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Efficiency Analysis of Hydrogen Fuel Cell Power Systems for Off-Grid Applications

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ABSTRACT: *The escalating environmental hazards associated with the use of fossil fuels call for eco-friendly alternative renewable energy conversion sources. One of these renewable energy measures is the development of a hydrogen fuel cell, a device which directly converts the potential of chemical fuel into electrical power without combustion. This study evaluates the efficiency of a hydrogen fuel cell power system for off-grid applications with an aim to show how much energy can be generated from a locally produced hydrogen powered device, and for how long an electrical load (1Ω resistor) in the form of bulbs of varying loading sizes is carried. For the power and performance evaluation of the cell, multimeters equipped with integrated voltmeters and ammeters were employed for their accuracy, with a power generator, functioning through a rectifier, supplying a direct current of 3.45A at a known voltage of 18.2V, providing the means to calculate the energy input into the developed fuel cell. The results assessments, revealed that power levels steadily fall as time progresses, an occurrence caused by the depletion of reactants and the continuous accumulation of reaction products, which ultimately lead to decreasing electrochemical activity and subsequently decreased power generation. The graph readings show the dynamic behaviour of the fuel cell's performance depicted by the distinct pattern followed in the relationship between time and power output.*

KEYWORDS: hydrogen fuel cell, fuel cells, off-grid applications, renewable energy technologies, proton exchange membrane fuel cells, sustainable energy cycles

INTRODUCTION

In the wake of the escalating environmental hazards associated with the use of fossil fuels, there is an increasing need to explore eco-friendly alternative energy technologies capable of mitigating the energy crisis facing modern society. Consequently, the adoption of advanced, renewable energy conversion mechanisms and strategies has become essential in the energy landscape of the 21st century (Hosseini & Wahid, 2016; Mamlouk & Scott, 2015; Zarrin et al., 2014). One of the key strategies in this endeavour is exploring energy carriers that can store intermittent renewable energy, leading to sustainable energy cycles for human consumption (Bose et al., 2011; Leong et al., 2013; Omasta et al., 2018).

The conversion of solar energy into hydrogen fuel by water splitting is an exemplary eco-friendly renewable energy technology that can be easily integrated into fuel cells (Vijayakumar & Nam, 2019; Wu, 2016). Fuel cells are efficient devices that directly convert the potential of chemical fuel into electrical power without combustion. They consist of three main parts: anodes, cathodes, and an electrolyte in between. The way a fuel cell works is by starting a chemical reaction at the anode's catalytic layer. This reaction creates protons and electrons. The protons move through the electrolyte towards the

cathode, while the electrons follow an external path through a circuit to reach the cathode as well (Ijaodola et al., 2018).

Fuel cells are ideal for a diverse range of applications. They are simple, operate at wide temperature ranges, have fast refuelling and start-up operation mode, and exceptional energy density profiles. When selecting fuel cells, important factors to consider include the temperature they work best at, the type of fuel they use, their intended use, and the materials used for their electrolyte membrane. These parameters determine the precise electrochemical reactions that occur within the fuel cell (Abdelkareem et al., 2020, 2021; Olabi et al., 2022). The adoption of fuel cells facilitates the pursuit of sustainable energy cycles, ensuring that society can continue to meet its energy needs in the future. The potential for fuel cells spans a wide range of applications, with each type offering specific advantages, making fuel cells a valuable asset in the transition towards a sustainable energy future. Exploring scholarly literature reveals a taxonomy comprising six distinct archetypes of fuel cells, each defined by the unique characteristics of their electrolyte membrane materials. These archetypes include proton exchange membrane fuel cells (PEMFCs), anion exchange membrane fuel cells (AEMFCs), molten carbonate fuel cells (MCFCs), phosphoric acid fuel cells (PAFCs), solid oxide fuel cells (SOFCs), and direct methanol fuel cells (DMFCs) (Li et al., 2009; Schechter, 2002). Among these, PEMFCs emerge as frontrunners, characterized by a remarkable array of attributes that encompass their operational efficiency across a wide temperature range, their compact and streamlined design philosophy, their ability to function effectively over varying current densities, their latent potential for cost and size reductions, extended stack lifespan, rapid start up, and adaptability within a high thermal spectrum (Authayanun et al., 2015; Liao et al., 2013; J. Yang et al., 2012). The fundamental idea on how PEMFCs work is that, at the anode, hydrogen molecules transform into protons and electrons through a process called oxidation. The protons then move through the electrolyte membrane, reaching the cathode. Simultaneously, electrons travel along an external path, eventually reuniting at the cathode. The culmination of this process occurs when electrons, hydrogen, and oxygen combine in a harmonious interaction, resulting in the creation of water. This reaction is summarized as;

$2H_2 + O_2 \rightarrow 2H_2O$.

Key Contributions

This paper seeks to contribute to the broader scientific knowledge of fuel cell technology and offers insightful deductions with regards to power generation and retention from fuel cell performance allowing for an exploration of off-grid applications of hydrogen fuel cells. At its core, this paper seeks to explore the efficacy of hydrogen fuel cells for off-grid applications, and advance the development of sustainable energy solutions for electrical systems. It therefore provides a useful framework for researchers and producers of fuel cell systems.

LITERATURE

Fuel cells have risen to prominence as a pivotal catalyst in propelling the prospective hydrogen economy forward. While the past two decades witnessed fuel cells predominantly as replacements for internal combustion engines and power sources in stationary and portable contexts, it's crucial to acknowledge that the roots of fuel cell technology extend across centuries. The purpose of this section is to present the development of the fuel cells across the time (historical background). After wards, present the basic working operation of fuel cells, point out the various fuel cell types available based on electrolyte membrane, review the current state of fuel cells and their applications across the 19^{th} to 21^{st} century, and lastly review the demonstration and commercialization of fuel cell systems over history.

Overview of Fuel Cells

Fuel cell stands as an ingenious apparatus. It harnesses the power of electrochemical reactions occurring between hydrogen and oxygen at its anode and cathode, yielding both electricity and heat. A remarkable feature of this process is that its sole by product is water, underlining its eco-friendly nature and encapsulating the mastery of chemical engineering. Setting it apart from conventional energy systems, the fuel cell achieves an impressive energy conversion efficiency ranging from 40-50% (Sopian & Daud, 2006). In stark contrast to conventional energy setups, the fuel cell is characterized by its minimal moving components. This inherent simplicity not only translates to reduced maintenance expenses and noise levels but also contributes to an extended operational lifespan. Moreover, the fuel cell's modular construction offers the flexibility to adjust its power output through the strategic addition or removal of modules, all without necessitating an extensive overhaul. Bolstered by its high energy efficiency and environmentally conscious attributes, the fuel cell demonstrates its adaptability to various fuel sources. This includes the utilization of pure hydrogen, natural gas, and methanol, even enabling the direct production of hydrogen fuel. A notable highlight of the fuel cell's design lies in its ability to capitalize on high temperatures for enhanced performance, particularly in combined heat and power generation, further amplifying its energy efficiency (Sopian & Daud, 2006). This advanced and ground breaking technology manifests in several distinct commercial fuel cell variations. These encompass the alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC), polymer electrolyte membrane fuel cell (PEMFC), and direct methanol fuel cell (DMFC). Each of these variants carries its own set of distinctive characteristics, advantages, and limitations, all of which are comprehensively outlined in figure 1. This array of fuel cell types not only underscores the diversity within the operation of the different fuel cell types technology but also highlights its potential to revolutionize the landscape of sustainable energy generation.

