GREEN HYDROGEN PRODUCED FROM SEAWATER

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STUDENT DECLEARATION

This is to certify that the thesis entitled, **"GREEN HYDROGEN PRODUCED FROM SEAWATER"** is an outcome of the investigation carried out by the author under the supervision of **Md. Mostofa Hossain**, Head of Mechanical engineering, Sonargaon University (SU). This thesis or any part of it has not been submitted to elsewhere for the award of any others degree or diploma or other similar title or prize.

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ABSTRACT

The transition to sustainable and clean energy sources has become a pressing global priority. Green hydrogen, produced through electrolysis using renewable energy sources, has emerged as a promising solution for energy storage and carbon-free fuel production. This thesis explores the integration of wind power and PEM electrolysis for green hydrogen production. The objective is to assess the feasibility and efficiency of this coupled system. Experimental measurements of voltage, current, and hydrogen production were conducted. The results demonstrate successful integration and high efficiency, highlighting the potential of this approach for sustainable hydrogen generation. The findings contribute to the understanding of green hydrogen production and offer insights for future research and development in renewable energy integration. This thesis provides valuable information for policymakers and industries seeking to utilize green hydrogen as a clean energy source.

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
MCFC	Molten carbonate fuel cell.
PAFC	Phosphoric acid fuel cell
PEM	Proton exchange membrane alkaline fuel cell
PEMFC	Proton exchange membrane fuel cell
PFSA	Perfluoro sulfonic acid
SOEC	solid oxide electrolyser cell
SOFC	solid oxide fuel cell
PV	Photovoltaic
EU	European Union
NASA	National Aeronautics and Space Administration
B.C	Before Christ

LIST OF MATHEMATICAL SYMBOLS

Symbol	Unit	Meaning
I	A	Electric current
R	Ω	Electrical resistivity
T	S	Time
U	V	Voltage
V	m^3	Volume
W	J	Energy
H	/	Energy efficiency

CHAPTER – 1

INTRODUCTION

1.1 BACKGROUND

The world around us is driven by the escalating demand for energy brought on by the quick growth of technology. The primary problem, however, is that a sizeable amount of the world's energy and electricity come from fossil fuels, whose supplies are quickly running out. These hydrocarbon-based fossil fuels emit detrimental environmental consequences during combustion, including CO2 emissions and solid particles that contribute to atmospheric pollution. Fossil fuels have the advantage of being simple to store in designated tanks and warehouses and having the capacity to be used immediately. In contrast, renewable energy sources like solar and wind energy depend on weather conditions, making their utilization less consistent. Despite this, the global trend leans towards reducing reliance on "dirty" energy sources and adopting greener and more sustainable alternatives.

The solar power market has experienced remarkable growth and transformation in recent years. Governments, businesses, and communities worldwide have recognized the immense potential of wind energy as a renewable and sustainable power source [1]. Technological advancements, improved PV module efficiency, and favorable government policies promoting clean energy have contributed to the rapid expansion of the solar power market. According to the Ember a non-profit organization by EU, the cumulative installed capacity of solar energy reached a staggering 1TW in April 2022, with year-on-year growth continuing to show strong momentum. Solar power projects are increasingly being deployed onshore and offshore, harnessing the abundant Solar resources available in diverse geographical locations [2]. The cost competitiveness of solar energy has also improved significantly, making it an attractive choice for utilities and investors seeking to diversify their energy portfolios and reduce carbon emissions. The continuous advancement of solar power technologies, coupled with favorable market conditions and increasing public awareness of the need for clean energy, positions the solar power market as a key player in the global energy transition.

To maximize the effective utilization of renewable energy sources, it is crucial to efficiently store excess energy or electricity. This enables the availability of power even when solar or wind power plants cannot operate due to unfavorable conditions. Chemical energy storage devices offer a potential solution to the energy storage challenge. While batteries, such as Li-ion batteries, are commonly used, they have limitations in terms of lifespan, charging and discharging issues, and lower energy density, making them unsuitable for large-scale electricity storage. To address these limitations, hydrogen emerges as a viable option for energy storage. Through the process of electrolysis, energy can be converted into hydrogen, which can be conveniently stored in liquid or gas form within tanks. Subsequently, hydrogen can be reconverted into electricity and water using fuel cells, with the additional benefit of heat generation in the process.

Although the current efficiency of the hydrogen production and fuel cell cycle is not optimal, it holds immense potential for further development. Hydrogen technologies are envisioned to play a substantial role in the future electrical infrastructure, particularly in the storage of electricity obtained from renewable sources. Hydrogen storage offers greater flexibility without significant limitations, effectively addressing the challenge of maintaining a consistent electricity supply—a critical concern in the field.

1.2 OBJECTIVES

The objective of this thesis is to investigate the energy conversion from solar energy to electricity using PV module, as well as the production of green hydrogen through a Proton Exchange Membrane Water Electrolyser (PEMWE). The thesis is divided into two main parts: a theoretical study and an experimental investigation. In the theoretical part, the fundamental aspects of solar power and PEMWE technology will be explored. This includes an basic understanding of solar power energy. Furthermore, the fundamentals of PEMWE technology will be studied, encompassing chemical reactions, the composition of PEMWE and commercial electrolysers and the unique properties of hydrogen as a fuel.

The second part of the thesis will involve experimental work using a micro-laboratory system comprising a micro-solar power system and a micro-handmade water electrolyser for green hydrogen production. The characteristics of the solar power system will be measured, and the limitations of the water electrolyser will be identified. By coupling the two technologies, the system's operation will be optimized to achieve maximum hydrogen production. To accomplish this, a literature review on solar power energy and electrolyser characteristics will be conducted.

The specific objectives of this thesis include:

- Describing the experimental system to be used and outlining its characteristics.
- Developing an experimental matrix to guide the experimental work.
- Conducting measurements of current & voltage according to the established experimental plan.
- Try to produce hydrogen from salt water.
- Drawing relevant conclusions based on the analysis of results.
- Providing an outlook for future work in the field, highlighting potential avenues for further research and development.

By achieving these objectives, this thesis aims to contribute to the understanding of energy conversion from solar power to electricity and the production of green hydrogen, while also identifying potential areas for optimization and future research.

1.3 METHODOLOGY

The methodology employed in this thesis encompasses both theoretical and experimental approaches to achieve the stated objectives. The theoretical part of the study involves a comprehensive analysis of solar power technology and PEMWE systems. Extensive research was conducted by reviewing scholarly articles, relevant academic papers, specialized publications, and reliable online resources to acquire a profound understanding of the operational principles, performance characteristics, and efficiency aspects of solar energy and PEMWE technology. Furthermore, a mathematical model of the solar energy was developed to enhance the theoretical study and provide valuable insights into its behavior.

In the experimental part, a series of carefully designed setups were implemented to validate the theoretical findings and investigate the performance of the solar energy and the PEMWE system. The experimental setups involved the deployment of a solar energy system under controlled conditions to measure its power output and other relevant parameters. Additionally, a PEMWE (home made electrolyzer) system was utilized to perform electrolysis experiments. The experimental configuration consists of a battery-powered electrolyser, storage tanks for hydrogen and oxygen, a fuel cell, and voltage and current measuring instruments.

The experimental data collected was then analyzed and compared with the theoretical predictions to assess the accuracy of the developed models and gain practical insights into the performance of the coupled solar power and PEMWE system.

1.4 LIMITATION AND BOUNDARIES

1. This experimental study focuses solely on the examination of Proton Exchange Membrane (PEM) fuel cells and electrolysers, specifically utilizing a PEM model. The analysis and findings presented in this research are confined to this particular type of technology and may not be directly applicable to other fuel cell or electrolyser variants.

2. Due to practical constraints, the experiments are conducted within a controlled environment. Solar power energy is simulated using either a bulb or a constant voltage source, such as a battery and a regulated dc power supply with voltage & current regulation system. It is important to note that the absence of actual outdoor solar conditions may introduce certain limitations regarding the representation and accuracy of real-world scenarios.

3. The experimental setup involves an electrolyser with a maximum power output of 25W which will be operated in the voltage range of 0V to 12V Consequently, this voltage limitation imposes restrictions on the testing of heavy loads or everyday devices that may require higher voltage levels.

4. An additional limitation arises from the solar energy utilized in the experiments, which generated a significantly higher amount of energy than the electrolyser's range of values. As a result, it was necessary to implement measures to limit the PV module energy output, ensuring compatibility and preventing potential damage to the electrolyser.

