Montana Tech Library

Digital Commons @ Montana Tech

Graduate Theses & Non-Theses

Student Scholarship

Spring 2022

INCREASING HYDROGEN PRODUCTION IN ELECTROLYSIS WITH A MAGNETIC FIELD

Laurie Battle

Follow this and additional works at: https://digitalcommons.mtech.edu/grad_rsch

Part of the Other Civil and Environmental Engineering Commons

INCREASING HYDROGEN PRODUCTION IN ELECTROLYSIS WITH A MAGNETIC FIELD

by

Laurie Battle

A project report submitted in partial fulfillment of the
requirements for the degree of

Master of Science in Environmental Engineering

Montana Tech
2022

Abstract

Hydrogen is an important energy carrier that has no carbon emissions when energy is extracted and also can be used as energy storage to increase the practicality of many renewable energy sources. The prominent methods of hydrogen production make use of fossil fuels, resulting in carbon emissions. Electrolysis is a lesser used technology for hydrogen production in which electricity splits water molecules into oxygen and hydrogen gases. If the electricity is sourced from renewable energies, this process releases little to no carbon and the resulting hydrogen is termed "green hydrogen." While electrolysis and fossil fuel methods have comparable efficiencies of hydrogen production, the use of electricity results in electrolysis having a significantly higher cost. To make electrolysis feasible for large-scale hydrogen production, energy losses must be decreased to improve its efficiency. This study investigates the combined impact of electrolyte concentration and the application of a magnetic field on hydrogen production rates in alkaline electrolysis. Previous studies have shown the existence of an optimal electrolyte concentration that results in the highest rate of hydrogen production, typically around 30 wt% at room temperature. Other studies have shown that applying a magnetic field increases the conductivity of the electrolyte solution, which should increase the rate of hydrogen production. If the magnetic field is oriented to result in an upward Lorentz force, the resulting convection along with the Lorentz force encourages gas bubbles to dislodge from the electrodes, which reduces resistance and increases the active area of the electrodes. In this project, alkaline electrolysis was performed at room temperature using 1.8 V with KOH as the electrolyte. The flow rate of the electrolyte solution was fixed at 50 cc/min, and the volume of hydrogen produced was measured with a water displacement system. The electrolyte concentration was varied between 5 wt% - 30 wt%. At each selected concentration level, electrolysis was performed once without a magnet and once with a 1T magnetic field, created by permanent magnets oriented to create an upward Lorentz force. The results showed that at each concentration level, the magnetic field increased the rate of hydrogen production, with the largest increase at 10 wt%. The optimal concentration was approximately 30 wt% with no magnetic field, but with a 1 T magnetic field the optimal concentration was reduced to 10 wt%. Thus, applying a magnetic field calls for a reduction in electrolyte concentration, which results in cost savings, in addition to the benefit of a higher hydrogen production rate.

Keywords: Alkaline electrolysis, Hydrogen production, Magnetic field, Electrolyte concentration, Gas bubbles

Acknowledgements

I wish to thank Dr. Kumar Ganesan, my advisor for this project, for his guidance and support. I also thank all of the faculty members in the department of Environmental Engineering for sharing their expertise. I want to express thanks in particular to my committee: Dr. Kumar Ganesan and Dr. Robin Bullock in Environmental Engineering, and Dr. John Kirtley in Chemistry.

Table of Contents

List of Tables

List of Figures

List of Equations

Introduction

The use of renewable energies is growing in response to declining reserves of fossil fuels and to the need for reducing carbon emissions associated with combustion of fossil fuels. Many types of renewable energies have fluctuations in their energy supply, and a variety of energy storage devices have been developed to address this issue. Hydrogen is a promising energy carrier and is thought to be an essential component of a renewable energy future (Momirlan & Veziroglu, 2005), particularly since energy extraction from hydrogen produces no carbon emissions. As an energy carrier, hydrogen could improve the feasibility of renewable energy sources by providing stored energy during periods of low production. However, the current primary methods for hydrogen production make use of fossil fuels. Electrolysis, a lesser used technology for hydrogen production, releases little to no carbon emissions when powered by renewable energy sources, but its efficiency must be increased to make electrolysis more competitive with fossil fuel methods. This project is an attempt to improve the rate of hydrogen production in electrolysis by using a magnetic field.