Fuel cell	Temperature (°C)	Efficiency (%)	Application	Advantages	Disadvantages
Alkaline fuel cell (AFC)	50–90	50–70	Space application	High efficiency	Intolerant to CO_2 in impure H_2 and air, corrosion, expensive
Phosphoric acid fuel cell (PAFC)	175–220	40–45	Stand-alone & combined heat & power	Tolerant to impure H_2, commercial	Low power density, corrosion & sulfur poisoning
Molten carbonate fuel cell (MCFC)	600–650	50–60	Central, stand-alone & combined heat & power	High efficiency, near commercial	Electrolyte instability, corrosion & sulfur poisoning
Solid oxide fuel cell (SOFC)	800–1000	50–60	Central, stand-alone & combined heat & power	High efficiency & direct fossil fuel	High temperature, thermal stress failure, coking & sulfur poisoning
Polymer electrolyte membrane fuel cell (PEMFC)	60–100	40–50	Vehicle & portable	High power density, low temperature	Intolerant to CO in impure H_2 and expensive
Direct methanol fuel cell (DMFC)	50–120	25–40	Vehicle & small portable	No reforming, high power density & low temperature	Low efficiency, methanol crossover & poisonous byproduct

Figure 1. Types of fuel cells with their application potentials (Sopian & Daud, 2006).

General Considerations in Construction of Fuel Cells

Fuel cells are devices that transform the stored chemical energy in hydrogen and oxygen into heat and electricity. This happens through a series of chemical reactions that take place at different parts of the cell, known as the anode and cathode. A modern fuel cell consists of a thin proton exchange membrane surrounded by two special catalytic layers made from specialized plastic. These components work together to generate power. In a basic setup, a catalyst layer with about 100 grams of catalyst per square meter (equivalent to 10 milligrams per square centimetre) is crucial for achieving the required power output. The anode takes in hydrogen fuel, while the cathode receives oxygen or air. These reactions lead to the production of electric current and water, which need to be managed properly. Heat dissipation in high-powered fuel cells is managed by sturdy back plates placed on the anode and cathode (Vishnyakov, 2006).

Furthermore, fuel cells come in various sizes, from small to large, and the precision of their surfaces is important for their efficiency. Creating back plates that maintain high precision across different temperatures can be resource-intensive. However, a flexible carbon cloth acts as a solution by serving as a bridge between the rigid back plate and the catalytic area. This cloth allows gases and water to flow while conducting electron current, helping the fuel cell deal with potential imperfections and reducing the cost of back plate production. The operation of a fuel cell requires all its parts to work together as a cohesive unit. It relies on two main factors for current flow: the external electric current carried by negatively charged electrons and the internal charged ion current confined within the fuel cell. In acidic fuel cells, the proton H+ moves between two strategically positioned catalyst layers. Also, the process of a fuel cell's operation begins at the anode, where hydrogen molecules split into protons and electrons. This is mirrored at the cathode, where electrons combine with oxygen, resulting in the creation of water (Vishnyakov, 2006).

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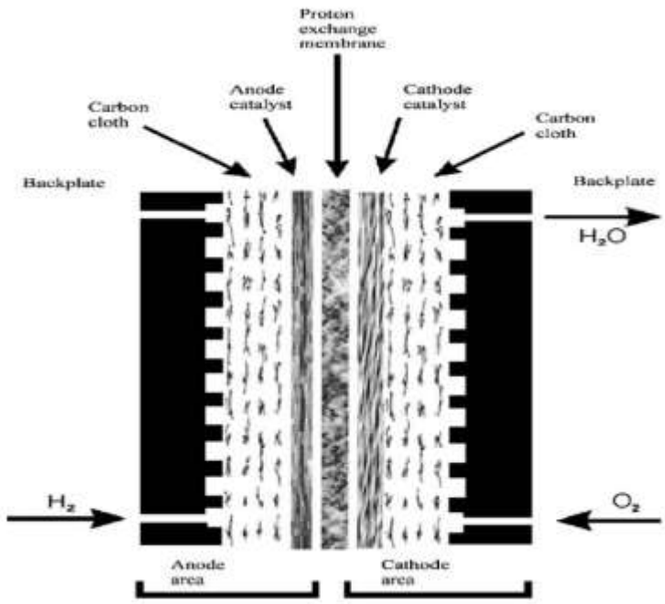

Figure 2. Essential components of a basic fuel cell device (Vishnyakov, 2006)

HISTORICAL BACKGROUND OF FUEL CELLS

19th Century: The Beginnings

The origin of fuel cell principles remains a topic of contentious debate, with two luminaries vying for credit. Christian Friedrich Schönbein, a German chemist, embarked on the first scientific expedition into the field of fuel cells in 1838 and published his results in the January 1839 issue of Philosophical Magazine, earning him recognition by the Department of Energy of the United States (Bossell, 2000). However, Sir William Robert Grove, an English polymath, challenged this narrative, attributing the conceptual genesis of the hydrogen fuel cell to his pioneering work (Sahu & Basu, 2014). Grove interposed two platinum electrodes in a sulphuric acid bath on one end, with separate confinement of oxygen and hydrogen in vessels leading to an incessant current flowing between the electrodes. He progressed through the amalgamation of electrode pairs, creating a "gas battery," the precursor to the modern fuel cell. A protracted rivalry between Grove and Schönbein ensued, each ardently championing their unique approaches to fuel cell experimentation. Prior to the conceptualization of fuel cells, the discovery of their corollary, the electrolytic decomposition of water into hydrogen and oxygen, emerged from the partnership between Sir Anthony Carlisle and William Nicholson, esteemed British savants, in 1800 (Faraday, 1991). Using the potency of the voltaic battery, they interposed conducting threads tethered to the battery's electrodes, immersing the other extremity into saline. The conducive synergy between water and conductor orchestrated the evolution of

hydrogen and oxygen gases, marking the inception of chemical metamorphosis through electrical prowess.

In 1889, Ludwig Mond and Carl Langer documented the Mond process, outlining a sequence of steps for the production of nickel. This involved using perforated platinum electrodes and a gas supply generated by a battery. The resulting symphony of electricity - 6.5 milliamperes per square centimeter and 0.73 volts. By this discovery, etched their names into the annals of science (Chaurasia et al., 2003). In 1893, Friedrich Wilhelm Ostwald, revered as the founder of the chemistry-physics field, embarked on an exploration of fuel cell constituents. He dissected the intricate interplay of electrodes, electrolytes, oxidizing and reducing agents, anions, and cations like a theater performance, leaving behind a document of knowledge that resonates through time. Ostwald's epiphanies showcased Grove's postulations about the intricate interactions hidden at the interface between the electrode, electrolyte, and gas. This enlightenment soon paved the way for monumental strides in fuel cell chemistry (Stambouli & Traversa, 2002).

