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Model of Solar Hydrogen Power and Fuel Cells System

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Abstract: This study is a real model which aims to show how the elements of the photovoltaic system, electrolyzer and fuel cells come to overcome and reform intermittent and fluctuating renewable energy. Some challenges of PV cells are sun set, cloudy skies, snow and dust. These environmental conditions block sunlight capture via photovoltaic, so, the electrolyzer produces gases and stores it via hydrogen tank. During normal day, PV generates electricity to feed the load, but if the sky is cloudy or raining or we have a lack of generation for any reason, the fuel cells will generate power to feed load directly, and this fuel will be the gases that were produced and stored via the electrolyzer the previous day.

Keywords: Photovoltaic, electrolyzer and fuel cells.

I. INTRODUCTION

Renewable energy will be more attractive now due to the need of meeting the demand for energy in the future. Many challenges have started to appear as a result of global warming, which is due to the increases of emission of carbon dioxide. High prices and a predicted depletion of oil are encouraging researchers to look at renewable energy sources. Hydrogen is a promising gas because of its abundance and its relationship with water. We can extract hydrogen from water and there are many ways, most notably, electrolyzer, steam reform, thermo chemical cycles, and partial oxidation.

Basic physics to understand where energy comes from in renewable energy. One example, solar cells.

All matter depends on the atom. Each body has countless small atoms. Each atom contains a nucleus which contains protons and electron rotate around the nucleus as shown in figure (1) below.

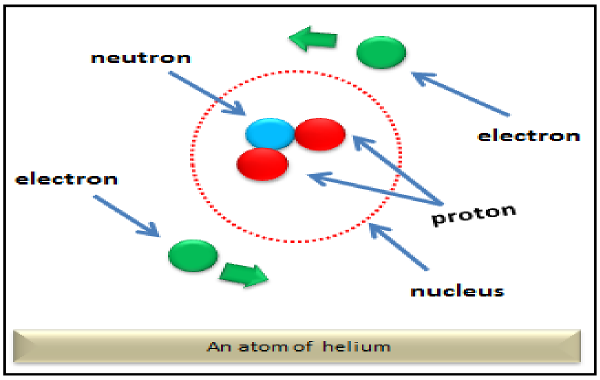

Fig.1. Shows component of an atom of helium

We could convert sunlight to electricity via Photovoltaic cells or solar cells. Solar cells are considered the best way to generate electricity because it is environmentally friendly. This means no damage on the environment and it slows the emission of greenhouse gases that we know will affect our planet earth.

II. ELECTROLYZER

Electrolyzer is a device which changes electrical energy from solar panels to hydrogen and oxygen gases. This device splits water molecules into its original ions, water (H2O) contains two hydrogen atoms and one oxygen atom. See Fig (2)

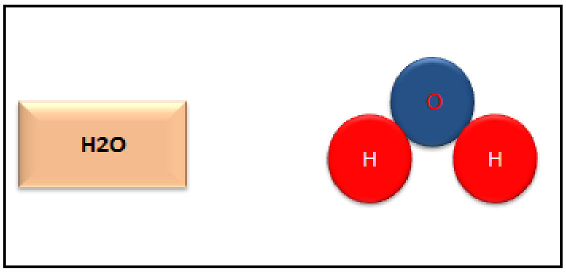

Fig.2. Shows water form.

The electrolyzer contains two chambers; each one has an electrode, Cathode (-) and Anode (+). The theory behind of the electrolyzer is more complicated, the electrolyzer splits water into hydrogen and oxygen gases. Hydrogen has a slightly positive charge and equals +1 electron (ev) for each atom and oxygen has a slightly negative charge and equals -2 electron (ev). One electron is 1.6×10^{-19} Coulombs, 1C = 1 Amp / sec.

So, if we connect water with the electrolyzer, the electron of hydrogen will be attracted to the negative charge electrode (cathode) and will win the electrons, then it will convert it to a gas form (H2). The oxygen electron will be attracted to the positive charge electrode (Anode) and will lose electrons, this mean, oxygen will band to form a gas as a following reaction.

$$\textbf{Anode}: \mathrm{H2O} \longrightarrow \tfrac{1}{2}\mathrm{O2} + 2\mathrm{H}^{+} + 2e^{-} \qquad (1)$$

From the Anode reaction above, it appears that the H2O molecule will dissociate into an electron, proton and oxygen atoms.

$$\textbf{Cathode}: 2\mathrm{H}^{+} + 2e^{-} \longrightarrow \mathrm{H2} \qquad (2)$$