CHAPTER – 2

THEORETICAL BACKGROUND

2.1 SOLAR ENERGY SYSTEM

2.1.1 History

Solar power, also known as solar electricity, is the conversion of energy from sunlight into electricity, either directly using photovoltaics (PV) or indirectly using concentrated solar power. Photovoltaic cells convert light into an electric current using the photovoltaic effect. Concentrated solar power systems use lenses or mirrors and solar tracking systems to focus a large area of sunlight to a hot spot, often to drive a steam turbine.

Photovoltaics were initially solely used as a source of electricity for small and medium-sized applications, from the calculator powered by a single solar cell to remote homes powered by an off-grid rooftop PV system. Commercial concentrated solar power plants were first developed in the 1980s. Since then, as the cost of solar electricity has fallen, grid-connected solar PV systems' capacity and production have grown more or less exponentially, doubling about every three years. Millions of installations and gigawatt-scale photovoltaic power stations continue to be built, with half of the new generation capacity being solar in 2021 [3].

In 2022, solar generated 4.5% of the world's electricity [4], compared to 1% in 2015, when the Paris agreement to limit climate change was signed [5]. Along with onshore wind, in most countries, the cheapest levelized cost of electricity for new installations is utility-scale solar [6,7].

Almost half the solar power installed in 2022 was rooftop [8]. Low-carbon power has been recommended as part of a plan to limit climate change. The International Energy Agency said in 2022 that more effort was needed for grid integration and the mitigation of policy, regulation and financing challenges [9].

2.1.2 Types of Solar power system

Photovoltaic Power System a solar cell, or photovoltaic cell, is a device that converts light into electric current using the photovoltaic effect. The first solar cell was constructed by Charles Fritts in the 1880s [10]. The German industrialist Ernst Werner von Siemens was among those who recognized the importance of this discovery [10]. In 1931, the German engineer Bruno Lange developed a photo cell using silver selenide in place of copper oxide [11], although the prototype selenium cells converted less than 1% of incident light into electricity. Following the work of Russell Ohl in the 1940s, researchers Gerald Pearson, Calvin Fuller and Daryl Chapin created the silicon solar cell in 1954 [10]. These early solar cells cost US$286/watt and reached efficiencies of 4.5–6% [10]. In 1957, Mohamed M. Atalla developed the process of silicon surface passivation by thermal oxidation at Bell Labs. The surface passivation process has since been critical to solar cell efficiency [12].

As of 2022 over 90% of the market is crystalline silicon [13]. The array of a photovoltaic system, or PV system, produces direct current (DC) power which fluctuates with the sunlight's intensity. For practical use this usually requires conversion to alternating current (AC), through the use of inverters [14]. Multiple solar cells are connected inside panels. Panels are wired together to form arrays, then tied to an inverter, which produces power at the desired voltage, and for AC, the desired frequency/phase.

Many residential PV systems are connected to the grid wherever available, especially in developed countries with large markets. In these grid-connected PV systems, use of energy storage is optional. In certain applications such as satellites, lighthouses, or in developing countries, batteries or additional power generators are often added as back-ups. Such stand-alone power systems permit operations at night and at other times of limited sunlight.

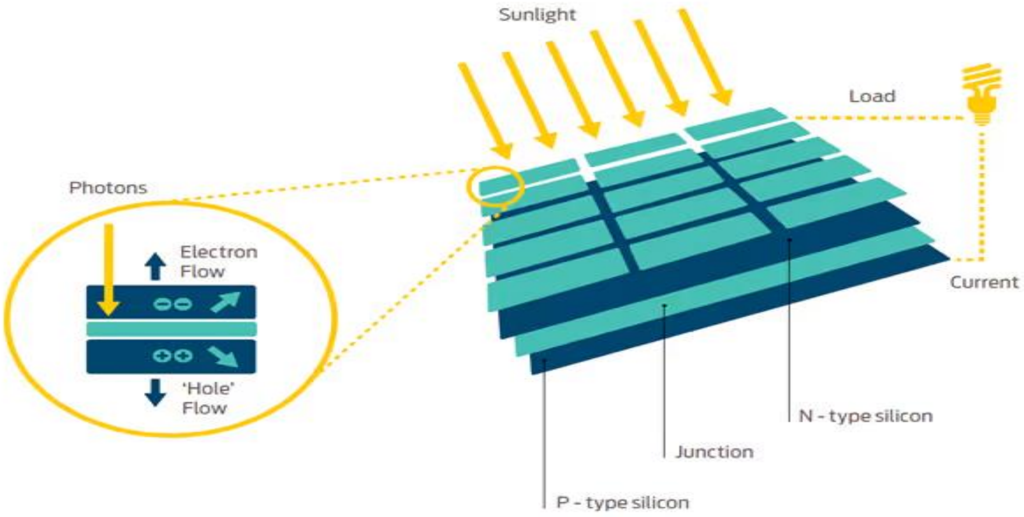

Figure 2.1: Photovoltaic Power System

Concentrated Solar Power also called "concentrated solar thermal", uses lenses or mirrors and tracking systems to concentrate sunlight, then use the resulting heat to generate electricity from conventional steam-driven turbines [15].

A wide range of concentrating technologies exists among the best known are the parabolic trough, the compact linear Fresnel reflector, the dish Stirling and the solar power tower. Various techniques are used to track the sun and focus light. In all of these systems a working fluid is heated by the concentrated sunlight and is then used for power generation or energy storage. Thermal storage efficiently allows overnight electricity generation, thus complementing PV. CSP generates a very small share of solar power and in 2022 the IEA said that CSP should be better paid for its storage [16].

As of 2021 the levelized cost of electricity from CSP is over twice that of PV. However, their very high temperatures may prove useful to help decarbonize industries (perhaps via hydrogen) which need to be hotter than electricity can provide.

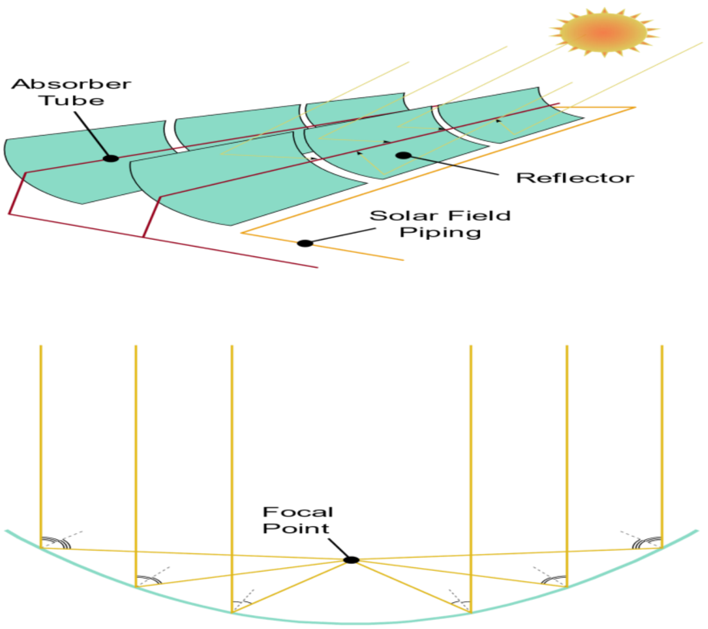

Figure 2.2: Concentrated Solar power System

Hybrid Systems combines solar with energy storage and/or one or more other forms of generation. Hydro, wind and batteries are commonly combined with solar. The combined generation may enable the system to vary power output with demand, or at least smooth the solar power fluctuation. There is a lot of hydro worldwide, and adding solar panels on or around existing hydro reservoirs is particularly useful, because hydro is usually more flexible than wind and cheaper at scale than batteries, and existing power lines can sometimes be used [17].