Going forward, the first practical embodiment of fuel cell principles came to realization in 1896 through William W. Jacques' efforts (Appleby, 1990). Walther Nernst went on to establish zirconium as a steadfast solid electrolyte in 1900. Grove's contribution, a compendium comprising 50 monocells crowned with 31.75 mm wide platinum electrodes, revealed the necessity for an expansive arena where gases, electrolytes, and electrodes could engage in a nuanced interplay. Mond and Langer, however, strode forth refining Grove's work and paving the way for a new age of fuel cell evolution by materializing porous, three-dimensional electrodes that brought combustion and coal into the fuel cell conversation. In contrast to Grove's belief that only the purest hydrogen could be used as fuel, they believed coal could be its source. Their vision though was swathed in optimism, predicting the 20th century would be crowned by electrochemical combustion, where fuel cells would reign unhindered over Rankine's cycle, with its inefficiency and pollution. This shifting paradigm, however, remains unrealized in the 21st century, an irony that often exists between aspirations and realization.

20th Century Concept of the Fuel Cell

In the late 19th and early 20th centuries, fuel cell research witnessed significant strides by notable scientists such as William W. Jacques and Emil Baur. Their contributions laid the foundation for fuel cell development, culminating in noteworthy advancements in the discusS of fuel cell systems (Stone & Morrison, 2002). Molten carbonate fuel cell advancement was achieved by Emil Baur in 1921, utilizing high-temperature solid oxide electrolytes. Baur's experimentation with electrolytes during the 1930s showcased his dedication to pushing the boundaries of fuel cell capabilities. Meanwhile, William W. Jacques accomplished significant milestones in increasing fuel cell power output with the construction of a potent 1.5 kW fuel cell stack and a 30 kW fuel cell. These systems exemplified Jacques' commitment to achieving robust performance.

The early 1930s marked a critical moment in fuel cell development, with Thomas Francis Bacon's ground-breaking work on alkaline fuel cells. His pioneering design in 1933 introduced a practical hydrogen and oxygen fuel cell that used electrochemical processes to convert oxygen and hydrogen into electricity. His 1939 research employed nickel electrodes within a high-pressure cell to prevent electrolyte flooding in electrode pores. Fuel cell technology played a crucial role in World War II, with Bacon developing fuel cells for use in Royal Navy submarines. After the war, his innovations extended into the 1950s with a demonstration of alkaline fuel cells featuring 25.4mm diameter electrodes. These fuel cells showcased exceptional reliability, capturing the attention of Pratt & Whitney, which subsequently acquired the Apollo spacecraft's fuel cell patent (Andújar & Segura, 2009). Furthermore, in the 1950s, Teflon's integration and other advancements paved the way for contemporary aqueous electrolyte fuel cell technology. Teflon's integration marked a pivotal enhancement, fine-tuning the performance of aqueous electrolyte fuel cell technology. This pioneering material found applications in fuel cells with platinum electrodes and acidic electrolytes, as well as carbon electrodes with alkaline

electrolytes. Also, collaborative spirit, exemplified by Marshall and Bacon aerospace drove fuel cell advancements. This collaboration with Bacon facilitated a '40-cell' fuel cell boasting a commendable 5 kW output and 60% efficiency. Bacon's emphasis on maximizing current density served as a cornerstone for enhancing efficiency between electrodes, and his legacy paved the way for contemporary research in fuel cell technology.

Further research in the mid-20th century marked a pivotal moment in the evolution of fuel cell technology. Thomas Grubb, a chemist at General Electric Company (GE), made a significant contribution by introducing an innovative modification to the conventional fuel cell design in 1955. Grubb's ingenuity involved utilizing an ion-exchange polystyrene membrane, saturated with sulphated properties, as the electrolyte. This ground-breaking change laid the foundation for improved fuel cell efficiency and performance. Additionally, the emergence of platinum catalysts, in particular, proved to be a game-changer for fuel cell systems. An example of this phenomena is seen in 1958, through Leonard Niedrach's innovation in depositing platinum into the ion-exchange polystyrene membrane. This finding demonstrated the catalytic capability for platinum deposited into ion-exchange polystyrene membrane to produce hydrogen oxidation and oxygen reduction reactions. This breakthrough had far-reaching implications, leaving an indelible mark on monumental projects like NASA and McDonnell Aircraft's Gemini program (Andújar & Segura, 2009).

In 1960s, the acceleration in research on acid electrolyte fuel cells marked a shift in focus towards alternative fuel cell designs. Researchers delved deeper into perfecting two distinct methodologies. Firstly, researchers explored the integration of a polymeric electrolyte, distinguished by simplicity and reliability. Secondly, a parallel avenue was developed, focusing on the potential of fuels derived from coal, which earlier seemed unattainable within the composition of alkaline fuel cells. After wards, the post-1970 era ushered in an array of improvements in fuel cell technology. Noteworthy advancements included greater electrode action areas, reduced catalyst expenditure, improved performance metrics, and a substantial increase in operational life for these innovative systems. This holistic amelioration paved the way for widespread applications, pushing fuel cells into spheres that were previously unattainable. The story of fuel cell innovation during the mid-20th century embodies the narrative of ingenuity, adaptability, and transformative breakthroughs. The intricate interplay between catalyst improvements, electrolyte refinements, and enhanced performance metrics underscored the unwavering commitment of pioneers such as William Jacques, Emil Baur, Thomas Bacon's, Marshall, Grubb. and Niedrach (Andújar & Segura, 2009).

21st Century: Present Day Application of Fuel Cells

In the 21st century, fuel cells play a vital role in a wide range of applications. The automotive industry, for instance, benefits greatly from fuel cell technology. It extends its influence to various types of vehicles like airplanes, ships, trains, buses, cars, trucks, motorcycles, and even forklifts. However, the scope of fuel cells applications extends far beyond this, encompassing diverse applications such as vending machines, vacuum cleaners, traffic lights, and powering modern homes. Fuel cells have also found their place in the digital world, supporting devices like mobile phones, laptops, and other portable electronics, providing a reliable source of power. Sectors like healthcare, law enforcement, and finance also rely on fuel cell systems to ensure a steady supply of electrical power. Notably, fuel cell technology demonstrates its eco-friendliness by making significant contributions to waste management and environmental conservation. For instance, it transforms methane gas produced during waste treatment processes into a valuable hydrogen-rich fuel (Andújar & Segura, 2009).

