Hydrogen Fuel Cell Technology: Emerging Trend in Renewable Energy Systems

Irmiya Bitrus
Department of Electrical/Electronic Engineering, The Federal Polytechnic Ilaro, Ogun State, Nigeria
b011823k@student.staffs.ac.uk; irmiya.bitrus@federalpolyilaro.edu.ng

Abstract

The NetZero agenda of 2050 requires a total switchover from the use of fossil fuel to renewable energy in all human activity for healthier and sustainable environment. It is as a result of the quest in the carbon neutrality that the need for a cleaner source of energy such as hydrogen fuel is at the front burner of modern technology. This paper presents the experimental research work on the determination of performance characteristics (reaction profile) of hydrogen fuel cell as a function of production time and the volume of hydrogen fuel. Mathematical model was used for theoretical determination of the cell efficiency; and the MATLAB software was used to determine the relationship between the volume, production time and the efficiency of the hydrogen generator. A positive linear relationship was observed for volume-Time curve, the generator efficiency decreases time increase in time as well as increase in volume.

Keywords: *carbon neutrality, hydrogen fuel cell, MATLAB software plot, efficiency, renewable energy.*

Introduction

It is beyond dispute that, as the world strives to achieve the NetZero objective of carbon emissions, the sooner we reduce our reliance on fossil fuels and increase our reliance on other clean energy sources, such as hydrogen fuel, the better (Aien & Mahdavi, 2020). Pure H_2 molecules do not exist for hydrogen. It may be used in large amounts because it is present in molecules like water and methane (Yan et al., 2022). The term "green hydrogen" refers to hydrogen produced through electrolysis from water molecules using a low carbon approach (Hwang & Choi, 2017).

A hydrogen fuel cell is an electrochemical membrane that converts chemical energy found in the fuel and oxidising agent into electrical energy by means of reduction and oxidation reaction cycles (Xie et al., 2022). Hydrogen fuel cells create energy that is safe, dependable, and effective. Instead of needing to be recharged like batteries do, it continuously creates hydrogen as long as the source is attached. An electrolyte membrane, cathode, and other elements make up a fuel cell (Sapkota et al., 2022). A catalyst splits the hydrogen molecules into protons and electrons when hydrogen flows through the anode and oxygen through the cathode (Gao et al., 2022). In order to create electricity and extra heat, protons must travel through a permeable electrolyte membrane while electrons must push through a circuit (Munson, 2016). At the cathode, oxygen, electrons, and protons come together to produce water molecules (Cruz-Manzo et al., 2013).

Since there are no moving parts in hydrogen fuel cell, it has the benefit of not experiencing wear and tear. As a result, it requires less upkeep and has great reliability. Fuel cells are environmentally friendly since they operate quietly (Bethoux, 2020).

Different hydro fuel cell types are offered in various scales and sizes. Among them are some of the followings: Fuel cells made of phosphoric acid, polymer membranes, solid oxide, alkaline, direct methanol, and molten carbonate are a few examples (Ghazanfari Holagh et al., 2022).

1.1 Chemical Reaction and Parameters for Hydrolysis

When a water molecule is added to a substance, the water molecule and the substance are split into two separate components, a process known as hydrolysis occurs (Jin et al., 2019). As a result, one portion of the target molecule gains hydrogen. At the anode, a catalyst oxidises the hydrogen, causing an electron discharge (Li & Nguyen, 2020).