1. Literature Review

1.1. Hydrogen as an Energy Carrier

Although hydrogen is abundant in nature, it rarely exists by itself and must be produced from another energy source. As such, hydrogen is an energy carrier, and its stored energy can be extracted when needed. A major advantage of hydrogen is that no greenhouse gas emissions result from energy extraction. Energy can be extracted from hydrogen by combustion to produce heat, with water and a small amount of nitrogen oxides as byproducts, or through fuel cells to produce electricity, with water and heat as the only byproducts (Lewis, 2021). A variety of hydrogen production technologies have been developed, but most hydrogen today is produced using fossil fuels, resulting in emissions of CO_2 and CO (Godula-Jopek, 2015). Water electrolysis, currently the secondary source of hydrogen production, uses electricity as the energy source. If the electricity is sourced from renewables, the carbon emissions associated with hydrogen production are minimal.

Although hydrogen has a higher energy content per unit mass than many energy sources, its energy content per unit volume is smaller due to the low density of hydrogen. To reduce the storage space, hydrogen is typically stored as either a compressed gas or as a cryogenic liquid, both of which require additional energy input. The large energy requirement to achieve cryogenic temperatures makes this option less efficient compared to storage as a compressed gas (Chisholm & Cronin, 2022). Electrolysers can be designed to produce hydrogen in partially compressed form with little additional energy expenditure, leaving a smaller amount of compression to be completed post-production (Godula-Jopek, 2015).

Stored hydrogen has a variety of applications, the earliest of which involved transportation, beginning in the 18th century with balloon travel. The first internal combustion vehicle was built in the early 19th century, with hydrogen and oxygen as the fuel source. In the 20th century, hydrogen began to be used as fuel for submarines and rockets, and the development of the fuel cell led to cars fueled by hydrogen (Godula-Jopek, 2015).

1.2. Methods of Hydrogen Production

Nearly all hydrogen production today (~95%) is via methods using fossil fuels (Chisholm & Cronin, 2022). One such method is steam methane reforming, in which hydrogen is separated from hydrocarbon fuels through a reaction involving steam via the reaction

$$\mathrm{CH_4 + 2H_2O \rightarrow CO_2 + 4H_2}.$$

Processes using fossil fuels emit CO_2 and CO, and hydrogen produced from such methods is termed “grey hydrogen.” Water electrolysis accounts for the remaining 5% of hydrogen production. In this method, electricity is applied to split water molecules, producing hydrogen as the product and oxygen as a useful byproduct. If the electricity used to perform electrolysis is derived from renewable sources, the product is termed “green hydrogen.” Electrolysis has the advantage of producing higher purity hydrogen compared to steam reforming (Holladay et al., 2009). Several additional technologies for producing hydrogen have been developed but are less mature, including biomass gasification, thermochemical water splitting, and photoelectrolysis (Holladay et al., 2009). Steam methane reforming is the technology used for most hydrogen production today, primarily due to its lower cost. The energy requirement to produce hydrogen from electrolysis is seven times higher compared to steam methane reforming (Grigoriev et al., 2020) and the cost of electrolysis is approximately three times higher in units of US$/kWh (Schoots et al., 2008). In an effort to reduce carbon emissions, alternative hydrogen production methods, including electrolysis, are being explored to improve their efficiencies to make them more competitive with steam reforming.

1.3. Theory of Alkaline Electrolysis

Currently, three technologies exist for performing water electrolysis: alkaline, polymer electrolyte (PEM), and solid oxide. All three have the same basic design consisting of an electrolyser containing water in either liquid or gas phase, in which electrodes supply current that splits water molecules into hydrogen and oxygen (Godula-Jopek, 2015). This study focuses on alkaline electrolysis, in which an alkaline electrolyte is added to water to increase its conductivity. Hydrogen is produced at the cathode and oxygen at the anode via the following reactions:

$$\text{Cathode: } 4\mathrm{H_2O} + 4\mathrm{e^-} \rightarrow 2\mathrm{H_2} + 4\mathrm{OH^-}$$

$$\text{Anode: } 4\mathrm{OH^-} \rightarrow \mathrm{O_2} + 2\mathrm{H_2O} + 4\mathrm{e^-}$$

$$\text{Overall reaction: } 2\mathrm{H_2O} \rightarrow 2\mathrm{H_2} + \mathrm{O_2}$$

A membrane is placed between the anode and cathode to allow hydroxide ions to pass through and to keep the two product gases separated. It should be noted that fuel cells perform these reactions in reverse, taking hydrogen and oxygen as input and producing electricity and water.