Stationary Applications of Fuel Cells

Fuel cell technology is widely used in stationary applications across more than 2500 locations in various sectors like healthcare, hospitality, offices, and schools. These systems seamlessly integrate into grid-based power generation, and in remote areas as fuel cells stand-alone sources of energy (Lee et al., 2007). With efficient conversion of hydrocarbons to electricity, they achieve up to 40% efficiency. These energy systems operate quietly and

cleanly, promoting environmental friendliness. In fields like telecommunications, computing, and the internet, reliability is crucial. Fuel cell technology stands out, boasting an impressive uptime of 99.999% (Williamson et al., 2004). When it comes to power supply, fuel cells and batteries work together in the 1 to 5 kW range. Fuel cells are especially useful in places without grid access, providing steady DC power to transmission towers and electronic devices. They contribute to sustainable progress by addressing toxicity and transforming energy. They convert methane gas, rich in hydrogen, into usable energy for various purposes. Breweries, powered by the energy of methane gas from untreated landfills, also benefit from fuel cell technology. Fuel cells enable the production of power from methane gas (a hydrogen-rich fuel utilized by some types of fuel cells), which decreases hazardous emissions. In order to use the methane produced in the untreated landfills, they have also been placed in the breweries of Sierra Nevada (California), Kirin, Asahi, and Sapporo (Japan), among others (Andújar & Segura, 2009).

Applications for Transport

Fuel cell technology continues to captivate researchers, developers, and transportation companies as a transformative force in the transportation sector. The Honda FCX Clarity marked a seminal milestone in the production of mass-produced fuel cell vehicle platforms, paving the way for the development of fuel cell-powered transport systems across the field of automotive applications, including buses, motorcycles, and trucks.

The appeal of using fuel cell-powered buses in cities is promising, as they help lower CO_2 emissions and reduce noise pollution. Even when fuelled by hydrogen from fossil sources, these buses deliver efficient performance. Fuel cell technology can counteract the excessive emissions commonly associated with diesel engines used in urban transportation. This not only reduces pollution but also contributes to overall environmental improvement. Similarly, fuel cell-powered motorcycles also hold potential for reducing the disproportionate emissions often seen in these vehicles. In addition, fuel cell technology finds diverse applications in the field of transportation, particularly in electric conveyor machinery and forklifts. It proves to be a powerful enabler, decreasing the need for frequent replacements and maintenance while ensuring a continuous power supply. In long-haul trucks, fuel cell-based auxiliary power units (APUs) have the potential to enhance fuel efficiency and lower pollution. Fuel cells also hold the promise of revolutionizing mining trains, enabling uninterrupted operations during halts and accelerations while reducing pollution. These fuel cell-driven auxiliary power units help decrease reliance on fossil fuels, resulting in sustainable cost reductions and contributing to environmentally resilient transportation. In recent years, extensive research and exploration have been dedicated to fuel cells as energy converters in transportation. They have become integral components of various vehicles like buses, mining trains, ships, and aircraft. The focus on generating hydrogen from renewable sources aligns with the goal of reducing CO_2 emissions. Fuel cells play a crucial role in the transportation sector, providing auxiliary power to vehicles and machinery that undergo continuous cycles of starts, stops, and breaks (Andújar & Segura, 2009).

Fuel cells are also well-suited as auxiliary power units for long-haul aircraft, offering benefits like noise reduction, energy efficiency, and fuel savings. They hold significant promise for ships, leading to emissions reductions far beyond terrestrial sources. Countries like Iceland are embracing fuel cells for auxiliary power in their fishing fleet. The transportation sector stands on the brink of transformation, with fuel cells paving the way for sustainable transport technology and reduced emissions in the future (Andújar & Segura, 2009).

Portable Applications

Fuel cells have the potential to revolutionize how we use energy in portable devices. They offer renewable and sustainable energy solutions, especially in places where there is no access to the grid. Fuel cells can replace polluting diesel generators, particularly in remote areas like campgrounds, providing an environmentally friendly alternative. This makes fuel cells valuable for a range of applications beyond just leisure activities (Kim & Kwon, 2008). Also, fuel cells are also resilient and reliable, making them suitable for military

operations and power outages. They outshine batteries due to their lighter weight and durability. Their transformative potential can change the way we consume energy

Micro Power Applications

Fuel cells are making their mark in the world of telecommunications, ushering in a new era of extended battery life for mobile phones and laptops. Tech giants like Samsung, Panasonic, Sanyo, Sony, Toshiba, and Motorola are leading the way in fuel cell-powered communication equipment (Ross, 2003). This advancement means that mobile phones can now operate for twice as long as their lithium battery counterparts. Even more impressive is that these phones can be fully charged in just ten minutes, a significant departure from the lengthy charging times we are accustomed to. Fuel cell-powered laptops can work continuously for up to five hours before needing a refill. Fuel cell technology also enhances the efficiency of small electronic devices like pagers, hearing aids, smoke detectors, video recorders, security alarms, and even calculators. These compact power sources are fuelled by methanol. The exceptional performance of fuel cells in these small-scale technologies highlights their ability to boost efficiency in various applications.

Fuel Cell System Demonstration and Commercialization

The commercial viability of fuel cell technology has become a reality with significant strides taken towards its commercialization. For example, among the fuel cell types, the phosphoric acid fuel cell (PAFC) has been successfully commercialized with its main focus being central stationary power for up to 11 MW. On the other hand, the molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC) have demonstrated their capabilities in stationary central power production up to 250 kW and 100 kW, respectively. This has prompted their preparation for the commercial market within the next five years. But, despite the success of fuel cell technology being established in buses, cars, motorcycles, and portable power units, hydrogen fuel cell devices face challenges and hurdles that have precluded full commercialization. The cost of manufacturing is one of the primary challenges the technology needs to address before it can be embraced for full commercial use (Sopian & Daud, 2006). However, fuel cell technology is making a significant impact in the world with the United States, Canada, Europe, Japan, and several other developing countries at the forefront of research, development, and commercialization. These nations have committed considerable effort towards driving the fuel cell technology to unprecedented heights. Figure 3 gives an idea on the status of commercialization of fuel cells as well as its future trends.

Commercialization status and trends of various types of fuel cells

Fuel cell	Commercialization status	Future trends
Phosphoric acid fuel cell (PAFC)	Commercial: 50–200 kW & 1–11 MW units Total: 65 MW worldwide, Technology leader: United Technologies	Increase PAFC installations Expand PAFC markets
Molten carbonate fuel cell (MCFC)	Demonstrator plant in California, 1997, 2 MW Production capacity of 250 kW prototypes at 400 MW in 2004 Technology leader: Fuel Cell Energy Inc.	Increase stationary applications
Solid oxide fuel cell (SOFC)	Demonstrator plant in Netherlands, 1998 100 kW Technology leader: Siemen Westinghouse	Increase stationary applications
Polymer electrolyte membrane fuel cell (PEMFC)	Ballard PEMFC powered bus demonstrator, 1993 Xcellsis commercial PEMFC powered bus by 2005 All major car manufacturers has PEMFC powered car prototypes Stationary (250 kW) & domestic power (1–50 kW) prototypes Technology leader: Ballard	Improve PEMFC performance for bus fleet operations Expand PEMFC markets

Figure 3. Showing commercialization status and trends of various types of fuel cells (Sopian & Daud, 2006).