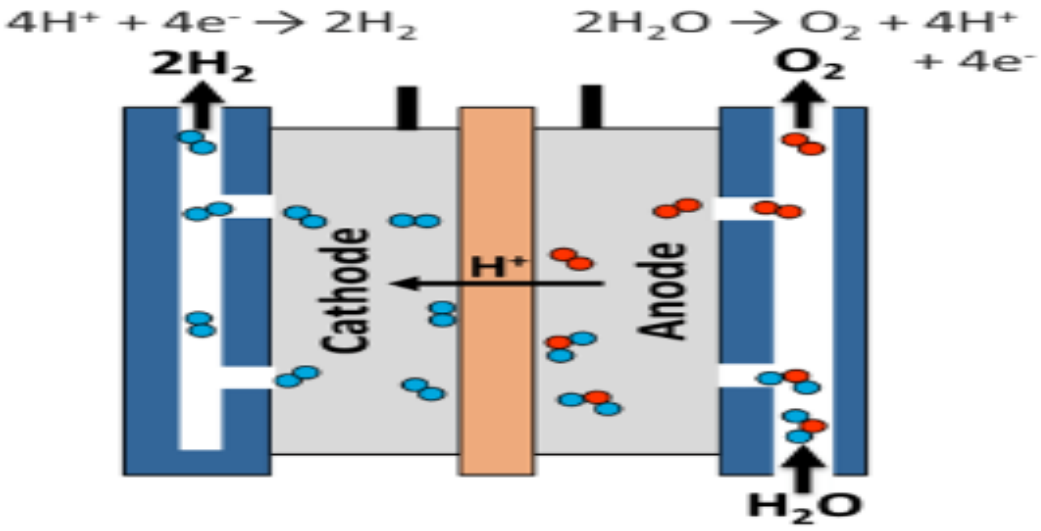


Figure 1.1: the schematic diagram of a hydrogen fuel cell. (U.S DEPARTMENT Of ENERGY, 2019)

Anode Reaction:

$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$ (1)

Cathode Reaction:

$4H^+ + 4e^- \rightarrow 2H_2$ (2)

Every time there is an electron flow from the anode, the negative cell in the hydrolysis process is created. From the outer circuit to the cathode, where they eventually become the positive pole of the cell, the electrons flow (Putheti et al., 2022). Hydrogen ions are simultaneously reduced (gain electrons) as they pass across the membrane and reach the cathode. The electrolysis method aids in the hydrolysis process (Garbe et al., 2020).

1.2 The Gas Constant, Fuel Value and the Heating Value

The amount of energy generated by one gram of fuel is the fuel value of hydrogen. The higher the energy density, the less energy is needed to transfer the fuel since it takes more energy to lift or move an object with a lot of mass (Nasharudin et al., 2014). As such, these properties of hydrogen make it possible for the fuel cell to operate at a very high efficiency and great reliability (Migliardini et al., 2017).

Hydrogen has the highest gas constant among all the ideal gases, this means that it has the highest energy at a particular temperature than all other ideal gases this makes it suitable for long hour operation at constant temperature (Heng et al., 2017).

The amount of heat released during hydrogen fuel use is its heat value. It serves as a gauge for energy density (Endo et al., 2020). The various properties of hydrogen which makes a perfect fuel for efficient system operation is highlighted in table 1.1.

Table 1.1: comparison of properties of ideal gases at room temperature (300K or 27^{o}C) (Bhattacharjee & Paolini, 2009)

Gas	Formula	Molar Mass	Gas constant	Specific Heat at Const. Press.	Specific Heat at Const. Vol.	Specific Heat Ratio
		M[kg/kmol]	R[kJ/kg.K]	Cp[kJ/kg.K]	Cv[kJ/kg.K]	k = Cp/Cv
Air	--	28.97	0.287	1.005	0.718	1.4
Argon	Ar	39.948	0.2081	0.5203	0.3122	1.667
Butane	C4H10	58.124	0.1433	1.7164	1.5734	1.091
Carbon Dioxide	CO2	44.01	0.1889	0.846	0.657	1.289
Carbon Monoxide	CO	28.011	0.2968	1.04	0.744	1.4
Ethane	C2H6	30.07	0.2765	1.7662	1.4897	1.186
Ethylene	C2H4	28.054	0.2964	1.5482	1.2518	1.237
Helium	He	4.003	2.0769	5.1926	3.1156	1.667
Hydrogen	H2	2.016	4.124	14.307	10.183	1.405
Methane	CH4	16.043	0.5182	2.2537	1.7354	1.299
Neon	Ne	20.183	0.4119	1.0299	0.6179	1.667
Nitrogen	N2	28.013	0.2968	1.039	0.743	1.4
Octane	C8H18	114.231	0.0729	1.7113	1.6385	1.044
Oxygen	O2	31.999	0.2598	0.918	0.658	1.395
Propane	C3H8	44.097	0.1885	1.6794	1.4909	1.126
Steam	H2O	18.015	0.4615	1.8723	1.4108	1.327

3.0 Methodology

3.1 Determining Fuel Cell Characteristic

The characteristics of the hydrogen fuel cell is determined by its electrical behaviour during the hydrogen production process. This behaviour is determined in terms of the relationship between current and voltage as well as the power and voltage produced during the electrolysis.