Alkaline electrolysers generally have lower cost compared to other electrolysis methods, primarily due to less expensive materials. The electrodes in alkaline systems are normally nickel or steel, whereas rare metals are often used in other types of systems (Schmidt et al., 2017). However, the operating costs for all types of electrolysis, primarily due to the use of electricity, are a major limiting factor.

1.4. Improving Efficiency

The efficiency of hydrogen production can be found by dividing the amount of energy stored in the produced hydrogen by the amount of input energy (Godula-Jopek, 2015). Although the efficiency of electrolysis is similar to that of steam methane reforming (~80%), the efficiency of producing the electricity required in electrolysis must be considered, effectively reducing the efficiency of the electrolysis process. Electricity production typically has efficiency less than 60% (Suppes & Storvick, 2006). At standard temperatures, 1.23 V of electricity is required to split a water molecule (Godula-Jopek, 2015). However, the applied voltage must be larger in practice to account for energy losses, and the efficiency of electrolysis can be improved by reducing these losses.

Several modifications to electrolysis systems have been studied as a means to reduce energy losses. Efficiencies are improved at higher temperatures due to increased conductivity and decreased voltage. However, high temperatures can decrease the stability of the electrolyser and requires the use of pressurized equipment which is an additional expense (Godula-Jopek, 2015). Typical electrolytes used in alkaline electrolysis include potassium hydroxide (KOH) and sodium hydroxide (NaOH). The preferred electrolyte is KOH because it has higher specific conductivity, although it is more expensive than NaOH (Godula-Jopek, 2015). De Souza et al. (2006) achieved improved efficiencies of hydrogen production by using certain ionic liquids as electrolytes.

Several electrode materials have been tested for improving electrolysis performance. Stainless steel and lead oxide are low cost materials that are resistant to corrosion, but lose stability in alkaline solutions at high voltage. Nickel is now commonly used due to its corrosion resistance, stability in alkaline solutions, and lower cost compared to many other viable metals. Several nickel alloys have been tested to increase the active surface area and the electrocatalytic activity (Godula-Jopek, 2015). Reducing the space between the electrodes generally improves efficiency by reducing resistance (Nagai et al., 2003). To take advantage of this, “zero-gap” electrolysis cells are designed with the electrodes placed in contact with the membrane. In these designs, the electrode material may be porous to allow the electrolyte to fill the membrane that the electrodes would otherwise block (Godula-Jopek, 2015).

1.5. Impact of Electrolyte Concentration

The efficiency of alkaline electrolysis is generally improved at higher electrolyte concentrations due to increased conductivity. However, the conductivity begins to decline at high concentrations due to electrolyte hydration (Lin et al., 2012). The ideal concentrations depend on the type of electrolyte and the operating temperature. For KOH and NaOH at 25^{o}C, the optimal concentrations are approximately 30 wt% and 20 wt%, respectively, and these increase at higher temperatures (Godula-Jopek, 2015).

1.6. Impact of a Magnetic Field

During electrolysis, gas bubbles collect around the electrodes, which reduces the active area of the electrodes and increases electrical resistance. Recent studies have investigated the use of magnetic fields to manage gas bubbles and reduce energy losses. Iida et al. (2007) demonstrated that a magnetic field improves energy efficiency of alkaline electrolysis by increasing mass transfer of ions which then promotes bubble movement, resulting in reduced cell voltage at high current densities. Koza et al. (2011) showed that a magnetic field enhances hydrogen production in an acid environment by promoting desorption of gas bubbles and reduction of bubble size. Lin et al. (2012) established that electrodes made of ferromagnetic materials yield the best results due to an internal magnetic field being induced by the external magnetic field, and the resulting stronger field creates higher mass transfer that increases bubble movement. The general consensus explaining improved efficiencies in the presence of a magnetic field is the higher mass transfer of charged particles, hydroxide ions in particular, results in desorption of gas bubbles from the electrodes, thus decreasing resistance and increasing the electrodes' active area.

