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EXPLORING HYDROGEN PRODUCTION THROUGH ELECTROLYSIS: A COMPARATIVE STUDY OF IDEAL AND REAL CONDITIONS AT ROOM TEMPERATURE

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ABSTRACT: The demand for oil and hydrogen is continuously increasing in the era of the industrial revolution. The significant growth in population is fueling a substantial need for energy, leading to the excessive exploitation of natural resources and an upsurge in greenhouse gas emissions. Ever since the adoption of the Paris Agreement in 2015, international organizations and the climate movement have been advocating for radical policies promoting the use of renewable energy sources and phasing out fossil fuels. To tackle this challenge, the development of environmentally sustainable energy solutions becomes highly crucial. One such recognized solution is hydrogen, which possesses the potential to serve as a carbon-free fuel with a higher calorific value compared to traditional fossil fuels. Hydrogen can be generated from various domestic resources. Presently, the most commonly utilized methods for hydrogen production involve Carbon Capture and Storage, as well as Steam Methane Reforming utilizing natural gas or coal gasification. However, employing electrochemical processes and renewable biomass as raw materials for hydrogen production is regarded as more eco-friendly and sustainable, despite being relatively more expensive. In this particular study, hydrogen production was achieved using the electrolysis method. The primary objective of this experiment is to compare the efficiency of hydrogen production between optimal conditions (VH_{2ideal}) and real-world conditions at room temperature (VH_{2real}), while considering the energy consumption per liter of hydrogen (V_{cell}). Based on the findings of the test, it can be deduced that attaining ideal conditions within the electrolysis system is challenging when operating at room temperature. Under ideal circumstances, the anticipated volume of produced hydrogen is 18.23 liters with a power consumption of 6,390 Watts per liter. However, when subjected to average room temperature conditions, the test results indicate an average power consumption of 6,633 Watts per liter.

Keywords: Buck Converter, Electrolysis, Hydrogen, Water

1. Introduction

Centuries ago, hydrogen started being utilized as a fuel source when hot air balloons were employed for lifting purposes. As the industrial revolution unfolded, the use of hydrogen as fuel became even more prominent, paralleling the surge in global oil demand.

In recent times, there has been an unprecedented population explosion, leading to a substantial upswing in energy requirements. This surge in energy demand has resulted in the excessive depletion of natural resources and a subsequent increase in greenhouse gas emissions, posing a detrimental effect on the environment. Consequently, the pursuit of sustainable and eco-friendly energy solutions has become increasingly imperative to address this pressing challenge [1].

Since the 2015 Paris Agreement, international agencies and the climate movement have paid great attention to the issue of renewable energy. This resulted in drastic policies aimed at gradually reducing the use of fossil fuels, including measures such as the elimination of subsidies for oil and gas. Although these measures aim to reduce negative impacts on the environment, they also have significant social and political implications.

One aspect that needs attention is the high number of poor people who rely on cheap fossil fuels to meet their daily needs. In developing countries with low economies, the elimination of fuel subsidies can have a direct impact on political and social conditions. Therefore, it is necessary to have a holistic and sustainable approach in overcoming this challenge, taking into account economic, social and political aspects simultaneously [2].

The utilization of biomass has gained popularity in developing nations where fuel oil and gas prices are exorbitant. In low economic circumstances, biomass is regarded as a favored and sustainable fuel option due to its cost-effective acquisition and minimal usage risks [3].

Residents living in rural areas, particularly those facing economic constraints, frequently depend on conventional biomass sources like firewood, charcoal, and agricultural leftovers to fulfill their cooking and heating requirements. This reliance on biomass stems from the fact that they have limited means to afford fuel oil and gas for their energy needs [4]. Nonetheless, the practice of burning biomass through open fires is widely recognized as ineffective, resulting in the emission of greenhouse gases and the production of environmentally harmful soot particles [5].

Although biomass is considered a more affordable, efficient and sustainable alternative to fossil fuels, there is a need to make efforts to improve the technology and practices of using biomass. This will help reduce greenhouse gas emissions and other negative impacts, while ensuring equitable and sustainable access to energy for populations that depend on biomass as their primary source [3][4][5].