3.2 Materials/Equipment

The following are the materials and equipment which were used for the experiment: Storage Cells, Power Supply Unit, Connecting Cables, Electrolyser, Hose, Time Recording Devices, Hose clamps, four (4) Number of Connecting Hoses, Stop Clock, Distilled Water.

3.3 Precautions

The experiment was managed such that the target voltage does not exceed 2.3V to avoid excessive high voltage which may damage the equipment.

3.4 Experimental Setup

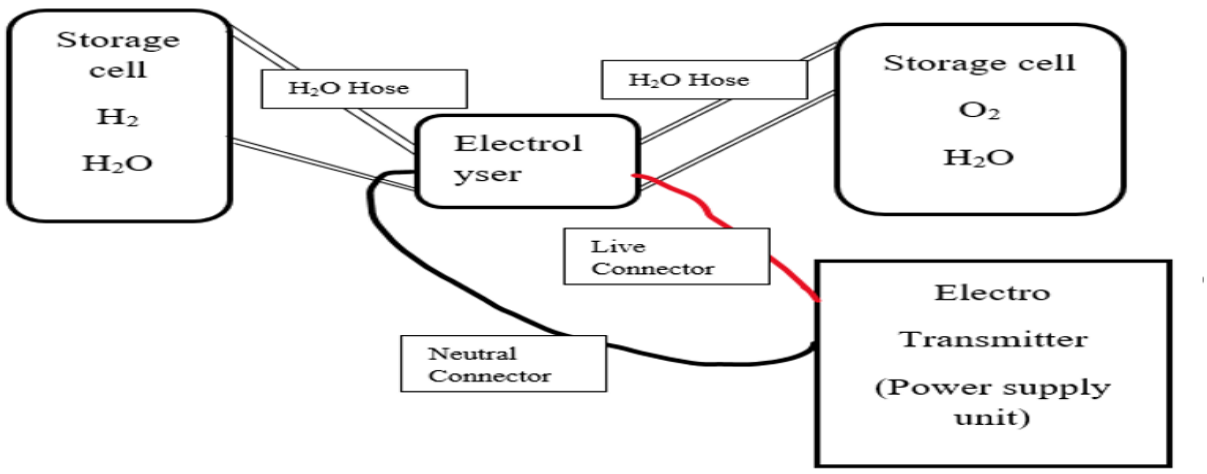


Figure 3.1: Experimental setup for hydrogen fuel generator

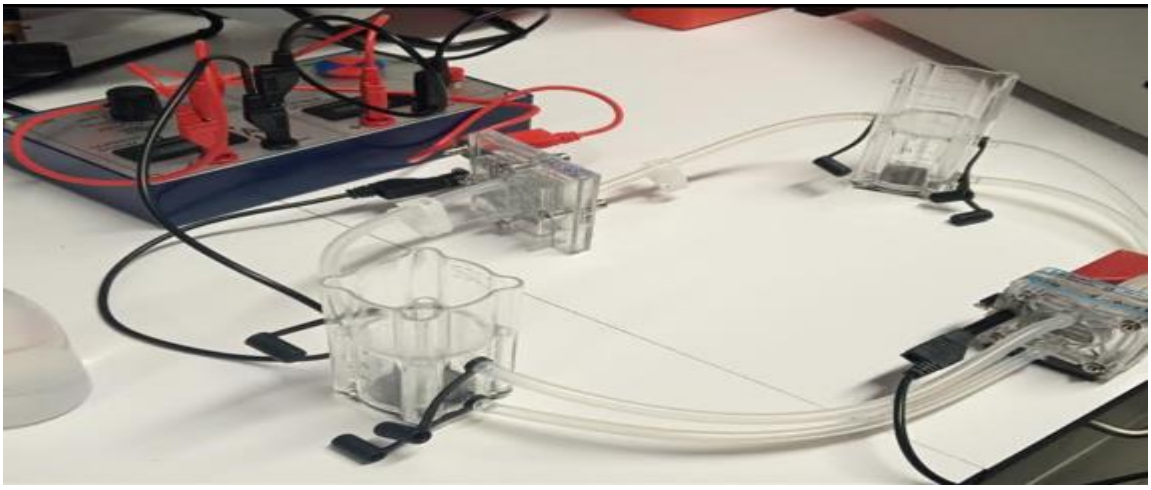


Figure 3.2: the setup of a Polymer Electrolyte Membrane (PEM) or hydrogen generator

At the anode, water reacts to produce positively charged hydrogen ions and oxygen (protons). The hydrogen ions move arbitrarily across the PEM to the cathode as the electrons go through an external circuit. Hydrogen gas is created at the cathode when hydrogen ions interact with electrons from the external circuit.

3.5 Experimental Procedure:

- The equipment was setup as shown in the block diagram in figure 3.2
- Distilled water was used to fill in the storage cells to a required volume of 30cm^3.
- The storage cells were emptied of oxygen and hydrogen.
- The storage cells ventilation points were closed before operation.
- The current of 600mA was set as a target current before the electrolyser.
- The current and the voltage generated by the device was recorded accordingly.
- The time, volume, current and voltage values were recorded.
- The observation was done in the interval of 5cm^3 starting from 10cm^3 until the volume of 30cm^3 was reached.
- The efficiency of the hydrogen fuel cell was determine using the mathematical model as shown in equation (3).