Lin et al. (2017) showed that a magnetic field increases the upward velocity of bubbles when the magnetic field is oriented to produce an upward Lorentz force to enhance the upward movement from the buoyancy force. The Lorentz force is given by

$$\vec{\boldsymbol{F}} = \boldsymbol{q}\vec{\boldsymbol{E}} + \boldsymbol{q}\vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}} \tag{1}$$

where $\boldsymbol{q}$ is the electric charge of the particles, $\vec{\boldsymbol{E}}$ is the electric field, $\vec{\boldsymbol{v}}$ is the particle velocity, and $\vec{\boldsymbol{B}}$ is the magnetic flux density. Due to the cross-product term in (1), the magnitude of the Lorentz force is maximized when $\vec{\boldsymbol{B}}$ is perpendicular to the direction of the current. In addition, the right-hand rule can be used to determine an appropriate orientation for $\vec{\boldsymbol{B}}$ that results in an upward Lorentz force while also keeping $\vec{\boldsymbol{B}}$ perpendicular to the current flow.

2. Materials and Methods

2.1. Research Objectives

The goal of this project is to analyze the combined effect of electrolyte concentration and an applied magnetic field on the rate of hydrogen production in alkaline electrolysis. This study builds on the work of Lin et al. (2012, 2017), which considered the impact of a magnetic field and other working parameters on current density. Since the hydrogen production rate is proportional to current, the results regarding current density should carry over to hydrogen production. This project measures the impact of the selected parameters on the hydrogen production rate directly by measuring the volume of hydrogen produced. These results will be used to determine the optimal parameter combination for improving efficiency of this type of system.

2.2. Equipment

A single cell alkaline electrolysis cell (model LBE-SC-F) was purchased from Light Bridge, Inc. to test the impact of electrolyte concentrations and a magnetic field on the rate of hydrogen production (Figure 1). The electrodes in the cell are made of nickel, a ferromagnetic material. The equipment for the experiment is shown in Figure 2. A hydrostatic pump is used to input the electrolyte solution into the cell, which is connected to a DC power supply. Hydrogen mixed with electrolyte solution is output from one valve, and oxygen mixed with electrolyte solution is output from a second valve. The oxygen/electrolyte solution is recirculated to the electrolyte solution, where the oxygen bubbles out. The hydrogen/electrolyte solution is first taken to a stoppered glass bottle to contain the liquid and allow the hydrogen to rise out of the bottle through a second tube through the stopper. The hydrogen travels to a water displacement system for measuring the volume of hydrogen produced. A magnetic field is supplied by permanent magnets, approximately 1 T, placed on either side of the electrolysis cell (Figure 3). The magnets are placed perpendicular to the electrodes and oriented to produce an upward Lorentz force. Detailed steps for conducting this experiment are provided in Appendix A.