When confronted with the task of mitigating greenhouse gas emissions and satisfying the ever-growing global energy requirements, it is important for us to find energy solutions that are environmentally friendly and sustainable. In this context, hydrogen is recognized as a fuel with great potential. One of the main reasons is that hydrogen offers a carbon-free solution, meaning that its use does not produce greenhouse gas emissions that contribute to climate change. In addition, hydrogen also has a high heating value compared to traditional fossil fuels such as oil or coal, making it an attractive option as an efficient and clean alternative energy source [6].

Hydrogen can be produced from various resources available in the country. The most commonly used hydrogen production methods today are Carbon Capture and Storage (CCS) and Steam Methane Reforming (SMR) using natural gas, or through coal gasification. This method is considered as the most cost-effective way to produce hydrogen [7][8].

The SMR process involves a chemical reaction between water vapor (steam) and methane (natural gas), producing hydrogen and carbon dioxide as byproducts. Meanwhile, CCS involves capturing and storing carbon dioxide produced during the hydrogen production process, with the aim of reducing greenhouse gas emissions into the atmosphere.

Nevertheless, it is crucial to acknowledge that while SMR and CCS techniques may offer cost advantages, there is a growing focus on exploring electrochemical processes and renewable biomass as essential components in hydrogen production. These innovative approaches are being pursued as they are considered more eco-friendly and sustainable solutions. The electrochemical method utilizes electrical energy to break down water into hydrogen and oxygen, while renewable biomass, such as crop residues or organic waste, can be processed into hydrogen through gasification or fermentation processes.

With further research and development, it is hoped that more sustainable and efficient hydrogen production technologies will continue to develop, helping us to move towards a future with cleaner and more sustainable sources of energy.

The primary challenge encountered in the advancement of hydrogen fuel lies in the exorbitant expenses associated with its production. Therefore, many studies have been carried out to find methods that can produce electrolytic hydrogen at low cost. Based on previous research on operational conditions for electrolytic hydrogen production, this study aims to explain how hydrogen is produced and what factors influence the hydrogen production process using sunlight as an energy source.

In this study, an MPPT (Maximum Power Point Tracking) controller is applied to adjust the needs of battery charging and electrolysis systems based on the optimal power tracking model of solar panels. By using an MPPT controller, the energy produced by solar panels can be efficiently optimized to support the hydrogen production process. In addition, the storage battery is used to support the buck converter system, which aims to avoid fluctuations in electrical power due to weather changes that can affect the performance of the electrolysis system. By adjusting the voltage variations made by the buck converter, the optimal working voltage for the electrolysis system can be found, thereby increasing the efficiency of hydrogen production.

By using this approach, it is hoped that hydrogen production by utilizing sunlight as an energy source can be carried out at a lower cost and in a more sustainable manner. This will help overcome key challenges in the development of hydrogen fuel and encourage the adoption of environmentally friendly renewable energy.

2. Fundamental of Water Electrolysis

2.1 Historical Background

Since the Paris Agreement in 2015, increased attention from international agencies and the climate movement has increased pressure to implement drastic policies regarding the use of renewable energy [2]. In the future, hydrogen is recognized as a renewable energy source that holds immense potential among various energy options [9]. Hydrogen can be produced from various resources available in the country. At present, the predominant methods for hydrogen production heavily rely on techniques like SMR and CCS, utilizing natural gas or coal gasification. These methods are renowned for their cost-effectiveness when compared to the employment of electrochemical processes and renewable biomass [7] [8]. However, by using renewable energy sources and water electrolysis process, the hydrogen produced can be categorized as green hydrogen which is environmentally friendly [10].

Previously, many studies have been conducted to examine the effect of several parameters in an effort to optimize hydrogen production through water electrolysis. Some of these studies highlight the importance of optimal electrode voltage [11], distance between electrodes [12], and electrolyte solution concentration [13] in achieving optimal operational conditions of water electrolysis. Through comprehending the impact of these variables, endeavors can be undertaken to enhance the efficacy of water electrolysis in hydrogen production. Consequently, this will expedite the progress and implementation of hydrogen technology as a pristine and sustainable energy alternative.