$$\eta = \frac{V_H \times H_u}{V \times I \times t} \qquad (3)$$

Where: *HU* = 9.9x10^6 J m^{-3} **(**lower heating value of hydrogen**),** hydrogen generator currents I, hydrogen generator voltage V; t is a time it takes to produce a particular volume of hydrogen; and V_H is the volume of hydrogen produced.

Efficiency at time t = 124s, current of 0.6A, hydrogen volume of 10m^3 and the generator voltage of 1.78V is given by:

$$\eta = \frac{V_H \times H_u}{V \times I \times t} = \frac{10 \ x \ 9.9x106}{1.78 \ x \ 0.6 \ x \ 124} = \mathbf{74.755\%}$$

Efficiency at time t = 191s, current of 0.6A, hydrogen volume of 15m^3 and the generator voltage of 1.78V is given by:

$$\eta = \frac{V_H \times H_u}{V \times I \times t} = \frac{15 \ x \ 9.9x106}{1.78 \ x \ 0.6 \ x \ 191} = \mathbf{72.798\%}$$

Efficiency at time t = 255s, current of 0.6A, hydrogen volume of 20m^3 and the generator voltage of 1.78V is given by:

$$\eta = \frac{V_H \times H_u}{V \times I \times t} = \frac{20 \ x \ 9.9x106}{1.78 \ x \ 0.6 \ x \ 255} = \mathbf{72.703\%}$$

Efficiency at time t = 327s, current of 0.6A, hydrogen volume of 25m^3 and the generator voltage of 1.78V is given by:

$\eta = \frac{V_H \times H_u}{V \times I \times t} = \frac{25x\ 9.9x106}{1.78\ x\ 0.6\ x\ 327} = \mathbf{70.869\%}$

Efficiency at time t = 393s, current of 0.6A, hydrogen volume of 30m^3 and the generator voltage of 1.78V is given by:

$\eta = \frac{V_H \times H_u}{V \times I \times t} = \frac{20x\ 9.9x106}{1.78\ x\ 0.6\ x\ 393} = \mathbf{70.761\%}$

4.0 Results and Discussion

4.1 Determination of Hydrogen Fuel Cell Efficiency

Efficiency at different time and volume was determined and the results were recorded in table 4.1 below.

Table 4.1: measured parameters of the electrolysis to determine the efficiency of hydrogen generator.