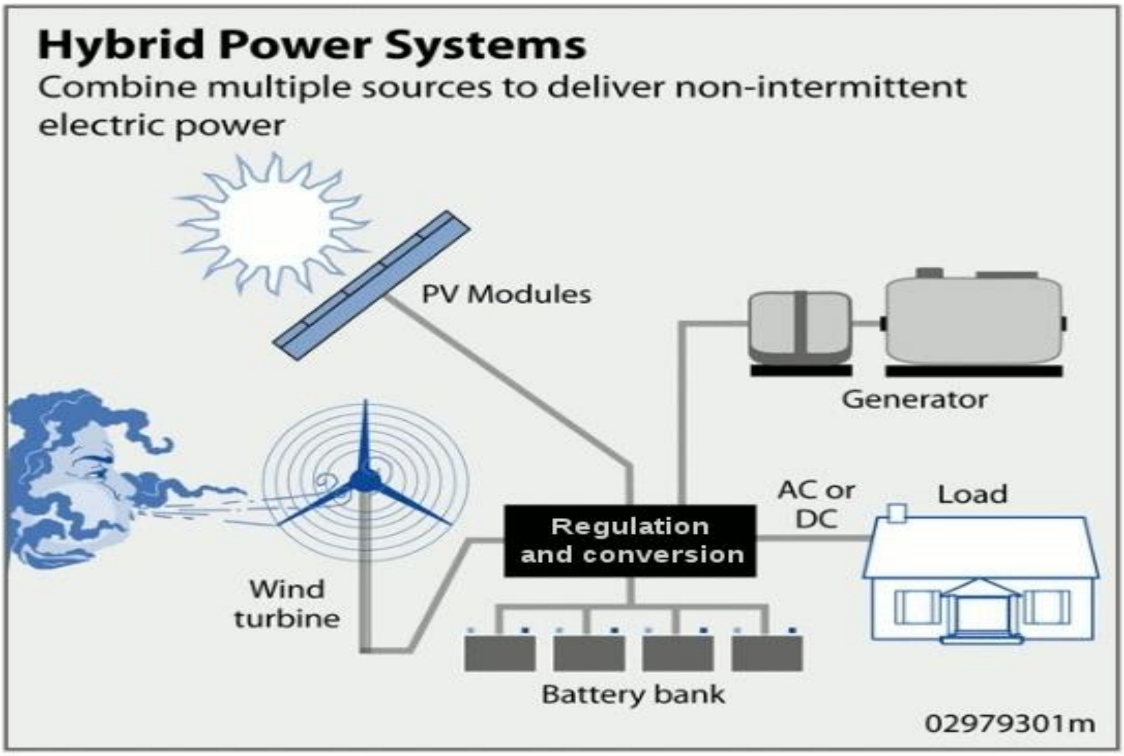

Figure 2.4: Hybrid system

2.1.3 Operation of Solar system

Solar panels are made out of photovoltaic cells that convert the sun's energy into electricity. Photovoltaic cells are sandwiched between layers of semi-conducting materials such as silicon. Each layer has different electronic properties that energized when hit by photons from sunlight, creating an electric field. This is known as the photoelectric effect – and this creates the current needed to produce electricity.

Solar panels generate a direct current of electricity. This is then passed through an inverter to convert it into an alternating current, which can be fed into the National Grid or used by the home or business that the solar panels are attached to.

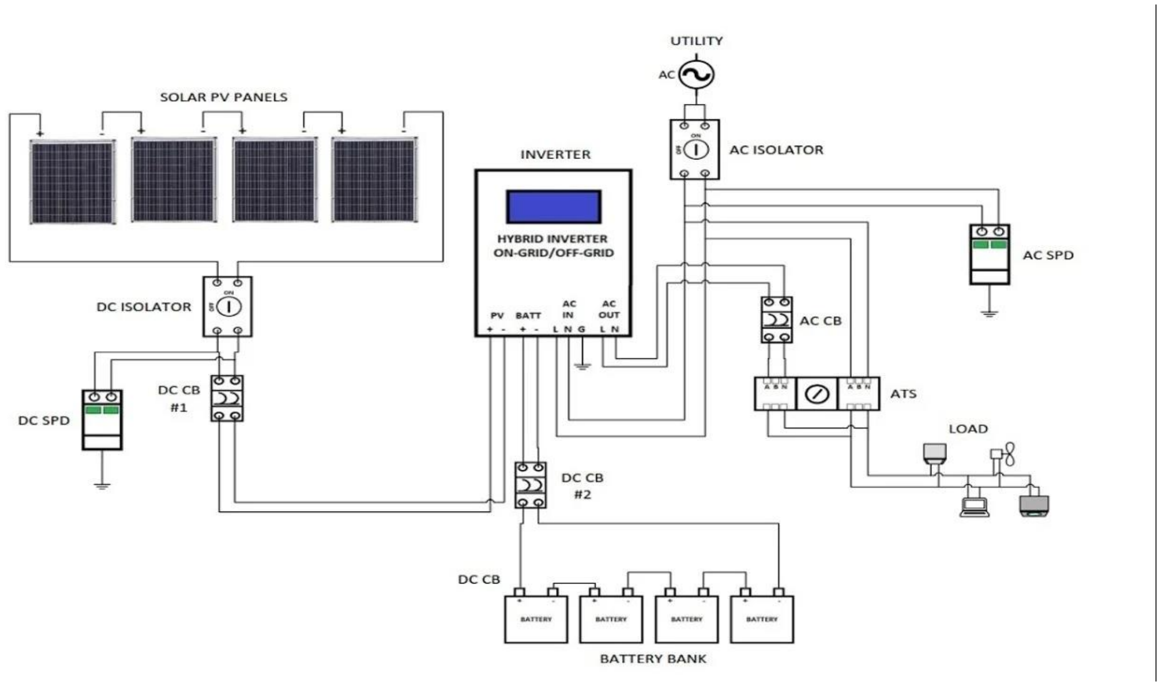

Figure 2.4: Solar System Operational Diagram

2.1.4 Advantages and Disadvantages of Solar power system

The photovoltaic cells are eco-friendly and provide clear green energy. At the time of electricity generation photovoltaic cell no effect to greenhouse gas emission by this it clears that non-hazardous to environment.

The solar photovoltaic panels which generate power is non-polluting and limitless. It also provides the support for local employment and sustainable development and also minimizes the carbon emission.

A photovoltaic system consists of solar modules, in which each of them having a number of solar cells, which generate electricity. Photovoltaic can be installations many ways some of may be ground-mounted, some may be rooftop-mounted, wall-mounted or floating mounted. The mount can be used as a solar tracker to follow the sun transversely along the sky.

The use of Photovoltaic as a source needs of energy storage systems. So, the power lines produce the additional costs and also causes many disadvantages one of them is unstable power generation. The photovoltaic have the life span of 10 to 30 years so they cost effective.

As we know except wind energy all the renewable energy has the intermittency problems because there is no sun during night and some times during day time due to cloudy sky or when it is raining. So, this makes the solar panel less reliable Occupy large area. The installation of solar panel requires more space. So, it is very difficult to select the area which occupy less space.

2.2 HYDROGEN TECHNOLOGY

2.2.1 History

The most prevalent element in the universe, hydrogen, has gained attention as a potential solution to the world's energy and environmental problems. Hydrogen technology has made great strides throughout history, transitioning from a purely scientific curiosity to an important actor in the quest for a sustainable energy future. When Swiss alchemist Paracelsus first spoke of hydrogen gas in the early 16th century, the history of hydrogen as a source of energy began. But it wasn't until the latter half of the 18th century that hydrogen's potential started to be utilized, owing to the ground-breaking work of English scientist Henry Cavendish, who separated and recognized hydrogen as a unique element.

When the 20th century arrived, hydrogen technology had made considerable strides. Sir William Grove developed the fuel cell idea in the early 1800s, which set the stage for the use of hydrogen in the production of electricity. Later innovations in the middle of the 20^{th} century raised the bar for hydrogen technology, such as the creation of the Proton Exchange Membrane (PEM) fuel cell by researchers at General Electric and the National Aeronautics and Space Administration (NASA). Fuel cells were adopted by the space industry as a clean and dependable energy source for spacecraft, demonstrating the usefulness of hydrogen-based energy systems.

Recently, there has been a resurgence of interest in hydrogen technology due to the pressing need to address climate change and move toward a low-carbon economy. Its potential to decarbonize numerous industries, including transportation, manufacturing, and electricity generation, has been acknowledged by governments, businesses, and researchers worldwide. As a clean and sustainable substitute for traditional fossil fuels, the idea of "green hydrogen", created through electrolysis powered by renewable energy sources, has gained popularity. Significant improvements in fuel cell efficiency, robustness, and cost reduction have been made over the course of hydrogen technology development. Additionally, sophisticated electrolyser technologies have been created for effective hydrogen synthesis.

We may grasp the state of the sector now and the enormous potential it offers for a sustainable energy future by comprehending the historical context and the ongoing progress of hydrogen technology.