Table 1 Global hydrogen production by source [14]

Source	Billion m3/year	Share (%)	Advantages	Disadvantages
Natural gas	240	48%	Low production cost; accessible infrastructure	The extraction of natural gas and the production of greenhouse gases have significant environmental consequences.
Oil	150	30%	Low production cost; accessible infrastructure	The process of extracting oil and the subsequent production of greenhouse gases have detrimental effects on the environment.
Coal	90	18%	Low production cost; accessible infrastructure	The extraction of coal and the resulting production of greenhouse gases have significant environmental consequences.
Electrolysis	20	4%	Can be produced with low greenhouse gas emissions when using	When fossil fuels are used as a power source, there are concerns

			renewable energy sources	regarding their low efficiency, high production costs, limited infrastructure, and the emission of greenhouse gases.
Total	**500**	**100 %**		

2.2 Basic Principles

The primary aim of water electrolysis is to generate oxygen and hydrogen gas through the breakdown of water. In this process, an electrolytic cell comprising two electrodes is employed, and these electrodes are linked to a power source by means of an electrolyte solution [15]. Figure 1 illustrates a basic setup of water electrolysis, comprising an electrolyte solution with an embedded anode and cathode. These electrodes are connected to an external DC power supply. Electrons flow from the terminal electrode to the cathode, where they interact with hydrogen ions (protons) and form hydrogen atoms. During the water electrolysis process, hydrogen ions migrate towards the cathode, while hydroxide ions move towards the anode. To collect the resulting hydrogen and oxygen gases at the cathode and anode respectively, gas collectors are employed (Figure 1). When water is electrolyzed with an acidic or neutral aqueous electrolyte, the reactions occurring at the electrode surfaces can be described using Equations (1, 2):

Cathode

$$2H^+_{(aq)} + 2^{e-} \rightarrow H_{2(g)} \quad (1)$$

E_0 = 0.00 V

Anode

$$H_2O_{(l)} \rightarrow \frac{1}{2}O_{2\,(g)} + 2H^+_{(aq)} + 2^{e-} \quad (2)$$

E_0 = 1.23 V

The combination of these two equations yields the overall reaction outcomes of water electrolysis, as depicted in Equation (3):

Overall

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \quad (3)$$

E_0 = -1.23 V

Nonetheless, in the electrolysis of alkaline water, which entails the utilization of a potent base as the electrolyte, the hydroxide anions are transported through the electrolyte to the surface of the anode. At this point, they relinquish electrons and subsequently return to the positive terminal of the DC power source. To enhance conductivity, potassium hydroxide (KOH) is commonly employed as the electrolyte in alkaline water electrolysis, although alternatives with higher conductivity are also available. Thus, for the electrolysis of water in an alkaline solution, the reactions taking place at the electrode surface can be elucidated through Equation (4, 5) as follows:

Cathode

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (4)$$

E_0 = -0.83 V

Anode

$$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^- \quad (5)$$

E_0 = 0,40 V

Naturally, when Equations 4 and 5 are combined, they yield an overall reaction comparable to Equation 3, where the theoretical cell voltage remains constant at -1.23 V. To ensure the occurrence of this reaction, it is necessary to pay attention to several important parameters in the electrochemical cell [12].

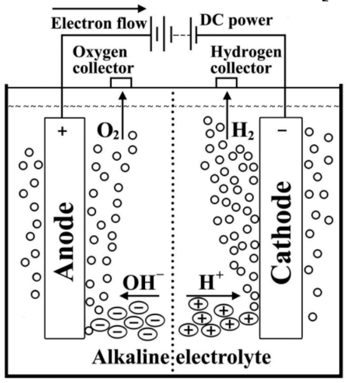

Figure 1 Basic scheme of a water electrolysis system [12]

2.2 Details of Electrolysis Calculations

In modeling electrolytic performance, empirical equations related to basic electrochemical phenomena are generally used. The fundamental equation mentioned above

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serves as the basis for calculating several essential parameters in the electrochemical cell electrolysis process, with a few examples presented below:

2.2.1 Voltage reversible (V_{rev})

The minimum voltage required to start an electrochemical reaction is known as the reversible voltage. Equations (6, 7) are used to calculate the alternating voltage based on Gibb's free energy (ΔG).

$$\Delta G = \Delta H - T\Delta S \quad (6)$$
$$\Delta G = n.F.V_{rev} \quad (7)$$

Where :

ΔG = Gibb's free energy (k Joule / mol)
ΔH = Enthalpy (k Joule / mol)
T = Temperature (°Kelvin)
ΔS = Thermal energy demand (J/K. mol)
N = Number of Moles
F = Faraday constant (96485 C/mol)

Equation (8) allows for the determination of the alternating voltage (V_{rev}) by considering various factors. These factors include the standard enthalpy change (ΔH = 286 kJ/mol), the entropy of the electrolysis process at a specific temperature (ΔS), and the standard free energy Gibbs for water separation (ΔG = 237.2 kJ/mol) [16]. Additionally, the Faraday constant (F), which has a value of 96485 C/mol, and the number of electrons involved in the reaction (n = 2) are also crucial parameters in this context.

$$V_{rev} = \frac{\Delta G}{nF} \quad (8)$$
$$V_{rev} = \frac{237.2\ k\ J/mol}{2\ .96{,}485}$$
$$V_{rev} = 1.229\ V$$

According to Equation (9), a specific cell voltage referred to as the enthalpy voltage or thermo-neutral (V_{enth}) cell voltage is necessary to facilitate the water electrolysis process. This voltage requirement is directly linked to the enthalpy reaction [17].

$$V_{enth} = \frac{\Delta H}{nF} \quad (9)$$
$$V_{enth} = \frac{286\ k\ J/mol}{2\ .96{,}485}$$
$$V_{enth} = 1.482\ V$$

2.2.2 activation voltage (V_{act})

Both the reversible voltage (V_{rev}) and the thermo-neutral cell voltage (V_{enth}) play a pivotal role in initiating a chemical reaction. However, an extra provision of potential, known as the activation voltage (V_{act}), is necessary. The magnitude of the activation voltage relies on the electrode coefficient and the temperature. Equation (10) enables the computation of the activation voltage under a constant temperature of 273° K.

$$V_{act} = A + B\ .\log(I) \quad (10)$$

Dimana :

V_{act} = Activation Volatge (Volt)
A = Anode and cathode constant
B = Anode and cathode constant
I = Flowing current (Ampere)

Literature provides the Anode (A) and Cathode (B) constants, and research indicates that stainless steel 316 (316SSS) exhibits a specific current of 10 mA.cm−2 with a voltage of η = 370 mV (0.37 V) in a 1.0 mol.L^{-1} KOH solution. Employing equation (10), it becomes possible to compute the activation voltage when the target current is 20A.

$$V_{act} = 0.37 + 0.37\ .\log(20)$$
$$V_{act} = 0.8513\ Volt$$

2.2.3 Ohmik Voltage (Vohm)

Voltage experiences a decline as a result of resistance encountered in electrolytes, electrodes, electrical wires, and similar components. This collective decrease in voltage is referred to as the Ohmic (V_{ohm}) voltage, which can be determined by employing equation (11)..

$$V_{ohm} = \frac{r}{A} I \quad (11)$$

Dimana:

V_{ohm} = Ohmik Voltage (Volt)
r = ohm Resistance (Ωm^2)
A = area elektroda (m^2)

During the design phase, the viscosity of the solution is disregarded, and the electrode is specifically constructed with an area (A) of 1.2 m^2. The resistance value (r) of 0.21 Ω/m^2 is assigned based on an electrification distance of 0.006 m. By employing the relevant equations, the ohmic voltage value can be derived.

$$V_{ohm} = \frac{0.21\Omega/m^2}{1.2m^2} 20A$$
$$V_{ohm} = 3.5\ Volt$$

2.2.4 Tegangan sel (Vcell)

$$V_{cell} = V_{enth} + V_{act} + V_{ohm} \quad (12)$$
$$V_{cell} = 1.482 + 0.8513 + 3.5$$
$$V_{cell} = 5.8333\ Volt$$