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From equation (2) and when we apply electrical field, hydrogen ion will be driven to the Cathode and it will combine with the electron in order to create hydrogen gas. See Fig (3)

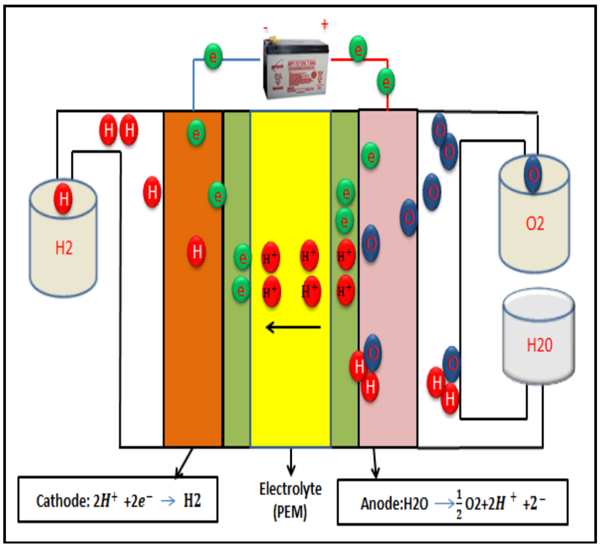


Fig.3. shows electrolyzer, Anode, Cathode and Membrane

Electrolyzers' efficiency

Efficiency (η) =$\frac{\Delta H}{\Delta G}$, (3)

When
ΔH *is the enthalpy change.*
ΔG *is the energy supplied the gas* or change of molar Gibbs free energy
$\Delta H - \Delta G$ is the amount of heat that is absorbed via the electrolyzer.
When the electrolyzer operates at RTP the amount of ΔH and ΔG will be flowing.

So $\eta = \frac{285.9\frac{MJ}{K}mole}{237.2\frac{MJ}{K}mole}$ = 1.205 [7]. (4)

If we want to obtain the efficiency via expression of Voltage, we should divide equation (4) by (qneNo) = ne F where
q is the charge of electron
ne is the number of electrone that release
No is the Avogadro's number
F = qNo = Fradi's constant = 96.47× 10^6 C/Kmple.
and we will find $\eta = \frac{V_{High\ heating\ value}}{V_{Low\ heating\ value}}$
Where

$$V_{HHV} = \frac{285.4\frac{MJ}{K}mole}{2\times 96485.3\frac{Columbs}{Mole}} = 1.481 \text{ v per cell}$$

$$V_{LHV} = \frac{237.17\ \frac{MJ}{K}mole}{2\times 96485.3\frac{Columbs}{Mole}} = 1.23 \text{ v per cell,}$$

this mean, there is low value of voltage to separate water molecules to H2 and O2.

Efficiency = $\frac{\Delta H}{\Delta G} = \frac{V_{HHV}}{V_{LHV}} = \frac{1.481}{1.23} = 1.205$ (5)

So, Efficiency of electrolyzer at

RTP = $\frac{1.481}{V\ cell}$ (8)

It is clear from the equation that when the electrolyzer operate at less than 1.48 V it will absorb heat and tends to work under the ambient temperature, and if the electrolyzer operates above 1.48 V, the electrolyzer tends to work above the ambient temperature, and the amount of heat exchange in the environment will be calculated as.

Q = V- 1.48 I [7]. (9)

Fuel Cell

Fuel cells are the reverse of the electrolyzer. Hydrogen enters from the Anode side and oxygen enters from the Cathode side, a Proton Exchange Membrane (PEM) is important because it to allows hydrogen protons to pass to the oxygen side while at the same time blocking the electrons in order to force them pass through via extra circuit and thus combines with oxygen to create H2O.See Fig. (4)