2.2.2 Fuel Cells

A fuel cell is an electrochemical device that, often through a redox reaction, converts the chemical energy held in a fuel into electrical energy. It works by continually providing fuel and an oxidant to the cell, enabling the fuel's energy to be transformed into heat and electricity throughout the oxidation process. Fuel cells provide a more direct and effective energy conversion method than conventional heating plants, which rely on multi-stage conversions and mechanical energy generation.

Fuel cells' capacity to complete this energy conversion in a single step eliminates the need for additional conversions and minimizes energy losses. This is one of their main advantages. Additionally, because there are no moving parts in fuel cells, there are fewer energy losses and no mechanical wear. When compared to conventional methods and technologies, this attribute not only improves overall efficiency but also helps to the minimal maintenance needs of fuel cell systems.

Fuel cells are relatively inexpensive to manufacture since there are fewer parts that need to sustain high loads and temperatures [18]. A fuel cell typically comprises of a housing and an electrolyte membrane that is permeable and speeds up the required chemical reactions. Because of their straightforward design, they are more affordable and have a greater chance of being widely used in a variety of applications.

2.2.2.1 Use of fuel cell

Fuel cells offer a wide range of applications and possess significant advantages over traditional energy harvesting devices. One of their notable characteristics is their exceptional energy conversion efficiency, enabling the extraction of more energy from the same amount of fuel. Moreover, fuel cells serve as a promising alternative to fossil fuels due to their minimal emissions. The by-products of hydrogen oxidation in fuel cells are primarily heat, making them environmentally friendly. The production of hydrogen, however, remains a concern in terms of emissions. The three main categories of hydrogen production are grey hydrogen, obtained from natural gas; blue hydrogen, derived from natural gas with captured CO_2 emissions; and green hydrogen, produced through electrolysis. Green hydrogen, being the most ecologically sound, is experiencing an increase in production, making fuel cells even more appealing.

The automotive industry sees significant potential in fuel cells, particularly for electric vehicles. Fuel cells offer greater driving range compared to batteries and eliminate the need for extended charging periods. Their application extends beyond cars and includes buses, ships, trucks, and even vehicles used in warehouses, delivery services, and forklifts. Hydrogen-powered fuel cells are also being explored for aviation and space projects. Prototypes like Pathfinder and Helios are investigating the feasibility of using fuel cells in aircraft, while hybrid fuel cell systems powered by solar cells have been implemented in unmanned aircraft, theoretically enabling unlimited or continuous flight.

Fuel cells are also finding use in stationary applications. They serve as backup generators in uninterruptible power supply (UPS) systems, providing reliable power for hospitals and data centers. In fact, companies like Microsoft have successfully powered entire data centers using hydrogen cells for up to two days. Portable fuel cells are gaining traction as mobile generators, proving advantageous for camping due to their quieter operation, lighter weight, and increased power output compared to traditional internal combustion engine generators. The concept of portable fuel cells originated from NASA, where they were initially developed for heat, electricity, and water generation in rockets and space vehicles [19]. Additionally, the quiet operation, low exhaust temperature, and long-term usability make fuel cells suitable for submarine propulsion.

2.2.2.2 Types of fuel cells

The Phosphoric Acid Fuel Cell (PAFC) utilizes a phosphoric acid solution (H3PO4) as the electrolyte, trapped between two platinum-coated graphite electrodes. It operates optimally at temperatures between 180 °C and 210 °C. PAFCs offer excellent reliability and durability, with low operating costs due to the affordability of the electrolyte. However, high temperature operation requires electrolyte replenishment as it evaporates. PAFCs also rely on expensive platinum catalysts and are susceptible to carbon monoxide and sulphur contamination from impure fuels.

Molten Carbonate Fuel Cells (MCFCs) use alkali metal and carbon compounds (Li_2CO_3 or K_2CO_3) as electrolytes. CO_2 is necessary for their operation, and they function at temperatures between 600 °C and 700 °C, generating electricity and heat. MCFCs require expensive materials prone to rapid degradation due to the corrosive electrolyte. The most powerful MCFC cell plant currently has a capacity of 2.5 MW and covers an area of 500 m^2.

Solid Oxide Fuel Cells (SOFCs) employ solid ceramic electrolytes. They operate at high temperatures ranging from 600 °C to 1000 °C. SOFCs face challenges such as thermal expansion of materials, sealing methods, and overall reliability. They offer high efficiency, around 90 %, with electricity and heat production. Due to their flexibility in fuel usage, they are often employed for heat generation. Despite their reliability, they are not yet widely adopted. Siemens Westinghouse is an example of an SOFC with a power output of 220 kW.

The Alkaline Fuel Cell (AFC) operates using a potassium hydroxide (KOH) solution as an electrolyte. It requires pure hydrogen and oxygen and has a working temperature range of 120 °C to 250 °C. AFCs do not need costly precious metal catalysts and have low electrolyte costs. However, they are sensitive to carbon dioxide (CO_2) concentration, which can degrade the electrolyte and hinder cell functionality. Water removal from the anode is crucial for AFCs to function properly.

Proton Exchange Membrane Fuel Cells (PEMFCs) employ a polymer membrane that selectively allows the passage of protons. Also known as "proton exchange membrane" fuel cells, PEMFCs will be explored in detail in the subsequent chapter.

2.2.2.3 Operation of fuel cells

A fuel cell is an electrochemical device that converts the chemical energy of fuel into electrical energy directly, without the need for prior conversion into heat. Various types of fuel cells operate based on this fundamental principle. Modern fuel cells typically consist of three essential components: the anode, the cathode, and the intermediate electrolyte, which selectively allows specific ions to pass through while inhibiting the transfer of unwanted electrons [figure 2.5].

In the case of Proton Exchange Membrane (PEM) fuel cells, hydrogen is supplied to the anode, where it undergoes a process called electrolysis, breaking down into positive hydrogen ions (H^+) and negative electrons (e^-). The positive ions travel through the electrolyte to the cathode, while the electrons flow through an external circuit, generating an electric current that can be utilized for various applications. At the cathode, oxygen is supplied, which undergoes reduction by accepting the electrons. The hydrogen ions and oxygen combine at the cathode, resulting in the production of water as a by-product.

The basic principle of operation remains similar across different fuel cell types, such as alkaline cells where OH^- ions are transported via the electrolyte, or Solid Oxide Fuel Cells (SOFCs) where oxygen ions (O^{2-}) play a role. The specific cathode and anode materials, as well as the fuel used, may vary, but the controlled reaction is enabled by the selective passage of ions through the electrolyte.

To ensure smooth operation, fuel cells require proper gas distribution to the electrodes. This is facilitated by the use of porous electrode materials coated with catalysts that enhance the electrochemical reaction. Since the energy released during an electrochemical reaction is relatively low, fuel cells are connected in series in a stack configuration to obtain higher voltage. These cells are interconnected through bipolar plates, enabling efficient power generation.

It is worth noting that fuel cells have a significantly higher energy conversion efficiency compared to traditional heat-based energy conversion methods. Only a small proportion of the energy is converted into heat, typically around 20 %, with the majority being converted into usable electrical energy. The efficiency of a fuel cell depends on its operating point and can vary based on different factors.