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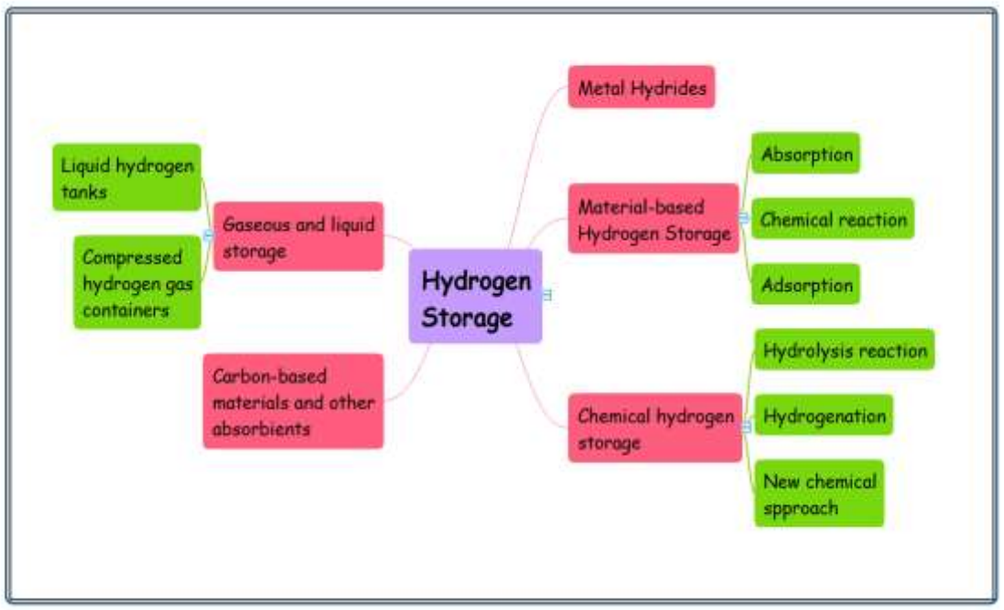
METHODOLOGY

In the bid to develop efficient and operational hydrogen-based power generation, a locally made hydrogen device have been constructed and tested. Interestingly, an abundant literature exists that proves the possibility of generating power from hydrogen-based energy sources. As a fuel, hydrogen has to be stored and this already constitutes a major drawback given that the common storage state is in the compressed gaseous and liquid forms. In its liquid form, hydrogen storage becomes very difficult as such state is maintained by even greater cooling energy than the energy sources from the hydrogen being stored. Lithium Boranuide LiBH4, is an efficient solid-state material for storing hydrogen. It has shown higher energy density compared to hydrogen in its liquid state. While research is ongoing towards the improvement of hydrogen storage materials and technologies, there is a need for attention to be drawn to efficient channelling and utilization of the energy generated in hydrogen-based energy sources.

Figure 4. Flow chart depicting various hydrogen storage methods



In this paper, we attempt to show just how much energy can be generated from a locally produced hydrogen powered device, and for how long it carries the intended load. In this case, electrical load in the form of bulbs of varying loading sizes are used to test the energy retention and distribution capacity of the fuel cell. Several methods have been used on industrial scale to supply hydrogen via coal gasification, natural gas reforms and water electrolysis. The most adopted process in the petrol and chemical allied industries is natural gas steam reforming. For all fossil fuel related generation of hydrogen, it is the cheapest method, and also recorded to show lowest levels of CO_2 emissions. For these types of applications, electrolysis method is generally not advised as it quickly turns becomes more expensive than necessary. It is however recorded to be the source of the high-purity hydrogen. As such, coal gasification is projected to be the most economically friendly option after 2030. Irrespective of the source, storage and distribution of the hydrogen generated power play critical role in the efficiency of the process. As such we have made detailed depiction of the test performed and data curated. Insights are then drawn from the analysis performed and deductions made to showcase the efficacy of adopting the hydrogen-based power system.

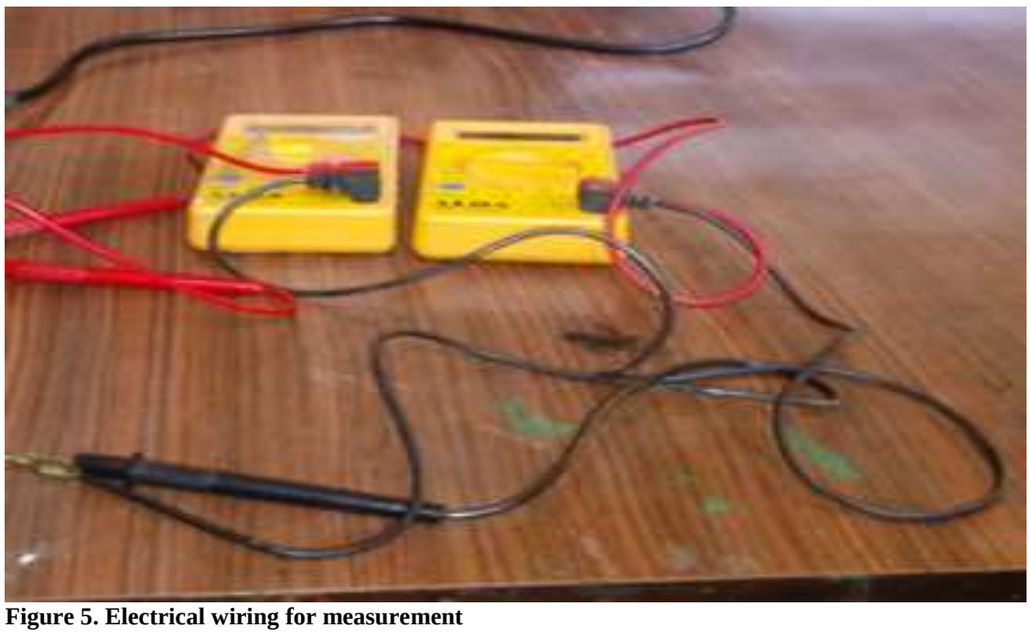


Figure 5. Electrical wiring for measurement

Experimental Measurements

In alignment with the experimental framework, our objective was to precisely determine the timeframe within which the generated energy dissipates in the fuel cell while concurrently capturing the I-V characteristics of the setup. A crucial aspect that holds significant influence is the choice of catalyst, which is anticipated to exhibit distinct energy dissipation patterns. Central to this investigation was the selection of catalyst and electrolyte concentration, pivotal factors governing the fuel cell's operation. The experimental process entailed systematic recordings and calculations of voltage and current levels at specific intervals during the fuel cell's operation. This was facilitated through the utilization of multimeters, probes, wires, and a light bulb connected to the fuel cell's terminals.

For the fuel cell experimentation, diverse electrolyte concentration variations were examined for the two electrolytes used. Empirical observation revealed that the utilization of 5 tablespoons of baking soda within 9 liters of water yielded an optimal electrolyte concentration in the hydrogen to oxygen generator. This strategic selection of catalyst and its precise quantity determination, combined with meticulous electrolyte preparation, resulted in a fuel cell that consumed notably less energy during electricity generation. It's noteworthy that exceeding the 5 tablespoons of baking soda would lead to an over-concentrated electrolyte, prompting a higher current draw from the DC generator. This excessive concentration could potentially undermine the overall power efficiency of the hydrogen fuel cell.