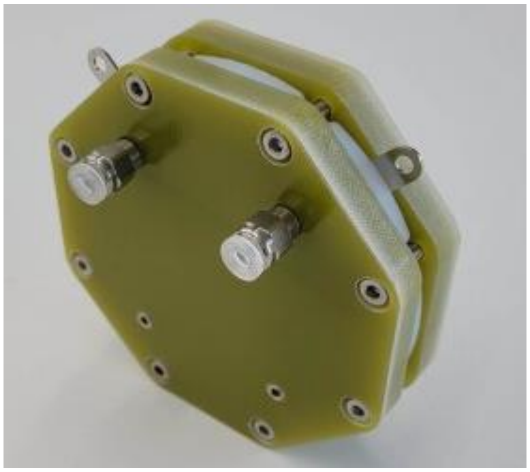

Figure 1. Alkaline electrolysis cell: 100 mm x 100 mm x 27 mm

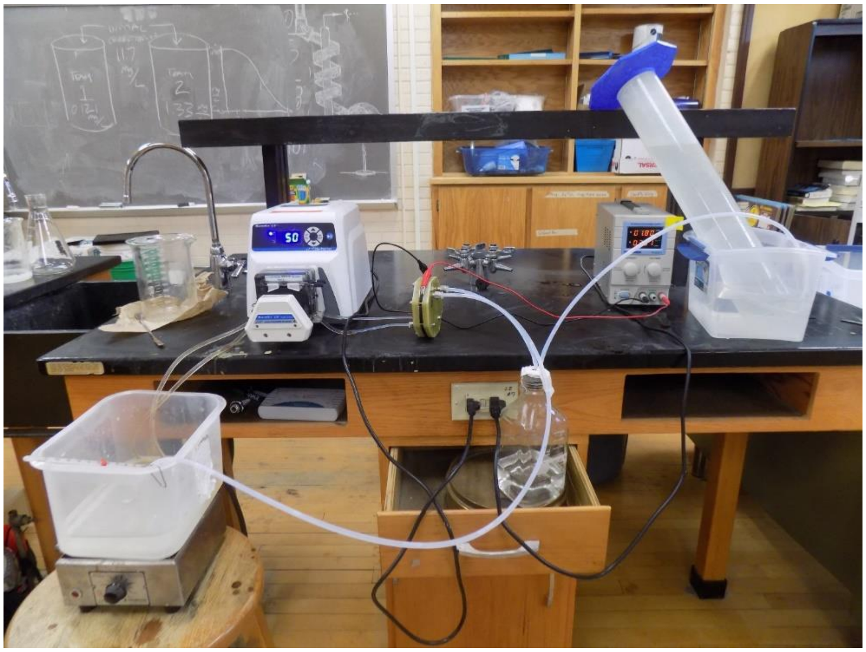

Figure 2. Lab equipment for performing electrolysis tests

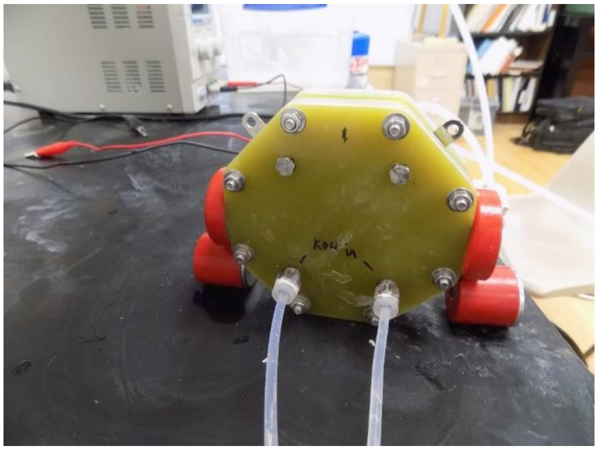

Figure 3. Placement of magnets near electrolysis cell. The magnetic field is perpendicular to the electrodes and creates an upward Lorentz force.

2.3. Experimental Design

For each trial, the pump was set at 50 cc/min, and the DC power supply provided 1.8 V, which are both recommended values from the manufacturer. The voltage 1.8 V was determined by the manufacturer to be sufficiently above the minimum of 1.23 V to account for energy losses. The system ran under atmospheric pressure at room temperature, and purified water at room temperature was used. The selected electrolyte was KOH, which was set at four concentration levels (wt%): 5%, 10%, 20%, and 30%. Electrolysis was performed at each of the selected electrolyte concentration levels once without and once with a 1 T magnetic field. In each trial, the system was allowed to run for 5 minutes for the hydrogen production rate to stabilize, followed by a 15-minute period during which the hydrogen volume was measured. The measured volume was then converted to standard temperature (298 K) and pressure (760 mmHg) and was corrected for water vapor pressure as follows:

$$V_{std} = V_{meas} \times \frac{P_{meas} - P_{wv}}{760\ mmHg} \times \frac{298\ K}{T_{meas}} \quad (2)$$

where V_{std} is the standardized volume, V_{meas} is the measured volume, P_{meas} is the measured pressure, T_{meas} is the measured temperature, and P_{wv} is the water vapor pressure at the measured temperature. These standardized volume measurements from (2) were then converted to hydrogen production rates in units of L/h.

3. Results

The detailed results from each 15-minute trial are listed in Table I, and the standardized hourly hydrogen production rates calculated from these results are plotted in Figure 4.

Table I: Experimental results

(a) No magnetic field

Electrolyte concentration (wt%)	**Temperature (^{0}C)**	**Pressure (mm Hg)**	**Water vapor pressure (mm Hg)**	**Measured volume (L) over 15 min**	**Standardized volume (L) over 15 min**
5%	24	618	22.4	0.50	0.39
10%	20	616	17.5	0.50	0.40
20%	21	616	18.7	0.56	0.45
30%	22	618	19.8	0.57	0.45

