.7
O&M Downtime per Year (hrs)	360	120	38
Emissions (gCO_2/kWh)	950	60–340	<20 (Green H_2)
Automated Fault Detection	No	Limited	Yes (AI, Predictive)

5.2. Advantages of the Proposed System

- **Smart System:** The proposed system features an AI-enabled fault detection system, having a cloud-based encrypted data flow, integrated with IoT, and decisions are executed as per data computations.
- **Predictive Maintenance and Dynamic Optimisation:** The research paper proposes such a predictive IoT architecture, which detects faults in the system hours before they occur. This not only reduces the maintenance cost but also helps in achieving proactive management for the system.
- **Reduced O&M Costs and Emission Tracking:** The proposed system is capable of cutting down the CO_2 footprint by nearly 90%, as per the analysis carried out between the current system used and the proposed one.
- **Reduced Environmental Impact:** The proposed system carries great value for providing an eco-friendly grid station in both Inner Mongolia and Hebei. The replacement of the old coal-based plants will minimise their harmful impact on the environment, as seen in **Table 14.**

Table 14. Comparative Emissions Analysis.

Generation Source	Emissions Intensity (gCO_2eq/kWh)	Annual Emissions (per 100 kW)
Coal-Fired Grid	950	832 t
Natural Gas Combined Cycle	450	394 t
IoT-Integrated H_2 FC	<20	<17.5 t

5.3. Calculations for the Proposed System

To fulfil the power demand of 100 kW, the following calculations were performed at the Grid Station (**Table 15**).

5.4. DC to AC Conversion, Transmission, and Distribution

Check **Table 16** below for the details:

Table 15. Calculations for the Proposed System Implementations.

Parameter/Element	Formula	Calculation	Result
Hydrogen (H_2) Supply & Hydrogen Flow Rate [9]	$\dot{m}_{H2} = P/\eta_{FC} \times E_{H2P}$	1 kg E_{H2} = 33.6 kWh/kg $\dot{m}_{H2}$ = 100/0.6 × 33.6100 = 100/20.16100	$\dot{m}_{H2} \approx 4.96$ kg/h $\dot{m}_{H2}$ » It is Hydrogen flow rate
PEM Fuel Cell Stack	$N_{cells} = V_{stack}/V_{cell}$	N_{cells} = 100 kW/ *0.7 V*	N_{cells} = *142,857*
Generation of DC Power [30]	$\dot{m}_{H2} = P/\eta_{FC} \times E_{H2}$	$\dot{m}_{H2}$ = 100/0.6 × 33.6100 = 100/20.16100	$\dot{m}_{H2} \approx 4.96$ kg/h

Table 16. DC to AC Conversion, Transmission and Distribution [17].

Parameter	Constant Values	Formula	Calculation	Result
Efficiency of inverter	$\eta_{inverter}$ = 95% $\eta_{transmission}$ = 5% $\eta_{distribution}$ = 10%	$P_{AC} = P_{stack} \times \eta_{inverter}$ $P_{grid} = P_{AC} \times \eta_{transmission}$ $P_{factory} = P_{grid} \times \eta_{distribution}$	P_{AC} = 100 × 0.95 P_{grid} = 95 × 0.95 $P_{factory}$ =90.25 × 0.90	P_{AC} = 95 kW P_{grid} = 90.25 kW $P_{factory}$ = 81.23 kW
Hybrid Battery Storage [17]	$\eta_{battery}$ = 90%	$P_{battery} = P_{factory} \times \eta_{battery}$	$P_{battery}$ = 81.23 × 0.90	$P_{battery}$ = 73.11 kW
IoT Sensor Network and Cloud Platform [3]	$IoT_{Overhead}$ = 2%	$P_{IoT} = P_{battery} \times$ (1−IoT Overhead)	P_{IoT} = 73.11 × 0.98	P_{IoT} = 71.65 kW

Table 16. *Cont.*

Parameter	Constant Values	Formula	Calculation	Result
Daily Hydrogen Consumption [10]		$P_{Daily\ Demand} = P_{Demand} \times$ Operating Hours H_2 *Daily Consumption* = $P_{Daily\ Demand} / \eta_{FC} \times E_{H2}$	$P_{Daily\ Demand} = 100 \times 8$ H_2 *Daily Consumption* = 800/ (0.6) × (33.6)	$P_{Daily\ Demand}$ = 800 kWh H_2 *Daily Consumption* = 39.68 kg/day

Energy Management System (EMS) [26]:

- $V_{delivered}$ = 220 V
- f = 50 Hz

The results of the calculations show that the 100 kW power requirement may be satisfactorily met with the proposed system. The hydrogen flow rate (around 4.96 kg/h) and the daily hydrogen consumption (39.68 kg/day) are acceptable for the system to work properly. Moreover, the energy loss in DC to AC conversion and transmission/distribution is minimised as well (the final output power is 71.65 kW after IoT overhead). This is a good result and shows that the proposed system could work for the desired application.