Hydrogen Volume (cm^3)	Time (s)	Voltage (mV)	Current (A)	Current (mA)	Efficiency (%)
10	124	1780	0.60	600	74.755
15	191	1780	0.60	600	72.798
20	255	1780	0.60	600	72.703
25	327	1780	0.60	600	70.869
30	393	1780	0.00	600	70.7610

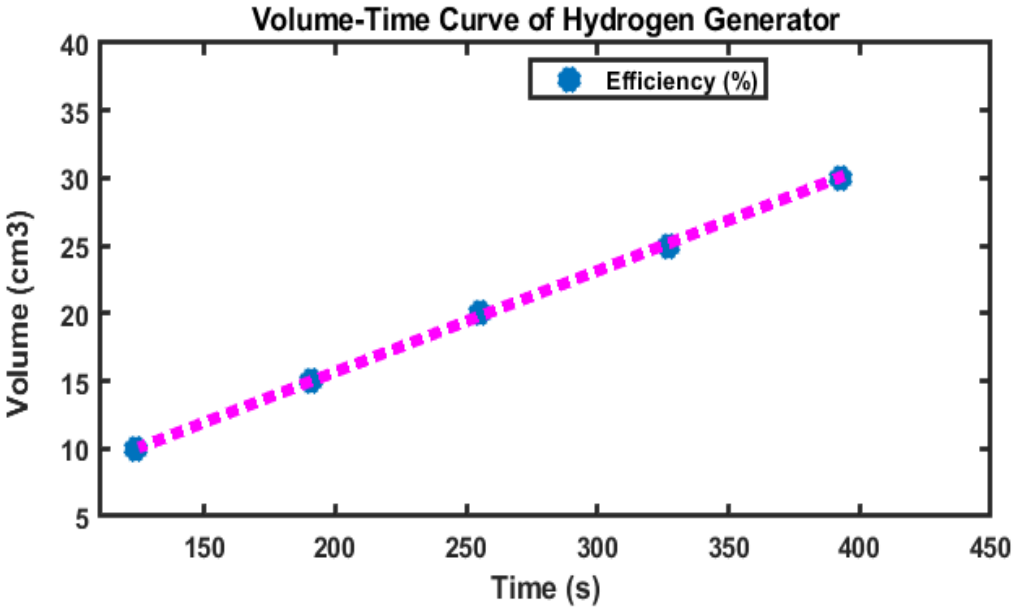


Figure 4.1: a volume versus time graph of hydrogen generator

The hydrogen generator's volume versus time graph is a liner graph. This shows that as the amount of hydrogen produced by the generator grows, the production time increases. The amount of hydrogen produced at time 61 seconds was $5cm^3$. When the timer reached 124 seconds, the generator produced $10cm^3$ of hydrogen.

At time 393 seconds, the largest amount of hydrogen produced was $30cm^3$. This implied linear reaction profile. That is, as long as the production volume of the hydrogen fuel cell increases, the production time will always be proportionate as indicated in figure 4.1. This is due to the fact that time, t and the amount of hydrogen created V_H are directly related. While t is in the denominator, V_H is in the numerator.