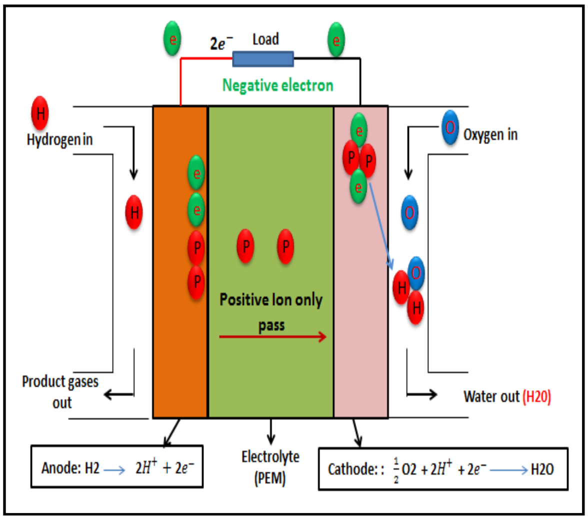


Fig.4. Shows how the fuel cell is operating

Anode: H2 $\longrightarrow 2H^+ + 2e^-$ (10)
Cathode: $\frac{1}{2}$ O2 + $2H^+$ + $2e^-$ $\longrightarrow$H2O (11)
Overall:H^+ + $\frac{1}{2}$ O2 $\longrightarrow$ H2O + Electrical Energy + Heat (12)

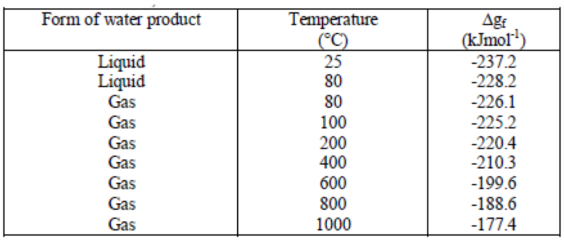
The equation above determines the amount of H2 that is needed to meet the demand load, and how much O2 is needed to feed the Cathode in order to keep the reaction continues and it will untimely provide us with data regarding water production.

During the reaction, energy will be released due to Gibbs free energy ΔG, and the Gibbs energy is the difference of (ΔG) between the reaction and the production as formula below:
ΔG of products – ΔG of reaction

$\Delta G = \Delta G$(H2O) – $\frac{1}{2}\Delta G$(O2) – ΔG(H2) (13)

Also, at the absolute temperature of 298.15 K, the enthalpy of (H2 &O2) will be zero, and the enthalpy of formation will equal the difference between product and reaction depending on the state of water (- 285.9 KJ/Mole) if it is liquid and (- 241.8 KJ/ Mole) if it is a gas [6][7].

Gibbs free energy is not constant, its change depending on the temperature and the state of (H2O) liquid or gas, as shown in fig. 5. [7] [9]



Form of water product	Temperature (°C)	Δg_f (kJmol^{-1})
Liquid	25	-237.2
Liquid	80	-228.2
Gas	80	-226.1
Gas	100	-225.2
Gas	200	-220.4
Gas	400	-210.3
Gas	600	-199.6
Gas	800	-188.6
Gas	1000	-177.4

Fig.5. Shows the amount of Gibbs free energy depending on the state of H2O & T. [9]

III. PERFORMANCE OF FUEL CELL

1- Thermodynamic

Under standard conditions, the amount of energy (ΔG) that will be delivered to the load as

$$\Delta H - T^* \Delta S \tag{14}$$

Where:
ΔG is the change in molar Gibbs free energy
ΔH is the change in molar enthalpy energy
T is absolute temperature of 298.15 K.
ΔS is the change in molar entropy
So. The thermodynamic value of ΔH and ΔG **are:**

$\Delta G(l)$ **= 237.13 KJ/mole** **&** $\Delta H(l)$ = 285.13 KJ/mole
$\Delta G(g)$ **= 228.57 KJ/mole** **&** $\Delta H(g)$ = 241.82 KJ/mole

So. We will measure the efficiency of FC during multiple states.

A- The efficiency of the theoretical dynamic when liquidity situation is

$$\eta_{th(l)} = \frac{\Delta G(l)}{\Delta H(l)} \times 100 = \frac{\mathbf{237.13\ KJ/mole}}{285.13\ KJ/mole} \times 100 = 83.16\ \%$$

(liquid)

B- The efficiency of the theoretical dynamic when gas situation is

$$\eta_{th(g)} = \frac{\Delta G(g)}{\Delta H(g)} \times 100 = \frac{228.57\ KJ/mole}{241.82\ KJ/mole} \times 100 = 94.5\ \%$$

(gas) [9].

2- Electrical efficiency $\boldsymbol{\eta_{ele}}$

Before we discuss electrical efficiency, we should know and study the factors that will affect open circuit voltage, such as, gas consideration, temperature and pressure. So, fig. (6) Shows the input and output of the fuel cells.