(b) With 1 T magnetic field

Electrolyte concentration (wt%)	**Temperature (^{0}C)**	**Pressure (mm Hg)**	**Water vapor pressure (mm Hg)**	**Measured volume (L) over 15 min**	**Standardized volume (L) over 15 min**
5%	24	618	22.4	0.59	0.46
10%	23	618	21.1	0.68	0.54
20%	22	618	19.8	0.64	0.51
30%	23	618	21.1	0.58	0.46

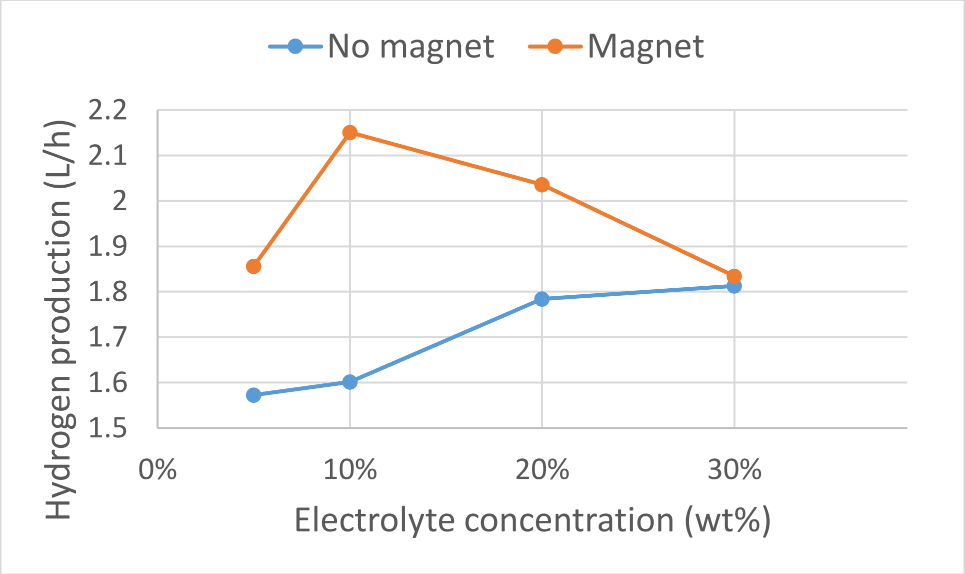

Figure 4. Volumetric flow rates of hydrogen

4. Discussion

4.1. Analysis of Electrolysis with no Magnetic Field

As seen in Figure 4, with no magnetic field, the hydrogen production rate increased with higher electrolyte concentrations, which was expected due to the increase in conductivity. The hydrogen production rate grew by 2% when the concentration was increased from 5% to 10%, by 11% when the concentration was increased from 10% to 20%, and by 2% when the concentration was increased from 20% to 30%. Alkaline electrolysis using KOH at room temperature generally has the best performance at 30% concentration. The results in Figure 4 indicate that there was very little gain in hydrogen production when the concentration increased from 20% to 30%, and it is expected that the production rate would decrease at larger concentrations.

4.2. Impact of Applying a Magnetic Field

At each concentration level tested, the presence of a 1 T magnetic field increased the hydrogen production rate. Table II lists the percentage increase by applying a magnetic field at each concentration level. The magnetic field provides the largest benefit at 10% concentration, and very little benefit is gained at 30% concentration. This can be explained by observing that without a magnetic field, the current density peaks at approximately 30% concentration. Thus, a solution at 30% concentration has less availability for increasing the current density when a magnetic field is applied.

With the applied magnetic field, the largest hydrogen production rate occurs at 10% concentration, so using a magnetic field allows for decreasing the amount of electrolyte to optimize performance, thus reducing the cost of the electrolyte. The best hydrogen production rate with no magnetic field is 1.81 L/h (at 30% concentration). In comparison, the best hydrogen production rate with the magnetic field is 2.15 L/h (at 10% concentration), an improvement of 19%.