Where:

Vcell = Cell voltage (Volt)

The summation of applied potentials during the electrolysis process, encompassing the enthalpy, activation, and Ohmic voltages, gives rise to the cell voltage or cell potential, commonly known as overvoltage. Equation (12) enables the calculation of the cell voltage [19]. Under ideal conditions at standard temperature and pressure (STP), the thermodynamic decomposition voltage of water is 1.229 V (1.23 V), accompanied by a 100% current efficiency. This implies that the theoretical energy consumption (Etheo) required for producing 1m3 H2 amounts to 2.94 kWh/m^{3}H$_2$. However, practical water decomposition necessitates a voltage ranging from 1.65-1.7V. Consequently, in industrial applications, the employed voltage typically falls within the range of 1.8-2.6 V. Consequently, the actual energy consumption surpasses the theoretical energy consumption by approximately 1.5 to 2.2 times. Therefore, the practical efficiency ranges from 48% to 70% [17]. In this particular study, a cell voltage (Vcell) of 5.8333 Volts was utilized.

2.2.5 Production Efficiency (Eff)

The efficiency of hydrogen production through electrolysis can be determined by employing Equation (13), which involves comparing the measured volume of gas (VH$_{2real}$) with the ideal volume of hydrogen (VH$_{2ideal}$) and expressing the result as a percentage:

$$Eff(\%) = \frac{VH_{2real}}{VH_{2ideal}}.100\% \qquad (13)$$

Dimana:

Eff(%) = system Efficiency (%)
VH$_{2real}$ = Volume of steaming gas (liter)
VH$_{2ideal}$ = Volume of steaming gas (liter)

Using faraday electrolysis laws, the ideal volume of hydrogen (VH$_{2ideal}$) is calculated as follows Equation (14):

$$VH_{2ideal} = \frac{I.V_m.t}{n.F} \qquad (14)$$

Where:

t = period t (dalam second)
V$_m$ = ideal gas molar volume (liter / mol)

$$VH_{2ideal} = \frac{20\ A.48.872\frac{Liter}{mol}.3600\ S}{2.96485\ C/mol}$$
$$VH_{2ideal} = 18.23487\ liter$$

Equations (15) provide the value of VM, which represents the ideal gas molar volume (measured in liters per mole) under standard conditions (with T = 298 K and P = 1 atm). The current (in Amperes) passing through the cell during the time period t (in seconds) is denoted as I, and F represents the Faraday constant (equal to 96485 C/mol).

$$V_m = \frac{n.R.T}{P} \qquad (15)$$

Where:

R = gas rated = 0,082 L atm / mol K
P = 1 atm

$$V_m = \frac{2.0.082\ L\frac{atm}{mol}K\ 298\ Kelvin}{1\ atm}$$
$$V_m = 48.872\ Liter/mol$$

For the purpose of simplifying calculations, hydrogen gas is assumed to behave as an ideal gas. Therefore, under standard conditions, the actual volume of hydrogen gas (VH$_{2real}$) can be determined using Equation (16):

$$VH_{2real} = VH_{2(measured)}\frac{T_{standart}}{T_{measured}} \qquad (16)$$

Dimana:

VH$_{2(measured)}$ = Measured gas volume (liters)
VH$_{2real}$ = Volume of natural gas (liters)
T$_{standart}$ = Ideal temperature (273 oKelvin)
T$_{measure}$ = Room temperature (298 okelvin)

Where VH$_{2(measured)}$ is the volume obtained by the transfer of alkaline water (l), Tstandard is the standard temperature (273^o Kelvin) and Tmeasured is the room temperature (in ^{o}Kelvin) [15].