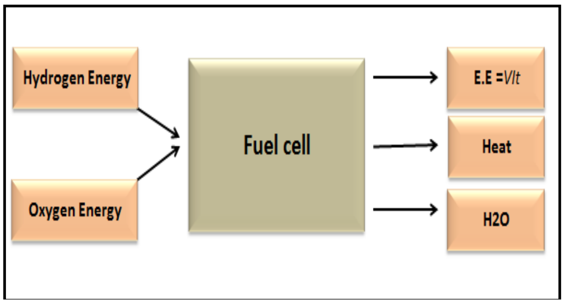


Fig.6. shows the input and output of the fuel cell

In order to calculate the power and energy output, we use the below formula.

$$P = I \times V \text{ while } \quad E = I \times V \times t \tag{15}$$

When you look at fig 2.4, you will find the input is chemical energy H2&O2, and these not easy to define because the chemical energy used enthalpy, Helmholtz and Gibbs free energy [9]. In this situation of fuel cells, if we have neglected the changing of temperature, pressure and volume, we will find that the energy will do external work which is a Gibbs free energy and it will equal the available energy that moves through the electron via an external circuit. Any work done by changing between the input and output by pressure, volume and temperature, and the available energy that will move electron is Gibbs free energy plus entropy. Fig. 2.3 mentioned above shows the values of Gibbs free energy, and we indicate the values that are negative, which means that the energy is released. If the fuel cell is reversible, which mean there are no loses, in this case ΔG is converted to electrical energy, and we can calculate the open circuit voltage (OCV).
If the FC is reversible:

$$\Delta G_{f=-2F} \times E \tag{16}$$

Where:
-2 being electron of H2 that passes around the external circuit. F being Faraday constant (96485 C)
E being the voltage of FC or the reversible voltage of the cell. Thus

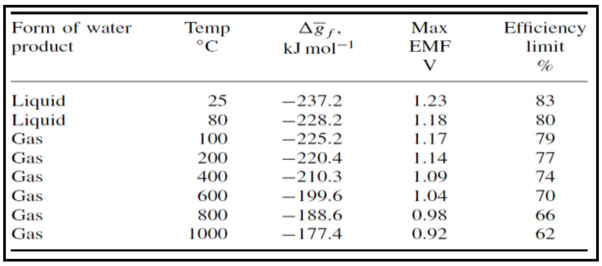
$$E=\frac{\Delta G_f}{2F} \tag{17}$$

Example to calculate OCV at (T = $25C^\circ$ and $200\ C^\circ$)

$$E_{25} = \frac{237.2KJ}{2\times96485} = 1.23\ V$$

$$E_{200} = \frac{220.4KJ}{2 \times 96485} = 1.14\ V$$

So, OCV will be affectted by temperature, which mean OCV drops if T increases as in fig.7 below.



Form of water product	Temp °C	$\Delta\bar{g}_f$, kJ mol^{-1}	Max EMF V	Efficiency limit %
Liquid	25	−237.2	1.23	83
Liquid	80	−228.2	1.18	80
Gas	100	−225.2	1.17	79
Gas	200	−220.4	1.14	77
Gas	400	−210.3	1.09	74
Gas	600	−199.6	1.04	70
Gas	800	−188.6	0.98	66
Gas	1000	−177.4	0.92	62

Fig7. Shows max OCV and efficiency limit at multi-temperatures [9]

The result is that the cell has resistant, when common measures of efficiency are considered, and the cell's resistant. This make $\boldsymbol{\eta_{ele}}$ less than thermal efficiency. So.

$$\boldsymbol{\eta_{ele}} = \frac{Maximum\ \ of\ electrical\ \ work}{\Delta H} \times 100 \tag{18}$$

If hydrogen's electron passes around external circuit, the work is W = charge × potential energy difference

$$\boldsymbol{\eta_{ele}} = \frac{W_{ele}}{\Delta H} = \frac{V_{cell}}{1.48}\ 100\% \tag{19}$$

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IV. RESULTS AND DISCUSSION

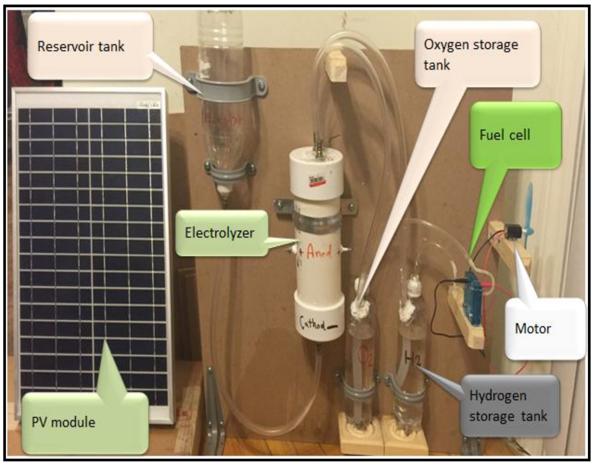


Fig.8. Shows components of the project

Gas production measuring.