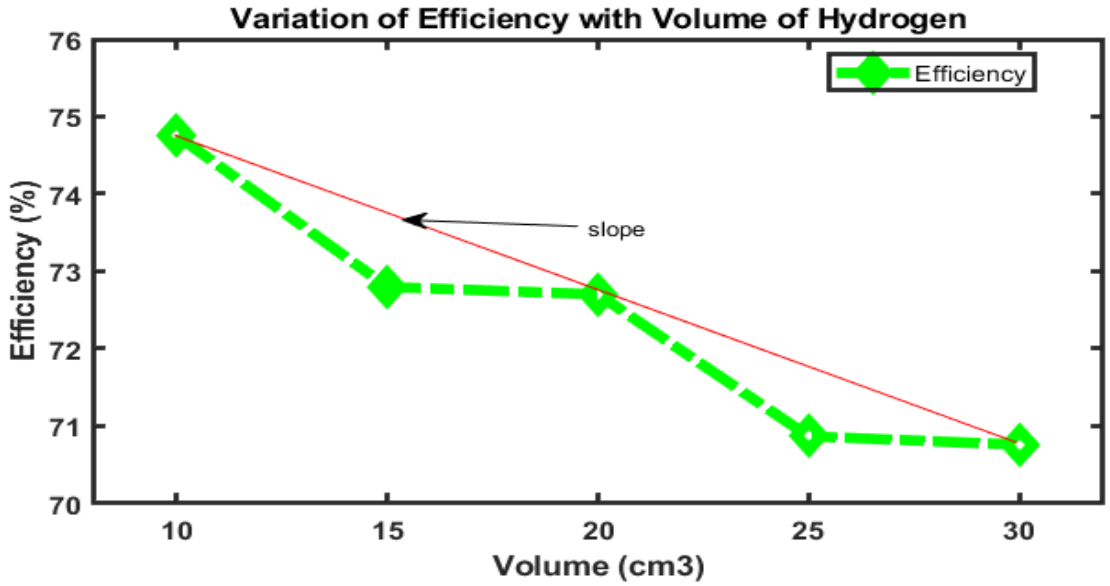


Figure 4.2: the variation of efficiency with Volume of a hydrogen fuel generator

The variation of efficiency with respect to increase in volume of a hydrogen fuel generator is depicted by figure 4.2. It is seen that the system efficiency is high at low volume of production but decreases with increase in volume of production. The variation is linear at the start of the production of $5cm^3$ and stabilises for another $5cm^3$. The trend repeated itself until it got the highest production volume of $30cm^3$. Overall, the trend is nonlinear; and this suggest that the system is real; and its efficiency could be improved upon.

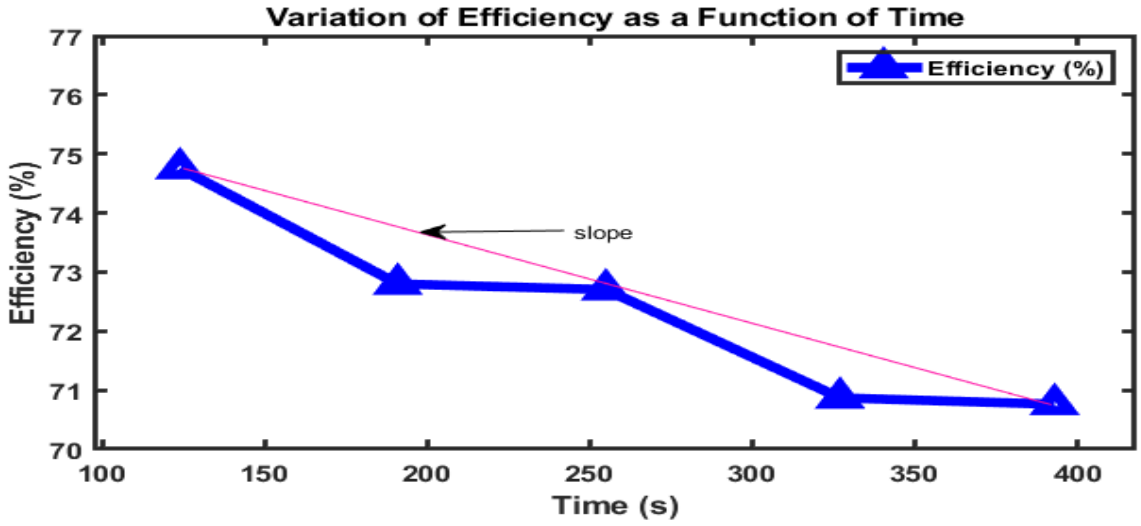


Figure 4.3: the variation of efficiency with Time of a hydrogen fuel generator

Figure 4.3. depicts the variation of efficiency with production time of a hydrogen fuel generator. A corresponding decrease in system efficiency with increase in the production time could be observed. Linear decreasing variation at the start of the production is observed but became stable after each 100s production time. The trend continues until the highest production time is reached. The overall characteristic is observed to be nonlinear decreasing, and this suggested instability in the system efficiency with increase in the production time of the hydrogen fuel.

4.2 MATLAB Code

The code for the plot of the characteristic curve was created in MATLAB software and presented in the appendix section of this article.