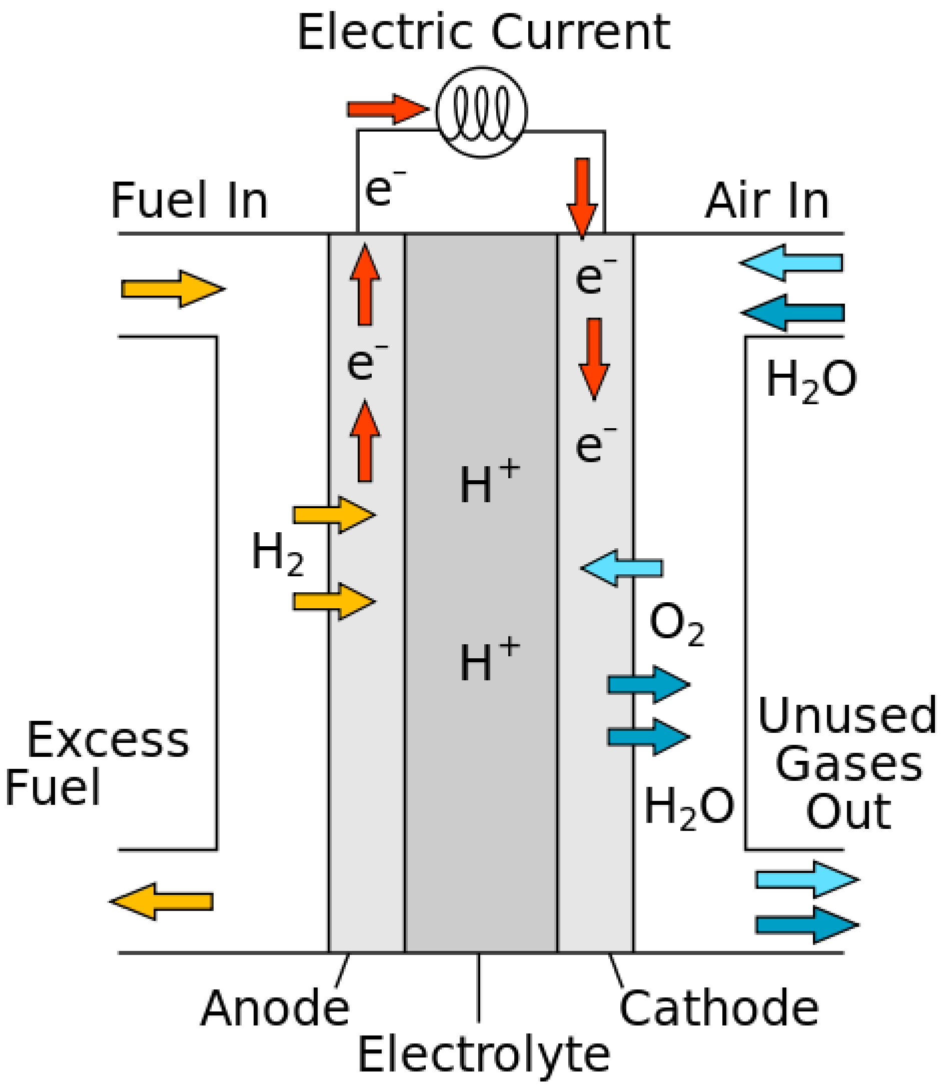

Figure 2.5: Internal structure of a fuel cell

2.2.2.4 Advantages and Disadvantages of fuel cells

Fuel cells offer significant advantages compared to traditional heat engines. Their higher efficiency, reaching around 70 %, is attributed to the electro-chemical process they rely on, which is not constrained by the limitations of the Carnot process or the second law of thermodynamics. In contrast, conventional engines, like gas turbines, typically have lower efficiencies of approximately 58 %, influenced by factors such as lubrication, wear, stretching, and humidity. Moreover, fuel cells produce minimal or no emissions as the reaction between hydrogen and oxygen results in water, making hydrogen a virtually emission-free fuel.

Another notable advantage of fuel cells is their quiet operation since they lack moving parts. Additionally, fuel cells can be flexibly employed across various applications and voltage ranges. By connecting multiple fuel cells in a stack, the voltage and power output can be regulated. However, the technology still faces challenges. Limited production scale leads to higher production costs, necessitating further debugging and optimization of production processes. The efficiency of fuel cells is influenced by fuel purity, gas distribution within the cell, temperature fluctuations, and the degradation of components like bipolar plates, membranes, and catalysts over time.

The production of pure hydrogen can be demanding and expensive, posing a disadvantage in certain cases. Moreover, the materials used in fuel cell construction, including catalysts and membranes such as platinum metals (PGM) or rare earth elements (REE), are costly and require high-temperature and corrosion-resistant properties [20]. The inconsistent production of these materials further compounds the issue. Despite these challenges, ongoing research and development efforts aim to address these limitations and enhance the widespread adoption of fuel cell technology in various industries.

2.2.3 Electrolysers

An electrolyser is a device designed to separate water molecules into oxygen and hydrogen atoms through a process called electrolysis. During electrolysis, the oxidation and reduction of chemical compounds occur at the cathode and anode under the influence of a direct electric current. The efficiency of electrolysis relies on factors such as the threshold breakdown voltage specific to each compound, as well as the properties of the electrodes and electrolytes used. The theoretical minimum voltage required to split water, known as the Gibbs free energy, is 1.23 V under standard ambient conditions of pressure and temperature (SATP) at 25 °C and 1 bar.

To facilitate the electrolysis process, additional energy in the form of heat or electricity must be introduced into the system, accounting for the energy difference between the reaction enthalpy of hydrogen and the Gibbs free energy. The operating conditions of electrolysers will be discussed further in detail. As electrolysers become increasingly efficient, particularly at large input power scales, the widespread adoption of electrolysers and fuel cells in various industries will become more feasible, promising a future where these technologies are extensively utilized.

2.2.3.1 Use of Electrolysers

Although the production of hydrogen through electrolysis is currently only a minor portion of total hydrogen production, it is the major application of electrolysers in industry. It is mostly created as a by-product of the electrolysis of water with an electrolyte, which also produces sodium hydroxide and chlorine often. The most common usage of electrolysis is in this industrial context.

$2NaCl + 2H_2O \rightarrow H_2 + Cl_2 + 2NaOH$ ……………..[21]

Numerous additional situations also make use of electrolysis. For example, it is used to produce oxygen in submarines and space missions by employing easily available resources like seawater and electric current. Additionally, the extraction of copper from ore requires the use of electrolysis. The ore is combined with sulfuric acid and salt during the electrolysis process, which causes pure copper to build up on the electrodes. Copper extraction is made significantly simpler and more successful using electrolysis, providing a more economical method. Similar to this, electrolysis is used to refine aluminum. Furthermore, by eliminating heavy metals, contaminants, and pollutants, electrolysis is a useful technique for cleaning up dirty wastewater. This application is commonly employed in treating wastewater from refineries, textile plants, and chemical facilities, aiming to eliminate as many impurities as possible.

A thin layer of metal is deposited onto a base material during the electroplating process, which is commonly used in industrial settings. This method improves the qualities and look of the treated products while also serving decorative and functional functions. The antithesis of electroplating, electrolysis is also used in an electrochemical treatment procedure that includes the removal of material rather than its addition.

2.2.3.2 Electrolyte

Pure water acts as a semiconductor but has a low conductivity for electric current. Consequently, unless a high potential is provided, causing autoionization, pure water would electrolyze slowly. An electrolyte is added to water to dramatically increase its conductivity in order to get around this restriction. The preferred electrolysis by-products will choose the electrolyte to use.

Because the anions in an electrolyte might compete with hydroxide ions for electron donors, care must be taken while choosing one. In the absence of oxygen release, an anion with a lower electrical potential will give up an electron rather than a hydroxide ion. Likely to donate an electron and prevent hydrogen release is a cation that has a higher electric potential than the hydrogen ion.

Suitable cations with higher electrical potential include Li+, Sr2+, K+, Ba2+, Rb+, Ca2+, Na+, Cs+, and Mg2+. Sodium and lithium are commonly utilized as they readily form soluble and cost-effective salts. In instances where an acid or base is employed as the electrolyte, issues with electron emission and acceptance are mitigated as they are challenging to oxidize. Strong acids such as sulfuric acid (H2SO4), or bases like potassium hydroxide (KOH) and sodium hydroxide (NaOH), are commonly utilized as electrolytes due to their excellent electron conductivity.

2.2.3.3 Types of Electrolysers

PEM, alkaline, and solid oxide electrolysers are the three main categories of electrolysers, which are separated by the substance of the electrolyte.

The SOEC, also known as a "solid oxide electrolyser cell", performs regenerative fuel cell operations or runs in reverse. It uses solid oxides or ceramics as the electrolyte and runs at high temperatures between 600 °C and 1000 °C. The most often utilized substance is zirconium dioxide (ZrO2) because of its high melting point, resistance to corrosion, and strength. Hydrogen and water are released at the cathode, whereas oxygen is released at the anode. However, the relative scarcity of zirconium makes their use more expensive, which restricts the spread of SOECs on the market.

The chemical industry uses **alkaline electrolysers** extensively because the gases and products generated during electrolysis rely on the electrodes and electrolyte that are used. Despite being capable of doing so, the choice of electrolyte is quite important. Electrolytes for water electrolysis can be sodium hydroxide (NaOH) or phosphorus hydroxide (KOH). In this procedure, the anode releases oxygen and water while the cathode releases hydrogen and water. The operating temperature range for alkaline electrolysers is 65 °C to 220 °C. They use more affordable catalysts than PEM electrolysers do, and they are more durable due to less anode catalyst degradation. Alkaline electrolyte also encourages improved gas purity by reducing gas diffusivity.