In terms of the power and performance evaluation of the cell, we employed multimeters equipped with integrated voltmeters and ammeters, chosen for their accuracy. Voltage and current are pivotal parameters in assessing fuel cell performance. The experimental setup, depicted in Figure 6, enabled the measurement of either of these quantities individually. The power generator, functioning through a rectifier, supplied a consistent direct current of 3.45A at a known voltage of 18.2V, providing the means to calculate the energy input into the developed fuel cell. The 1Ω resistor, employed as the load, is visibly linked by the two red wires in Figure 5. Additionally, Figure 6 illustrates the incorporation of a multimeter to monitor the voltage generated at various time intervals.

Figure 6. Hydrogen fuel cell test setup.

The I–V Characteristic Curve

The I-V characteristic curve represents the electrochemical behavior of an electrolytic fuel cell in terms of the connection between cell voltage and current. In the process of electrolysis, temperature significantly affects I–V curve and should be considered during the design of a Hydrogen fuel cell. The development of the cell voltage with the current begins logarithmically and becomes linear as the current rises. This is because in the low-current range, activation phenomenon dominates while in the high current range, ohmic phenomenon dominate. The activation voltage is very nonlinear and often varies logarithmically with the electric current running through the cell, while the ohmic voltage is typically mostly proportional to the electric current that passes through the cell. A typical I-V characteristic curve is shown in Figure 7. This shows that the curve is highly dependent on the process temperature. Indicated in the figure are the reversible voltage V_{rev} and the thermo-neutral voltages V_{tn} given respectively as

$$V_{rev} = \frac{\Delta G}{zF} \quad (3.1)$$

$$V_{tn} = V_{\Delta H} = \frac{\Delta H}{zF}, \text{ for ideal process} \quad (3.2a)$$

$$V_{tn} = \frac{\Delta H}{zF} + V_{irre}, \text{ for non-ideal process} \quad (3.2b)$$

$$\Delta G = \Delta H - T\Delta S \quad (3.3)$$

where $z = 2$ is the number of electron moles transferred per hydrogen mole, $F = 96\,485\ C/mol$ is the Faraday constant which represents the charge on one mole of electrons, T is temperature in Kelvin, ΔS is the change in entropy, ΔG is the Gibb's free energy change, ΔH is the process enthalpy change, V_{irre} the parasitic voltage due to the irreversibilities; the water vapor contained in the hydrogen and oxygen flows, the lower temperature and pressure of the supply water with respect to the operation set-points, and the fact that the process is not actually adiabatic (Ursua et al., 2012). At standard conditions, that is at 298.15 K and 1atm, $\Delta G = 237.21\ kJ/mol$, $\Delta H = 285.84\ kJ/mol$ and $\Delta S = 0.1631\ kJ/mol\ K$ giving $V_{rev} = 1.229\ V$ and $V_{tn} = 1.481\ V$. It can be seen that V_{rev} is much more influenced by pressure and temperature than the V_{tn}. A sample variation of ΔG, ΔH and $T\Delta S$ at standard pressure is shown in Figure 7.

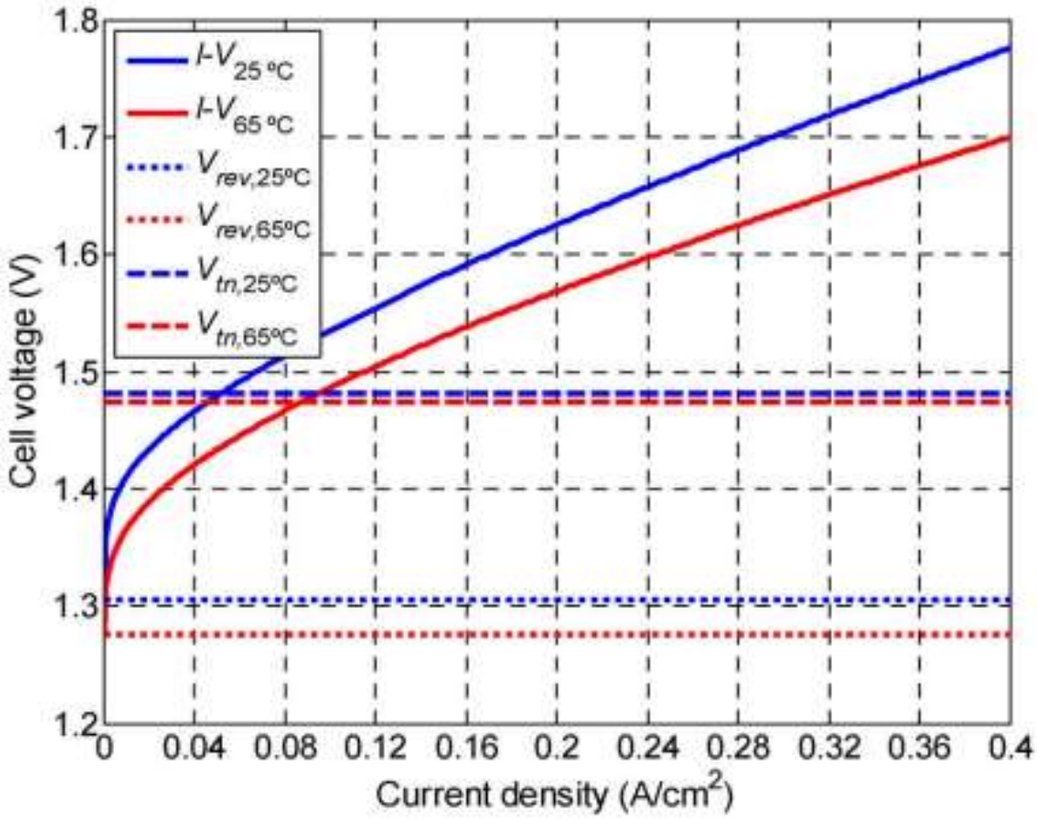


Figure 7. Typical I-V characteristics curve for fuel cell

RESULTS

The characteristics observed in the fuel cell from its performance are detailed in table 4.1. In this table, the voltage, current and corresponding power measured at different intervals are present. They show the performance and give useful insight on the operation and usefulness of the fuel cell.