6. Limitations of the Proposed System

Besides the previously highlighted advantages, the proposed system presents some drawbacks, as discussed in the following:

1. **High Initial Costs:** The research paper only discusses the feasibility and demand of the IoT-integrated hydrogen fuel cells, but it will require a great deal of upfront investment, particularly in remote regions like Inner Mongolia and Hebei.
2. **Scalability Challenges:** There can be a great deal of difficulties when scaling the application of the proposed system to match the requirements of a large-scale industry while keeping the system reliability and operational accuracy.
3. **Environmental Constraints:** The particular regions in China are characterized by extreme weather conditions, which vary from −25 °C to 38 °C, which would require designing and engineering the IoT-integrated hydrogen fuel cells to match these extreme weather conditions for the impactful performance of the system's durability.
4. **Hydrogen Supply Chain:** Establishing a reliable and cost-effective hydrogen supply chain in remote areas is a logistical challenge with the implementation of such an advanced system, while keeping its reliability and cost-effectiveness, in remote areas such as Inner Mongolia and Hebei.
5. **Maintenance Complexity:** Handling advanced IoT smart systems and AI-driven systems requires specialized skills for the maintenance and troubleshooting of the advanced system when implemented on such a commercial scale.
6. **Energy Efficiency Limitations:** Our research work claims that attaining an efficiency of 58% in real-world conditions will be far more difficult due to operational losses.
7. **Data Security Risks:** Despite having the integration of the AES-256/TLS and blockchain as a part of the smart system, there are still cyber threats that remain a great concern for the IoT-based system.
8. **Battery Dependency:** The reliance on lithium-ion batteries for load balancing introduces additional environmental and cost concerns.
9. **Regulatory Barriers:** Regulatory barriers for the smart system for compliance with China's local energy and environmental regulations will be a challenge for the smart system, which is to be implemented in Hebei and Inner Mongolia.
10. **Public Acceptance:** There is less awareness of the hydrogen fuel cell technology in the general public across the two regions, Inner Mongolia and Hebei, China. The proposed technology stack requires a marketing campaign for awareness in the public.

7. Conclusions

Our research paper provides an in-demand and feasible pathway for the industries in Hebei and Inner Mongolia region from a coal-dependent electricity source to a sustainable and reliable energy solution, as discussed in the potential of IoT-integrated hydrogen fuel cells. The integration of IoT-controlled PEMFC technology stack backed by AI as an additional yet optional component will help the industries to achieve significant efficiency gains, CO_2 emission reductions, and operational reliability. The proposed system holds great potential for empowering a sustainable industry with eco-friendly spheres; still, there are great obstacles to deal with, such as the high initial cost of the hydrogen supply chain, data security risks, regulatory barriers, and, most importantly, public acceptance. If implemented commercially for acquiring performance efficiency of the industrial sector in the region, there needs to be work done on the overall cost reduction for expanding the implementation of the technology stack discussed, as well as improvement of the infrastructure development of the system, along with the seamless integration of advanced machine learning (ML) models for gaining accurate automation.

This innovative approach represents a critical step toward achieving China's clean energy goals and fostering industrial growth in remote regions.

- **Cost Reduction:** For the scalability of the reduction of the initial cost reduction, there is a requirement to lower the overall pricing of the hardware and hydrogen fuel cells utilized in the assembly of the smart system, which will itself reduce overall implementation of the system, which can only be achieved through mass production and technological advancement.
- **Scalability Design:** The scalability of the proposed system requires a very specific design, which will enhance the scalability of the IoT-integrated hydrogen fuel cells for implementation in large-scale industrial applications.
- **Thermal Management:** Weather region developed and deepened thermal management systems to ensure efficient operational viability in extreme temperatures.
- **Hydrogen Infrastructure:** Hydrogen Investment in supportive networks for production, storage, and distribution of hydrogen to facilitate infrastructure for large-scale utilization.
- **Local Competency:** Program Develop local competency to operate and support the management of integrated systems through dedicated training.
- **Optimization:** Optimization Research new materials and designs to maximize the energy efficiency of PEM fuel cells.
- **Cybersecurity:** Continuously revise and recalculate protective measures in the growing area of cyber defense.

Author Contributions

Conceptualization, E.U.K.; methodology, A.A.K.; validation, M.B. and S.I.M.; formal analysis, E.U.K. and S.I.M.; investigation, E.U.K.; resources, E.U.K.; data curation, E.U.K.; writing—original draft preparation, E.U.K.; writing—review and editing, E.U.K.; visualization, F.B. and S.I.M.; supervision, M.B. and S.I.M.; project administration, M.B. All authors have read and agreed to the published version of the manuscript.

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Data can be made available on formal request.

Conflicts of Interest

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