Table II: Percentage increase in hydrogen production by applying a magnetic field

Electrolyte concentration	**Percentage increase from applying magnetic field**
5%	18%
10%	34%
20%	14%
30%	1%

4.3. Electrolyte Cost

Applying a magnetic field reduces the cost of the electrolyte by two mechanisms. Firstly, the higher rate of hydrogen production using equivalent rates of input electrolyte solution results in a lower electrolyte cost per unit of hydrogen produced. Secondly, applying a magnetic field calls for decreasing the concentration of electrolyte for optimal performance. The electrolyte cost for producing 1 L of hydrogen are listed in Table III, based on a price of $0.04 per gram KOH. These costs were calculated based on the flow rate of the electrolyte solution (50 cc/min for all trials), the electrolyte concentration, and the corresponding hydrogen production rate from this study (Figure 1). At each concentration level, the cost decreases (or remains the same in the case of 30% concentration) by applying a magnetic field, due to the increased rates of hydrogen production. The cost of the electrolyte to produce 1 L of hydrogen for the optimal performance of 30% concentration without a magnetic field and the optimal performance of 10% concentration with a magnetic field is 2.8¢ and 0.6¢, respectively, corresponding to a decrease of 79%.

Table III: Electrolyte cost to produce hydrogen

Electrolyte concentration	**Hydrogen cost ($/L) No magnetic field**	**Hydrogen cost ($/L) With magnetic field**
5%	0.004	0.003
10%	0.008	0.006
20%	0.017	0.015
30%	0.028	0.028

5. Conclusions and Recommendations

5.1. Conclusions

This study investigated the combined impact of electrolyte concentration and an applied magnetic field on the rate of hydrogen production in alkaline electrolysis. The experimental results demonstrated that applying a magnetic field by placing magnets perpendicular to the electrodes while holding a constant voltage increases the hydrogen production rate at all tested electrolyte concentration levels. The percentage increase due to the magnetic field was largest at the 10% concentration level, and the improvement was negligible at 30% concentration. Among all parameter combinations tested, the best performance was attained with a magnetic field at 10% concentration. The corresponding hydrogen production rate was 19% higher than the best performance among the trials with no magnetic field, which occurred at 30% concentration. The cost of the electrolyte to produce 1 L of hydrogen was calculated for each selected parameter combination, showing that the electrolyte cost decreases by 71% by using the optimal concentration with a magnetic field (10%) rather than the optimal concentration without a magnetic field (30%).

Electrolysis is a low carbon method for producing hydrogen when performed using renewable energy and also produces high purity hydrogen which is needed for fuel cells. Thus, electrolysis is an important technology for hydrogen production as the energy sector moves towards decarbonization. Improving the efficiency of hydrogen production in electrolysis is essential for making electrolysis competitive with fossil fuel methods of producing hydrogen.

5.2. Recommendations

The primary recommendation resulting from this study is the application of a magnetic field during alkaline electrolysis, which increases the rate of hydrogen production while calling for a reduction in electrolyte concentration to optimize the performance. For the 1 T magnetic field used in this study, the optimal electrolyte concentration was 10%. This value may change under different strengths of the magnetic field and type of electrolyte used, so the optimal concentration should be identified by testing using the particular equipment and magnets.

Immediate future work following this project is to perform multiple replicates to verify the results. In addition, the oxygen produced during electrolysis could be measured to verify the measured hydrogen and oxygen volumes are in the proper stoichiometric ratio, which would help validate the volume measurements. A variety of operating parameters could be further examined to quantify their impact when combined with a magnetic field on the rate of hydrogen production. Some parameters that could be tested on the equipment used in this project include cell voltage, electrolyte solution flow rate, and temperature. Recent interest in using local water in a former open pit mine, the Berkeley Pit, for electrolysis suggests further studies on this water source. This water must be treated because electrolysis requires highly purified water, so different water purification methods could be performed on these samples, including deionization, distillation, and double distillation, before performing electrolysis. Another possible study is to apply magnets with varying levels of magnetic field strengths to determine the optimal strength for hydrogen production. Since electricity is the primary operating cost in electrolysis (Kaninski et al., 2006), additional analysis could be performed on the electricity cost savings by using a magnetic field. To perform this analysis, the current would need to be measured in addition to the voltage during each trial, from which the electrical power and cost of electricity could be computed.

6. References Cited

Chisholm, G. & Cronin, L. (2022). Hydrogen from water electrolysis. In *Storing energy* (pp. 559-591). Elsevier.

De Souza, R. F., Padilha, J. C., Gonçalves, R. S., & Rault-Berthelot, J. (2006). Dialkylimidazolium ionic liquids as electrolytes for hydrogen production from water electrolysis. *Electrochemistry communications, 8*(2), 211-216.

Godula-Jopek, A. (2015). *Hydrogen production: by electrolysis*. John Wiley & Sons.