PEM electrolysers stand out among the many varieties as being particularly noteworthy. They have the benefit of producing high-quality hydrogen, requiring little maintenance, and—most importantly—responding quickly to fluctuating voltages from renewable energy sources. They operate between 40 and 80 degrees Celsius. PEM electrolysers are therefore ideal for generating energy from renewable sources. They are also better at handling large electric currents than alkaline electrolysers are. In chapter 2.2.3.5, more information on PEM electrolysers will be given.

2.2.3.4 Operation of electrolysers

Anode, cathode, and electrolyte are the three main parts of an electrolyser. Depending on the type of electrolyser used, a different electrolyte may be used.

The electrolyte is positioned between the separated anode and cathode. Water (H2O) undergoes electrolysis or breakdown at the anode. At this point, hydrogen ions with positive charges, oxygen, and electrons are liberated. In the direction of the cathode, the free electrons move via the electrical conductor. The positively charged hydrogen ions move through the electrolyte at the same time, eventually joining the free electrons at the cathode [figure 2.6].

Two chemical equations for the anode and cathode reactions can represent this process:

2H2O → O2+ 4 H+ + 4 e– …………………[22]

4 H+ + 4 e– → 2 H2

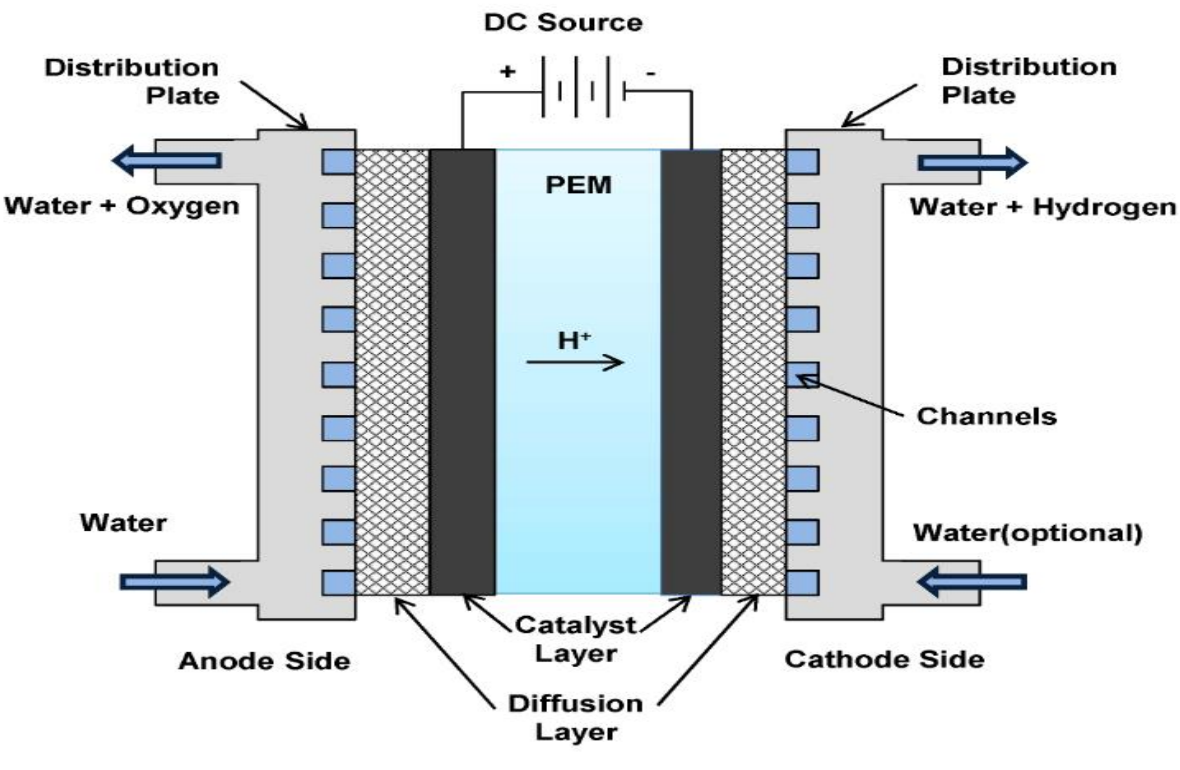

Figure 2.6: Internal structure of a PEM electrolyser.

2.2.3.5 PEM electrolyser

PEM (Proton Exchange Membrane) electrolysers are reversible devices that can work as both fuel cells, which use fuel to produce electricity, and electrolysers, which use voltage to produce hydrogen. PEM electrolysers have a number of benefits over alkaline electrolysers, including reduced mass and dimensions, lower energy usage, higher efficiency, improved voltage tolerance, production of purer gases during electrolysis, improved safety and reliability, and the ability to compress hydrogen for storage.

When General Electric created the first electrolyser using a solid polymer electrolyte in the 1960s, the idea for PEM electrolysers were born. The catalyst is coated on both sides of the electrolyte, which acts as the anode and cathode and is often a proton-permeable membrane. Proton-permeable membrane (PPM), polymer electrolyte membrane (PEM), or rarely solid polymer electrolyte (SPE) electrolysis are terms used to describe this technology.

Multiple smaller electrolysers are joined in larger, more potent electrolysers to improve voltage and power production. The most effective electrolysers right now are PEM ones, which can achieve 85 % efficiency.

The electrolyser contains an electrolyte with an anode and a cathode during operation. The electrolyte (water) goes through oxidation when an electric voltage is supplied to the electrodes. At the anode, oxygen, hydrogen protons, and free electrons are liberated. While the protons travel through the proton exchange membrane to the cathode, where they combine with electrons to generate diatomic hydrogen, oxygen can be collected at the anode.

The PEM membrane enables high proton permeability, little gas mixing, adaptability across a broad power range (100 % of rated power), compact system design, and high-pressure operation. Its thinness (20-300 mm) is yet another positive trait. Typically, sulfonic acids, notably PFSA (perfluoro sulfonic acid) material, make up the membrane. Membranes made from PFSA material are also produced by other manufacturers. The membrane in the electrolyser becomes moist and acidic when water is added, allowing hydrogen protons (H^+ cations) to pass through while remaining impermeable to negative anions.

PEM electrolyzes provide a flexible and effective option for producing hydrogen, finding use in a variety of industries and advancing renewable energy technology.

CHAPTER-3

EXPERIMENT

3.1 PEM EXPERIMENT

3.1.1 Equipment

POWER SUPPLY UNIT

The electrical energy required to run the PEM electrolyser is provided by the power supply unit employed in the experiment [figure 3.1]. It provides the system with a controlled and adjustable voltage, enabling the electrolyser to operate under the preferred operating conditions. For reliable measurements and analysis during the experiment, a steady and consistent electrical current flow is ensured by the power supply unit.

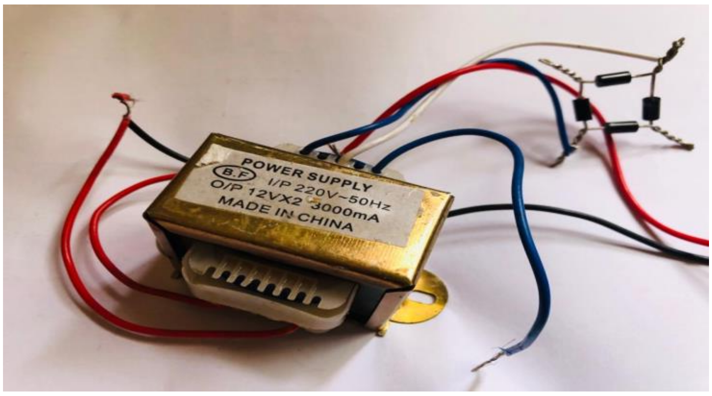

Figure 3.1: Power supply unit.

MULTIMETER

A voltage and current meter are also necessary for the measurements [figure 3.2]. Two multimeters, which we will set up differently, will be used.