2.3 Method

2.3.1 Design of hydrogen reactor

Hydrogen reactors with DC current source suplay settings consist of several key components shown in Figure 2. Solar panels are used as a source of DC power generation generated from solar radiation. Solar Controller Charger is used to maintain the charging condition of the battery and load to always be at the optimal working voltage. Storage batteries are used to store energy from solar panels to avoid power fluctuations due to solar panel working conditions. Buck converter is used as a DC power source converter of batteries used as a supply of DC power current reactors (anodes and cathodes). Hydrogen reactors are the main load in this system, which is used as a hydrogen generator of water electrolysis processes with electoral specifications, buck converter, battery, solar charger controller, and solar panels shown in Tables 2 through 6.

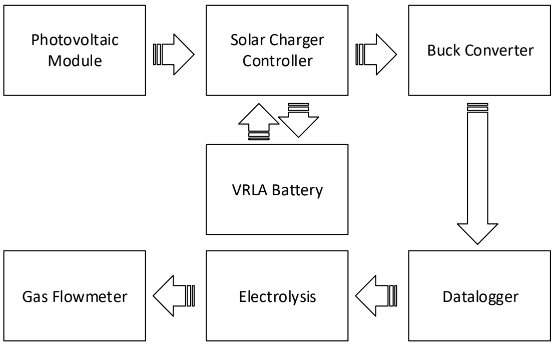

Figure 2 Basic scheme of a water electrolysis reactor

Table 2 Specification of electrode

Materials	Stainless Steel
Area	1,2 m^2
Cross section	1 sisi
Number of electrodes	16 (8 Cathode, 8 Anode)

Table 3 Specification of buck converter

Power	600 Watt
V Operation Input	2 – 30 Volt
V Operation Output	0 – 29 Volt
Max Current	22 A

Table 4 Specification of battery

Type	VRLA Battery
Rated Voltage	12 Volt
Capasity	35 AH

Table 5 Specification of solar charger controller

Power	600 Watt
V Operation Input	2 – 30 Volt
Max Current	20 A

Table 6 Specification of solar panel

Type	Polycristaline
Power	100 WP

2.3.2 Results and Discussion

The purpose of this test was to compare the effectivity of electrolysis system production in room temperature conditions (VH_{2real}) and under ideal conditions (VH_{2ideal}) with energy consumption (V_{cell}) per liter of H_2. Figure 3 shows stainless steel plates used as electrolysis electrodes, Figure 4 shows electrical reactor tubes filled using electrolyte solutions, Figure 5 shows buck converter system blocks and dataloggers can be monitored on a PC (Personal Computer). The measuring balance is used as a parameter of H_2 gas flow at the time of electrolysis (Figure 6).

Figure 3 Stainless Steel Electrode

Figure 4 Reactor Electrolysis

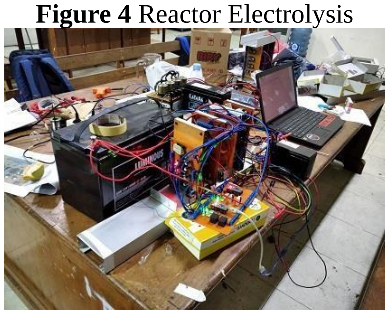

Figure 5 Buck Converter and Datalogger

Figure 6 Gas Flow Meter

Table 7 presents the test results and calculation of electric power usage per liter of hydrogen production.

Table 7 The ratio of electric power consumption per liter of hydrogen (3600 Second)

Ideal			Real		
VH_{2ideal} (Liter)	I_{ideal} (A)	V_{ideal} (V)	VH_{2real} (Liter)	I_{real} (A)	V_{real} (V)
18.23487	20	5.833	18.1	20	6.2
			18.2	20	5.9
			18.2	20	5.9
			18.3	20	6.1
			18.0	20	6.2
			18.4	20	6.1
			18.2	20	6.0
			18.2	20	6.3
			18.3	20	5.8
			18.2	20	5.9
P/liter (Watt/l)	6.390		P/liter (Watt/l)	6.633	

3. Conclusions

From the tests that have been conducted, it can be concluded that the ideal condition of an electrolysis system is difficult to achieve in room temperature conditions, the results showed in ideal conditions, the expected hydrogen volume of 18.23 liters was obtained with a power consumption of 6,390 Watts / Liter, but in the room conditions the average test results showed that the average power consumption consumed was 6,633 Watts / Liter.

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