5.0 Conclusions

The mathematical and experimental procedures for calculating the efficiency of the hydrogen fuel generator were carefully examined. The system characteristics with variation in the production time as well as the volume of the hydrogen fuel produced were critically analysed. Additionally, a method for determining the hydrolysis's parameters as well as the chemical reaction's equation were described. Physical parameters that affect the efficiency of the hydrogen generator, such as fuel value, gas constant, and heating value, were thoroughly studied.

It is observed that the efficiency of the hydrogen generator is a function of the production and the volume of the hydrogen fuel produced. The trend of the variation is nonlinear and hence could be controlled.

6.0 References

Bhattacharjee, S. (Sooby), & Paolini, C. (2009). Property evaluation in The Expert System for Thermodynamics ("TEST") web application. *Calphad*, *33*(2), 343–352. https://doi.org/10.1016/j.calphad.2008.10.008

U.S DEPARTMENT Of ENERGY. (2019). *Hydrogen Production: Electrolysis*. Energy.gov. https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis

Aien, M., & Mahdavi, O. (2020). On the Way of Policy Making to Reduce the Reliance of Fossil Fuels: Case Study of Iran. *Sustainability*, *12*(24), 10606. https://doi.org/10.3390/su122410606

Yan, Q., Ketelboeter, T., & Cai, Z. (2022). Production of COx-Free Hydrogen and Few-Layer Graphene Nanoplatelets by Catalytic Decomposition of Methane over Ni-Lignin-Derived Nanoparticles. *Molecules*, *27*(2), 503. https://doi.org/10.3390/molecules27020503

Hwang, G.-J., & Choi, H.-S. (2017). Hydrogen Production Systems through Water Electrolysis. *Membrane Journal*, *27*(6), 477–486. https://doi.org/10.14579/membrane_journal.2017.27.6.477

Xie, M., Chu, T., Wang, X., Li, B., Yang, D., Ming, P., & Zhang, C. (2022). Effect of mesoporous carbon on oxygen reduction reaction activity as cathode catalyst support for proton exchange membrane fuel cell. *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2022.06.131

Sapkota, P., Brockbank, P., & Aguey-Zinsou, K.-F. (2022). Development of self-breathing polymer electrolyte membrane fuel cell stack with cylindrical cells. *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2022.05.175

Gao, M., Konysheva, E. Y., & Yang, J. (2022). Tailoring kinetics of Cr-chemisorption over La0.6Sr0.4Fe0.8Co0.2O3 cathode material through its porosity variation. *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2022.03.076

Munson, S. (2016). Gas-Electric Harmonization Must Come Through Process Improvements. *Natural Gas & Electricity*, *32*(11), 24–26. https://doi.org/10.1002/gas.21911

Cruz-Manzo, S., Chen, R., & Rama, P. (2013). Study of current distribution and oxygen diffusion in the fuel cell cathode catalyst layer through electrochemical impedance spectroscopy. *International Journal of Hydrogen Energy*, *38*(3), 1702–1713. https://doi.org/10.1016/j.ijhydene.2012.08.141

Bethoux, O. (2020). Hydrogen Fuel Cell Road Vehicles and Their Infrastructure: An Option towards an Environmentally Friendly Energy Transition. *Energies*, *13*(22), 6132. https://doi.org/10.3390/en13226132

Ghazanfari Holagh, S., Abdollahi Haghghi, M., & Chitsaz, A. (2022). Which methane-fueled fuel cell is of superior performance in CCHP applications; solid oxide or molten carbonate? *Fuel*, *312*, 122936. https://doi.org/10.1016/j.fuel.2021.122936

Jin, Y., Kida, M., & Nagao, J. (2019). Structure H Clathrate Hydrates in Methane−Halogenic Large Molecule Substance–Water Systems. *The Journal of Physical Chemistry C*, *123*(28), 17170–17175. https://doi.org/10.1021/acs.jpcc.9b04691

Li, Y., & Nguyen, T. V. (2020). High Hydrogen Evolution Reaction (HER) and Hydrogen Oxidation Reaction (HOR) Activity RhxSy Catalyst Synthesized with Na2S for Hydrogen-Bromine Fuel Cell. *Energies*, *13*(15), 3971. https://doi.org/10.3390/en13153971