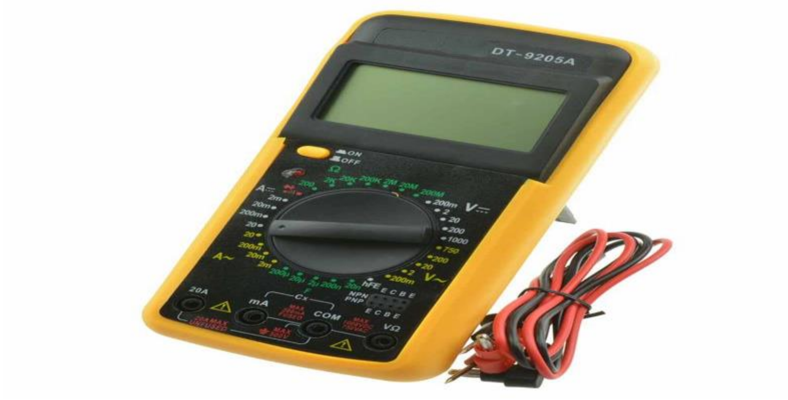

Figure 3.2: Multimeter

VOLTAGE & CURRENT REGULATOR

The electrical energy required to run the PEM electrolyser is provided by the power supply unit employed in the experiment. It provides the system with a controlled and adjustable voltage, enabling the electrolyser to operate under the preferred operating conditions. For reliable measurements and analysis during the experiment, a steady and consistent electrical current flow is ensured by the power supply unit.

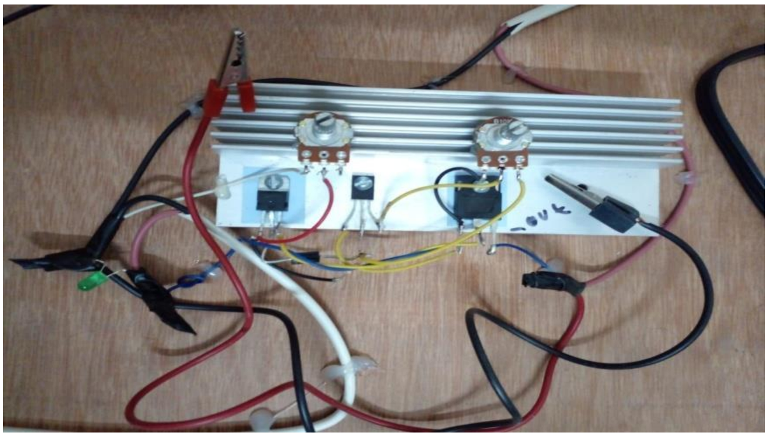

Figure 3.3: Voltage & Current Regulator

RESERVOIR TANK AND PEM ELECTROLYZER

As was already explained, the electrolyser creates oxygen O2 and hydrogen H2 from water in a ratio of 1:2. The power of the electrolyser is 2W. The tank is utilized to hold water, oxygen, or hydrogen [figure 3.4]. Water is present in a tank that has hydrogen or oxygen stored in it. This water acts as a seal for the tank as well as the medium from which we extract the different gases. 30 cm3 is the volume.

Figure 3.4: Reservoir Tank and PEM Electrolyzer

3.1.2 Preparation and course of the experiment

The electrolyser and fuel cell were meticulously prepared before the experiment began. To reach the ideal humidity, a vital step entailed immersing the PEM membrane in distilled water. The efficient movement of electrons was made possible by this. The fuel cell and electrolyser's performance was directly impacted by how moist the membrane was, thus care was made to avoid either scenario.

The electrolyser was properly set up, a continuous water supply was offered, and the device was connected to a source of constant voltage. Two tanks were connected in the appropriate manner to make the creation of hydrogen and oxygen easier. A 2V constant voltage source was used as opposed to a battery. The electrolysis reaction then started, producing hydrogen and oxygen as a by-product. The electrolyser's progress was observed, especially how much hydrogen and oxygen were produced. The gases were produced in a 2:1 ratio, as expected. This demonstrated that the electrolyser was set up and operated well.

To ensure optimal performance and consistency in the experiment, the resistance was set to an infinite value, allowing the electrolyser to receive the maximum voltage from the battery. This configuration aimed to enhance the efficiency of the electrolysis process and maintain stable conditions throughout the measurements.

Throughout the experiment, the production of hydrogen was closely monitored, recording the amount of hydrogen and the corresponding time intervals. By systematically adjusting the voltage, starting from 2 V and decreasing it incrementally by 0.1 V the relationship between voltage levels and the time required to produce 20 cm3 of hydrogen gas was observed.

Each measurement was done several times to confirm its accuracy and dependability. I wanted to reduce any potential inaccuracies and take into consideration any variations or swings in the data, so the measurements were repeated various times. The consistency and repeatability of the data were evaluated by repeating the measurements. It provided a more robust dataset for drawing inferences and accurately comparing various voltage levels, as well as aiding in the identification of any anomalies or outliers.

3.1.3 Measurements

Table 3.1: Measured and calculated data for the PEM analysis

Voltage (V)	Time (min)	Current (A)	Resistance (Ω)	Volume (cm^3)
12	3	2.43	∞	20
9	3	2.58		
10	3	2.20		

3.2 SOLAR POWER SYSTEM

3.2.1 Equipment

PV Module

A solar panel is a device that converts sunlight into electricity by using photovoltaic (PV) cells. PV cells are made of materials that produce excited electrons when exposed to light. The electrons flow through a circuit and produce direct current (DC) electricity, which can be used to power various devices or be stored in batteries. Solar panels are also known as solar cell panels, solar electric panels, or PV modules.

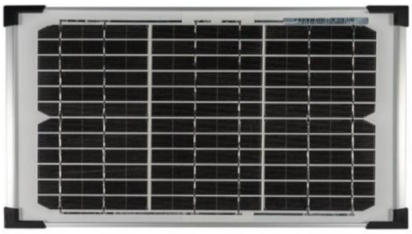

Figure 3.5: PV Module

Charge Controller

A solar charge controller manages the power going into the battery bank from the solar array. It ensures that the deep cycle batteries are not overcharged during the day, and that the power doesn't run backwards to the solar panels overnight and drain the batteries.

Figure 3.6: Charge Controller

Energy Storage

Batteries are by far the most common way for residential installations to store solar energy. When solar energy is pumped into a battery, a chemical reaction among the battery components stores the energy. The reaction is reversed when the battery is discharged, allowing current to exit the battery. Lithium-ion batteries are most commonly used in solar applications, and new battery technology is expanding rapidly, which promises to yield cheaper, more scalable battery storage solutions.

Figure 3.7: Energy Storage

3.2.2 Preparation and course of the experiment

The first step taken in the design process was configuring what the measurements that were going to be taken to characterize the solar panels. With the solar panel placed in the open sun with proper orientation, the open circuit characteristics of the solar panels in an ideal environment can be measured. With those results, a 10Ω resistor is inserted to determine the power characteristics supplied only by the solar panel. The operating manual provided with the system suggested an output voltage of 15V to 23.5V. With the solar panel operation confirmed, the DC Charge Controller can be connected directly to the output terminals of the solar panel, with another 10Ω resistor connected across the output 'battery side' terminals. During this stage, the first assumption of the functionality of the DC Charge Controller was assumed to monitor the charging state of the battery, as well as provide the DC-to-DC conversion of solar panel output voltage to the necessary 12V needed to charge the battery. After testing this device though, the concluded operation of the device was to simply monitor the output voltage at the battery terminals. Based on this, the testing procedure was reconfigured to be directly connected to battery to develop a complete understanding of its functionality. With the battery connected, the charging levels and time demands can be tested until the battery reaches its fully charged state. Once it has reached the fully charged state, load testing can be done on the system to determine the efficiency of the system with the battery included.

After the operation of the system with the battery is completely charged and fully tested, the AC Inverter can be connected based on the requirements of a 12V input. The inverter can then be tested based on the expected output voltage of 120V AC. Confirming that output, the load parameters of the complete system can be tested to find the efficiency of the inverter. When testing the inverter, it should be noted that if the inverter goes into a 'faulted' mode, where it will emit a high-pitched squeal and will not provide any output voltage. To reset the inverter, it will be necessary to turn the inverter off and back on at a suitable load value. If this does not correct the problem, the input of the inverter may also have to be reset by disconnecting and reconnecting the inverter. After my tests have been completed, an experimental procedure can be created specifically based on the limitations of the circuit elements tested in the design to further the understanding of solar panel powered system supported by the Electrical Engineering curriculum.