Table 1. Variation of cell voltage and current with time for the two catalysts

Time (s)	Voltage (mV)		Current (mA)		Power (IV)	
	NaCl	$NaHCO_3$	NaCl	$NaHCO_3$	NaCl	$NaHCO_3$
600	15	14	10.0	9.0	150	126
612	16	15	10.8	9.6	172.8	144
624	17	16	11.6	10.2	197.2	163.2
636	18	17	12.4	10.8	223.2	183.6
648	19	18	13.2	11.4	250.8	205.2
660	20	19	14.0	12.0	280	228
672	21	20	14.8	12.6	310.8	252
684	22	21	15.6	13.2	343.2	277.2
720	25	24	18.0	15.0	450	360
756	28	27	20.4	16.8	571.2	453.6
792	31	30	22.8	18.6	706.8	558
804	32	31	23.4	19.2	748.8	595.2
816	33	32	24.0	19.8	792	633.6
828	34	33	24.6	20.4	836.4	673.2
840	35	34	25.2	21.0	882	714
852	36	33.5	24.0	20.1	864	673.35
876	38	33	22.8	19.2	866.4	633.6
900	40	32.5	21.6	18.3	864	594.75
924	42	32	20.4	17.4	856.8	556.8
948	44	14	19.2	9.0	844.8	126

Figure 8 shows a graphic delineation of the current-voltage interaction especially with the different electrolytes used. However, these are values obtained for the charging, and use

state. In Table 2, we detail a time-based record of the decline in the power dissipated by the fuel cell during operation. Together, Tables 1, 2 and Figure 8 explains both useful power charged and used from the hydrogen fuel cell designed. The increasing values observed during the charging session and visible in the linear graphs in Figure 8 shows the capacity for the cell to accumulate power during charging.

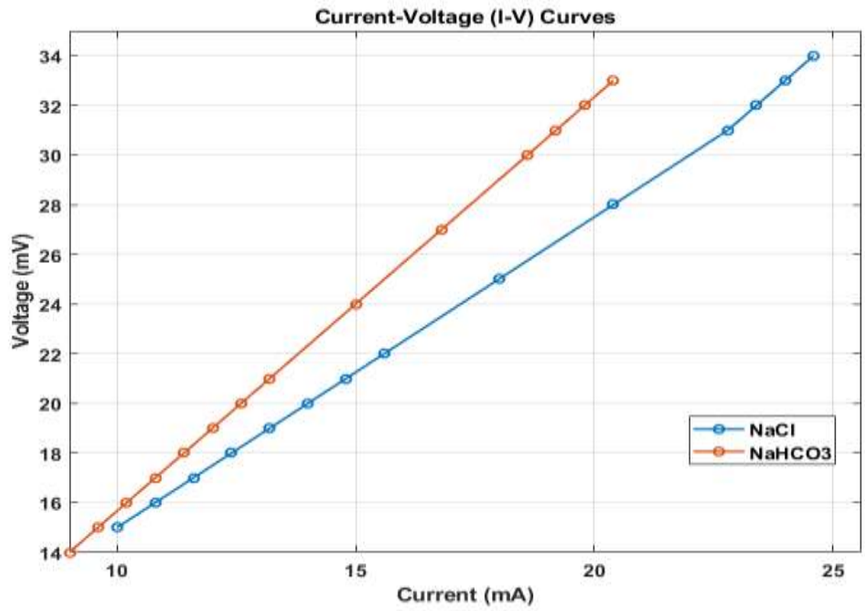


Figure 8. Current-Voltage characteristics of the fuel cell

Table 2 shows the reading of the power at 30 seconds interval when the fuel cell is not charging. It shows a sharp decline of the useful power gotten from the fuel cell.

Table 2. Power discharge with time

SN	Time (s)	Power (mW)
1	30	842.8
2	60	852.8
3	90	858
4	120	858.4
5	150	854
6	180	870
7	210	822.4
8	240	776
9	270	730.8
10	300	686.8
11	330	549.2
12	360	426
13	390	317.2
14	420	282.8
15	450	250
16	480	218.8
17	510	189.2
18	540	161.2
19	570	134.8
20	600	110

The graph in Figure 9 shows the unique characteristics of the power usage process. It can be used to arrive at useful deductions for the operation and design of the hydrogen fuel cell.

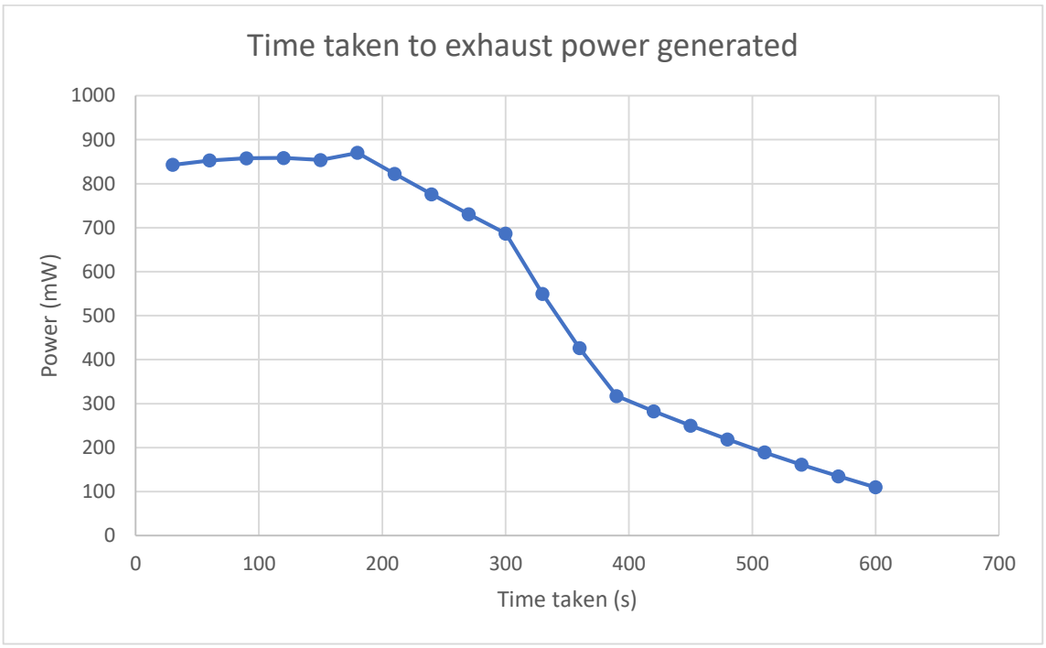


Figure 9 Time taken to consume (exhaust) the power in the fuel cell

DISCUSSION

Useful Deductions from the Data and Plots

Power Decay Pattern: As we assess the data, we find that the power levels steadily fall as time progresses. This reduction in power generation is a typical aspect of many energy storage devices, including fuel cells. It's a result of the depletion of reactants and the continuous accumulation of reaction products, which ultimately lead to decreasing electrochemical activity and subsequently decreased power generation. Also, the falling power output shows that the hydrogen fuel cell's performance is closely connected to the availability of reactants, especially hydrogen and oxygen. As these reactants are utilized throughout the electrochemical processes, the velocity of these reactions slows down, leading to a loss in power output. This underscores the need of maintaining a consistent supply of reactants to sustain the fuel cell's power production.