There are formulas to calculate the production of gases as flowing Collected data from the source was I= 20 Amp V= 6 Volt

Using a handy calculation after you convert power to Joules per second as following:

1 Watt = 1 J / second (20)

$20 \times 6 =$ 120 W = 120 J/ second
$120 \times 3600 =$ 432 000 J/hour

One liter of water gives 1358.3L H_2 & 679.15L O_2 [11]. In order to split one liter of H_2O to H_2 and O_2, we need 13170.9 KJ

So. 13170.9KJ / 423 $\frac{KJ}{hour}$ = 31.14 hours.

To figure out how many liters of H_2 per hour as following.

1358.9 liter / 31.14 h = 43 liters / hour. (21)

To figure out how many liters of O_2 per hour as following:

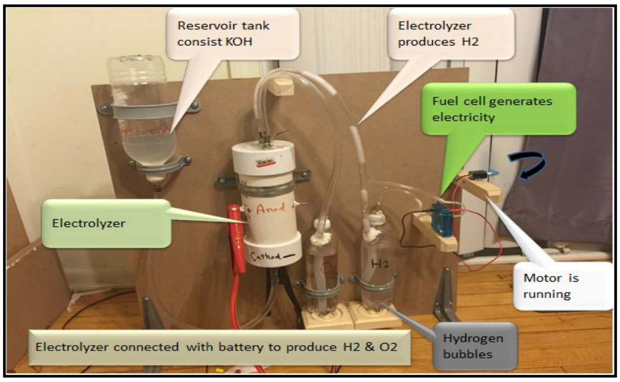
679.15 liter / 31.14 h = 21.81 liter / hour (22)

From equation (8) the efficiency of the electrolyzer at RTP $= \frac{1.481}{V\ cell} = \frac{1.481V}{6V} \times 100 = 24.68$ %

From the equation (21) and (22), it is clear that the electrolyzer has the ability to introduce enough gases 43 L / hour for hydrogen, we want to indicate that the amount of gas depends on current as eq .(9) . $H_2 = \frac{I}{2\,F} = \frac{I}{2 \times 96485.3}$. So, for this issue, we have replaced the PV module via battery that have the capacity to deliver the current demand.

In fig.9, which connects the battery with the electrolyzer, H_2 and O_2 are producing and stores in the tank and in the same time the FC feeds the load by electricity as shown in fig.9 below.

In fig. (10), we disconnected the battery in order to simulate the intermittent and fluctuating renewable energy. And we discovered that the electrolyzer will have stopped producing gases, but the FC has been generating electricity which is the result of using the gases in storage, see fig.(10)



A Condition found in fig. (9) Shows electrolyzer producing gases and the FC generates electricity

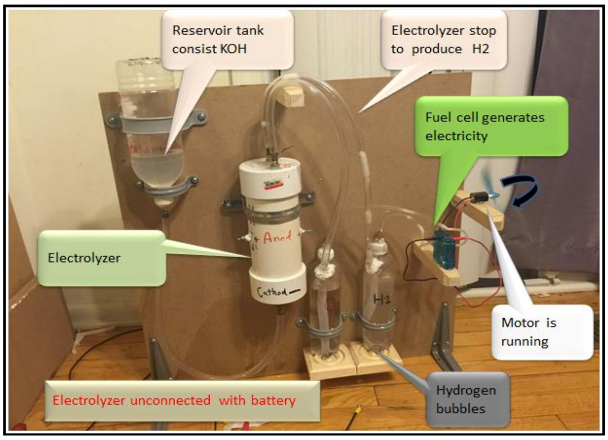


Fig.(10) shows when power was no longer supplied to the electrolyzer but the FC had been generating past power.

V. CONCLUSION

In this paper, the fuel cell was integrated with the electrolyzer to compensate for the lack of PV generation result caused by blocked sunlight or environmental conditions. This model is a practical experiment which will help students to understand the basic idea of renewable energy, and from results that shown in fig.(3.8) and fig.(3.7), we see that an increase of the current will lead to an increase in the hydrogen flow rate. This is important when producing enough gas in order to use it.

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