Putheti, P., Sharma, V. K., Friedlander, R., Menon, A., Dadhania, D., Muthukumar, T., & Suthanthiran, M. (2022). T-Cell-Positive, B-Cell-Negative Flow Cytometry Crossmatch: Frequency, HLA Locus Specificity, and Mechanisms Among 3073 Clinical Flow Cytometry Crossmatch Tests. *Experimental and Clinical Transplantation*, *20*(2), 180–189. https://doi.org/10.6002/ect.2021.0334

Garbe, S., Schmidt, T. J., & Gubler, L. (2020). Elevated Temperature Proton Exchange Membrane Water Electrolysis for Reduced Cost of Green Hydrogen Production. *ECS Meeting Abstracts*, *MA2020-02*(38), 2452–2452. https://doi.org/10.1149/ma2020-02382452mtgabs

Nasharudin, M. N., Kamarudin, S. K., Hasran, U. A., & Masdar, M. S. (2014). Mass transfer and performance of membrane-less micro fuel cell: A review. *International Journal of Hydrogen Energy*, *39*(2), 1039–1055. https://doi.org/10.1016/j.ijhydene.2013.09.135

Migliardini, F., Di Palma, T. M., Gaele, M. F., & Corbo, P. (2017). Hydrogen purge and reactant feeding strategies in self-humidified PEM fuel cell systems. *International Journal of Hydrogen Energy*, *42*(3), 1758–1765. https://doi.org/10.1016/j.ijhydene.2016.06.196

Heng, Z., Mingjie, L., Haiping, C., & Chentao, Y. (2017). Experimental Study of Constant Temperature Operation and Constant Flow Operation in Concentrating PV / T System. *Energy Procedia*, *105*, 869–874. https://doi.org/10.1016/j.egypro.2017.03.403

Endo, N., Segawa, Y., Goshome, K., Shimoda, E., Nozu, T., & Maeda, T. (2020). Use of cold start-up operations in the absence of external heat sources for fast fuel cell power and heat generation in a hydrogen energy system utilizing metal hydride tanks. *International Journal of Hydrogen Energy*, *45*(56), 32196–32205. https://doi.org/10.1016/j.ijhydene.2020.08.194

7.0 Appendix

7.1 MATLAB Code for the Efficiency Curve

```
function createfigure(X1, Y1)
%CREATEFIGURE(X1, Y1)
%  X1:  scatter x
%  Y1:  scatter y

% Create figure
figure1 = figure('InvertHardcopy','off','Color',[1 1 1]);

% Create axes
axes1 = axes('Position',...
   [0.13 0.178966789667897 0.771234567901235 0.693726937269373]);
hold(axes1,'on');

% Create scatter
scatter(X1,Y1,'DisplayName','Efficiency (%)','LineWidth',10,...
   'MarkerFaceColor',[0 1 0],...
   'Marker','*');

% Create ylabel
```

```
ylabel({'Volume (cm3)'},'HorizontalAlignment','center','FontWeight','bold',...
    'FontSize',13.2);

% Create xlabel
xlabel({'Time (s)'},'HorizontalAlignment','center','FontWeight','bold',...
    'FontSize',13.2);

% Create title
title('Volume-Time Curve of Hydrogen Generator',...
    'HorizontalAlignment','center',...
    'FontWeight','bold',...
    'FontSize',13.2);

% xlim(axes1,[110 450]);
% ylim(axes1,[5 40]);
% zlim(axes1,[-1 1]);
box(axes1,'on');
hold(axes1,'off');
% Set the remaining axes properties
set(axes1,'FontSize',12,'FontWeight','bold','LineWidth',2);
% Create legend
legend1 = legend(axes1,'show');
set(legend1,...
    'Position',[0.502181560796835 0.788597332085805 0.205056175798847 0.0603674525820364],...
    'FontSize',10.8);

% Create line
annotation(figure1,'line',[0.775034293552812 0.164609053497942],...
    [0.677121771217712 0.27859778597786],'Color',[1 0 1],'LineWidth',5,...
    'LineStyle',':');
```