It is worthy to note that the power decrease is likely influenced by factors such as the chosen catalyst and the concentration of the electrolyte. Changes in these elements could damage the efficiency of the electrochemical processes, thereby influencing power output. An optimum choice of catalyst and well-balanced electrolyte content may contribute to more consistent and sustained power production. The gradual reduction in power generation over time demonstrates a natural deterioration process in the fuel cell's functioning. This degradation may come from numerous causes, including catalyst deactivation, changes in electrode properties, and the development of reaction by-products. Addressing and limiting these degrading effects is crucial for ensuring the long-term efficiency and reliability of the fuel cell. The falling power pattern and the threshold value have relevance for the practical usage of the fuel cell. It illustrates that the fuel cell's power output would not be ideal for continuous high-power applications but may still be helpful for lower-power or intermittent applications where the declining power over time is acceptable. This understanding leads the right application cases for the fuel cell technology.

The graph depicting the relationship between time and power output follows a distinct pattern. Starting with an initial peak around 850 mW within the first minute, the graph showcases the dynamic behaviour of the fuel cell's performance. After the initial high-power phase, there is a gradual decline in power output as time progresses. This decline is attributed to the gradual consumption of reactants, such as hydrogen and oxygen, necessary for the electrochemical reactions within the fuel cell. As these reactants are utilized, the

electrochemical processes generating power gradually slow down. Following the initial decline, there is a notable period of relatively steady power output, albeit at a lower level, spanning from around 270 to 420 seconds. During this phase, the fuel cell maintains a stable but diminished rate of electrochemical reactions, indicating that it is still generating power, though not at the same efficiency as during the initial stages.

Beyond the steady phase, there is a second decline in power output, signalling a further reduction in available reactants. This decline highlights the pivotal role of reactant availability in the fuel cell's performance. As reactants become scarcer, the fuel cell's efficiency and power output decrease. The implications of this graph are significant for fuel cell operation. The initial high-power phase suggests that the fuel cell operates most effectively when reactants are plentiful. As the reactants deplete, the fuel cell's efficiency diminishes. Consequently, the graph suggests that the fuel cell is better suited for applications that require an initial burst of power followed by sustained lower power output over a defined period.

Implication to Research and Practice

This experimental study provides valuable insights into the performance characteristics of a hydrogen fuel cell. The results obtained from the investigation shed light on various aspects of the fuel cell's behaviour, including voltage-current relationships, power generation capabilities, and the influence of different electrolytes. These findings contribute to a deeper understanding of the factors that affect the efficiency and practical viability of the hydrogen fuel cells.

1. **Voltage and Current Variations:** The observed variations in voltage and current over time for both NaCl and $NaHCO_3$ electrolytes underscore the importance of electrolyte composition in fuel cell performance. The significant range of voltage (15 mV to 44 mV for NaCl and 14 mV to 34 mV for $NaHCO_3$) and corresponding current (10.0 mA to 24.6 mA for NaCl and 9.0 mA to 21.0 mA for $NaHCO_3$) highlights the impact of electrolyte choice on the electrochemical reactions within the cell. These variations indicate that different electrolytes influence the rate of electron transfer and overall power generation efficiency.
2. **Power Generation Differences:** The study also reveals noteworthy differences in power generation capabilities between the NaCl and $NaHCO_3$ electrolytes. The maximum power generated using NaCl (882 mW) exceeded that obtained with $NaHCO_3$ (714 mW). This discrepancy demonstrates the direct correlation between electrolyte composition and power output. The conductivity and concentration of the electrolyte play a crucial role in facilitating efficient ion transport and reaction kinetics within the fuel cell. The higher power output observed with NaCl suggests that it provides a more favourable environment for these processes.
3. **Reactant Availability and Power Decay Pattern**: A key finding of this study is the influence of reactant availability on the fuel cell's power generation. As time progresses, there is a gradual decline in power output due to reactant depletion. This power decay pattern is a common characteristic of energy storage devices, and its manifestation in the fuel cell reinforces the importance of maintaining a consistent supply of reactants to sustain power production. It's evident that the velocity of electrochemical reactions decreases as reactants are consumed, leading to reduced power output. This observation aligns with the understanding that the fuel cell's efficiency is closely linked to the availability of hydrogen and oxygen.
4. **Optimizing Electrolyte Composition:** The results of this study have practical implications for optimizing fuel cell performance. The variations in voltage, current, and power output emphasize the need for thorough investigation into electrolyte composition. Further research could focus on exploring a wider range of electrolytes, evaluating their conductivity and compatibility with the fuel cell materials. The aim would be to identify electrolytes that enhance the voltage, current, and power generation capabilities of the fuel cell. This optimization process is crucial for achieving maximum efficiency and long-term reliability of the fuel cell technology.

CONCLUSION

In this study, an in-depth investigation into the performance characteristics of a hydrogen fuel cell was conducted, yielding valuable insights that contribute to the understanding and advancement of this innovative energy technology. Therefore, the findings offer a comprehensive view of the relationship between electrolyte composition, reactant availability, and power generation efficiency. The examination of voltage and current variations over time with different electrolytes highlighted the substantial impact of electrolyte choice on the behaviour observed in the fuel cell. Observations of voltage range from 15 mV to 44 mV for NaCl and 14 mV to 34 mV for $NaHCO_3$, along with corresponding current variations between 10.0 mA and 24.6 mA for NaCl and 9.0 mA and 21.0 mA for $NaHCO_3$, underscored the diverse electrochemical reactions influenced by the electrolyte composition. These variations emphasize the importance of selecting an appropriate electrolyte to achieve desired voltage and current outputs.

Furthermore, the significant differences in power generation capabilities between the NaCl and NaHCO3 electrolytes validated the critical role of electrolyte conductivity and concentration in facilitating efficient ion transport and reaction kinetics. The recorded maximum power outputs of 882 mW for NaCl and 714 mW for $NaHCO_3$ substantiated the influence of the electrolyte on the overall power generation efficiency of the fuel cell. This finding provides crucial guidance for optimizing fuel cell performance based on specific application requirements. A central finding of this study was the inherent power decay pattern exhibited by the fuel cell over time. As reactants such as hydrogen and oxygen are consumed, there is a gradual decline in power output. This observation aligns with the behaviour of various energy storage devices and highlights the importance of maintaining a consistent supply of reactants to ensure sustained power production. The understanding of this power decay pattern aids in selecting suitable application scenarios where intermittent power output aligns with the technology's behaviour. To optimize the performance and practical viability of hydrogen fuel cells, the research recommends a comprehensive exploration of electrolyte compositions and concentrations. By delving into a broader range of electrolytes and their compatibility with fuel cell materials, researchers can identify electrolytes that enhance voltage, current, and power generation capabilities. This optimization is pivotal for achieving higher efficiency and extending the operational lifespan of fuel cell technology.

FUTURE RESEARCH

The findings guide the application of hydrogen fuel cells in various scenarios. The initial burst of power followed by sustained lower power output over time suggests that the technology is well-suited for applications where intermittent power generation is acceptable. This understanding is valuable for selecting appropriate application cases that align with the fuel cell's power decay pattern. Future research endeavours could explore advanced catalyst materials, electrolyte additives, and improved reactant management strategies to further enhance the fuel cell's efficiency and extend its operational lifespan.

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