3.3 COUPLING PEM AND SOLAR ENERGY

3.3.1 Preparations and course of the experiment

When coupling the wind turbine with the PEM electrolyser, it posed a challenge to precisely control the solar power within the desired voltage range of 11-20.5V. Due to the inherent variability of sunlight condition, it was difficult to consistently achieve the target voltage. To address this issue, a different approach was taken. The highest rotational frequency were selected, which ensured that the generated voltage would be on the higher end of the range. Subsequently, the voltage was regulated using the power supply while monitoring the time and current required to produce a specific volume of hydrogen. This approach allowed for a more controlled and accurate measurement of the electrolyser's performance, compensating for the limitations in directly adjusting the solar energy. By employing this methodology, the experiment could still assess the efficiency and operational characteristics of the wind turbine and its coupling with the PEM electrolyser, albeit through an alternative means of controlling the input voltage.

To assess the performance of the coupled system, various voltage values were controlled and measured. The time required for each set voltage to produce hydrogen gas was recorded, along with the corresponding current. This data allowed for the evaluation of the system's efficiency and the characterization of its response to different voltage inputs. By focusing on the time taken to produce a specific volume of hydrogen gas, the experiment aimed to understand the electrolyser's performance under varying wind conditions. The recorded current values provided additional insights into the electrochemical processes occurring within the PEM electrolyser.

The experiment involved systematically varying the voltage settings, capturing the time and current data for each condition. This approach allowed for the determination of the optimal voltage inputs that would yield efficient hydrogen gas production. Additionally, it provided valuable information on the system's responsiveness to different voltage levels and its overall energy conversion efficiency.

CHARTER - 4

RESULTS AND DISCUSSION

4.1 PEM RESULTS AND DISCUSSION

In terms of the effectiveness of hydrogen production, the PEM experiment produced substantial results. We gathered important information about the electrolyser's performance by adjusting the voltage settings and timing how long it took to create 20 cm3 of hydrogen. The findings identified an ideal range of voltages that enabled better output rates with quicker electrolysis periods [figure 4.1].

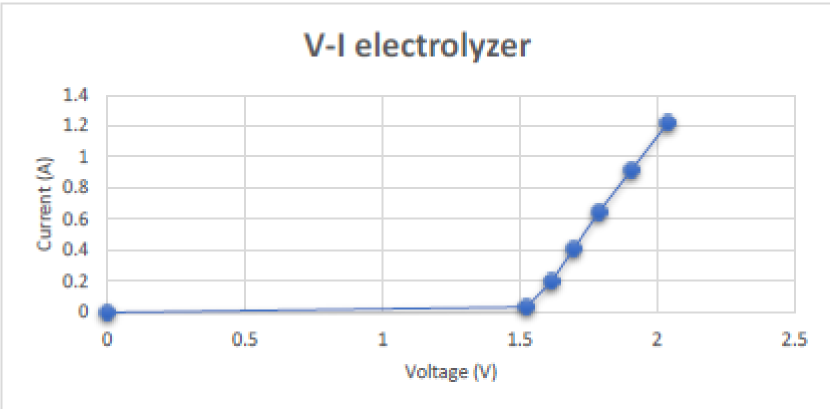

Figure- 4.1: Comparison measured values for PEM electrolyser

In addition, the PEM electrolyser's effectiveness was evaluated by comparing the amount of hydrogen produced to the electrical energy input. The experiment showed a high efficiency in producing hydrogen gas from electrical energy, underlining the promise of PEM electrolysis as a reliable and effective approach for producing hydrogen.

In the PEM electrolyser experiment, the efficiency was calculated for the highest voltage, considering that it resulted in faster hydrogen production. However, it was observed that the highest voltage did not necessarily correspond to the best efficiency. This discrepancy indicates that there exists an optimal operating point where the electrolyser achieves maximum efficiency, even if it may not produce hydrogen as quickly. By analyzing the data obtained at different voltage levels, it was possible to identify the voltage at which the electrolyser exhibited the highest efficiency, highlighting the importance of selecting the appropriate operating conditions to optimize energy conversion in the system.

$$\eta = V.H/U.I.T$$

Where H is the calorific value for hydrogen 11.523MJ/m^3 Where V is the volume of hydrogen produced and U, I, t stands for the voltage, current, and time measured to produced that volume of hydrogen.

The experiment also shed light on the electrolyser's sensitivity to changing voltages and how that affected hydrogen production . This knowledge is essential for maximizing the performance of PEM electrolysers and their effectiveness in real-world applications.

The PEM experiment's overall findings demonstrated this technology's capacity to produce hydrogen with great efficiency and highlighted its promise as a clean energy alternative. The research supports the creation of sustainable energy systems and advances methods for producing hydrogen.

4.2 COUPLING PEM AND SOLAR POWER RESULTS

The results from combining solar power and the electrolyser have shed important light on how these two technologies interact. Compared to the solitary electrolyser experiment, it did take longer to create hydrogen, but the efficiency was discovered to be incredibly high around 71.8 % (it was calculated for the higher voltage the same as in the PEM experiment). This result can be due to our purposeful emphasis on system optimization to guarantee maximum voltage delivery to the electrolyser. We sought to maximize efficiency by designing an efficient load that constrained the wind turbine's output. As a result, the experiment's lower current values are consistent with our predictions of a better efficiency curve at lower current levels.

The linked system's durability and adaptability are demonstrated by the fact that it was still able to operate at a high level of efficiency despite the prolonged hydrogen generation time. The significance of system optimization and the delicate balance needed between electrolysis and solar power generation are both highlighted by this finding. It also highlights the necessity to think about the system's total efficiency rather than only concentrating on optimizing power production. We have learned a lot about the trade-offs involved in obtaining maximum efficiency in coupled energy systems by examining the interaction between solar power and the electrolyser. Our research also highlights the need of locating the greatest efficiency point, which may not always correspond to the highest power output. This fact calls into question the widely held belief that a system's peak efficiency is represented by its maximum power. Instead, it emphasizes how crucial it is to identify the sweet spot where efficiency is maximized while balancing all of the relevant factors.

This result emphasizes the potential of combining hydrogen production and solar energy technology to produce sustainable and effective energy conversion. The development of large-scale renewable energy systems through additional study and system improvement could pave the way for a more environmentally friendly future.

CHAPTER - 5

CONCLUSIONS

In conclusion, this thesis was successful in achieving its stated goals, which included detailing the characteristics of the experimental system used and explaining it. The creation of an experimental matrix served as a clear direction for the methodical conduct of the investigation. To ensure proper data collection, measurements were carried out in accordance with the defined experimental strategy.

We have learned a lot from our experiments with the coupling of PEM electrolysers and wind turbines for hydrogen production. Even if the results are encouraging, it's crucial to recognize the difficulties and constraints that were experienced.

One significant challenge we faced was the limitation in our air tunnel, which prevented us from reaching the nominal capacities of the wind turbine. This restriction hindered our ability to fully explore the turbine's maximum potential and gather comprehensive data on its performance. To address this limitation, future experiments could be conducted in larger scale wind tunnels or real-world settings to obtain more accurate and representative results. Additionally, we encountered difficulties in controlling and maintaining the optimal load for the wind turbine. The turbine's power output proved to be too powerful at its optimal load, making it challenging to control the voltage within the desired range. This limitation necessitated the use of an infinite load, which impacted the controllability and precision of our measurements. Overcoming this challenge would require the development of advanced control systems or load management strategies to ensure optimal performance under varying conditions. Additionally, compared to the independent PEM electrolyser, the connected system's hydrogen production time was significantly longer. Future study may find success by looking into ways to improve reaction kinetics and boost output rates without sacrificing effectiveness. These results emphasize the significance of determining the best efficiency point rather than focusing only on maximum power and the necessity of balancing the performance of individual components within a coupled system.

Despite these difficulties, our research highlights the viability and potential of combining PEM electrolysers and wind turbines for the generation of clean energy. The great efficiencies attained by these technologies show that they are capable of assisting in the transition to sustainable energy. We can realize the full potential of these systems for clean hydrogen generation and renewable energy use by addressing the restrictions and further enhancing the integration and operation of these systems.

Suggestions for further work

Looking ahead, future work in this field should focus on refining the experimental setup and exploring strategies to enhance efficiency and overcome limitations, such as the constraints imposed by the experimental apparatus. Moreover, investigating the scalability and practical implementation of the coupled system in real-world scenarios would be beneficial.

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