Grigoriev, S. A., Fateev, V. N., Bessarabov, D. G., & Millet, P. (2020). Current status, research trends, and challenges in water electrolysis science and technology. *International journal of hydrogen energy, 45*(49), 26036-26058.

Holladay, J. D., Hu, J., King, D.L., & Wang, Y. (2009). An overview of hydrogen production technologies. *Catalysis toda*y, *139*(4), 244-260.

Iida, T., Matsushima, H., & Fukunaka, Y. (2007). Water electrolysis under a magnetic field. *Journal of the electrochemical society, 154*(8), E112.

Kaninski, M. P. M., Stojić, D. L., Šaponjić, Đ. P., Potkonjak, N. I., & Miljanić, Š. S. (2006). Comparison of different electrode materials – Energy requirements in the electrolytic hydrogen evolution process. *Journal of power sources, 157*(2), 758-764.

Koza, J. A., et al. (2011). Hydrogen evolution under the influence of a magnetic field. *Electrochimica Acta 56*(6), 2665-2675.

Lewis, A. C. (2021). Optimising air quality co-benefits in a hydrogen economy: a case for hydrogen-specific standards for NOx emissions. *Environmental science: Atmospheres, 1*(5), 201-207.

Lin, M. Y., Hourng, L. W., & Kuo, C. W. (2012). The effect of magnetic force on hydrogen production efficiency in water electrolysis. *International journal of hydrogen energy, 37*(2), 1311-1320.

Lin, M. Y., Hourng, L. W., & Wu, C. H. (2017). The effectiveness of a magnetic field in increasing hydrogen production by water electrolysis. *Energy sources, Part A: Recovery, utilization, and environmental effects, 39*(2), 140-147.

Momirlan, M., & Veziroglu, T. N. (2005). The properties of hydrogen as fuel tomorrow in sustainable energy system for a cleaner planet. *International journal of hydrogen energy, 30*(7), 795-802.

Nagai, N., Takeuchi, M., Kimura, T., & Oka, T. (2003). Existence of optimum space between electrodes on hydrogen production by water electrolysis. *International journal of hydrogen energy*, *28*(1), 35-41.

Schmidt, O., Gambhir, A., Staffell, Il, Hawkes, A., Nelson, J., & Few, S. (2017). Future cost and performance of water electrolysis: An expert elicitation study. *International journal of hydrogen energy*, *42*(52), 30470-30492.

Schoots, K., Ferioli, F., Kramer, G. J., & Van der Zwaan, B. C. C. (2008). Learning curves for hydrogen production technology: an assessment of observed cost reductions. *International Journal of Hydrogen Energy 33*(11), 2630-2645.

Suppes, G. J., & Storvick, T. (2006). *Sustainable nuclear power*. Elsevier.

7. Appendix A: Detailed Steps of the Experiment

- Obtain a peristaltic pump and attach tubing. This will pump the electrolyte solution from a container into the electrolyser. Place the suction side tubing in the electrolyte container and connect the pressure side tubing to the two input valves on the electrolyser.
- Run the tubing from the hydrogen and oxygen output valves to the chosen collection device.
    - For hydrogen, run the hydrogen output tube into a stoppered bottle through a hole in the stopper. Place another tube in a second hole in the stopper, and this tube should run to the hydrogen collection device, as the hydrogen will rise out of the stoppered bottle, now with the liquid separated out.
    - If oxygen is not being collected, this tube may be placed to discharge back into the container with the electrolyte solution.
    - If oxygen is being collected, use a system similar to the hydrogen collection method described above.
- Prepare the water displacement system for measuring gas volume (either hydrogen or oxygen)
    - Fill a wide container partially with water.
    - Fill a large cylinder with water. This cylinder should be sufficiently large to measure the expected volume of gas to be produced. Invert this cylinder so it sits in the bath water, spilling as little water as possible when inverting.
    - Obtain an “L”-shaped glass tube in which the gas output tube will be placed. The glass tube will be placed in the water bath to direct the gas output tube into the inverted cylinder.
- Prepare the electrolyte solution at the desired concentration and place in the container to be pumped into the electrolyser.
- If using magnets, place the magnets in the desired position.
- Obtain a DC power supply and place near the electrolyser. Turn the power supply on and set at the desired voltage. Connect the positive terminal to the electrode near the hydrogen production output valve on the electrolyser and connect the negative terminal to the electrode near the oxygen production output valve on the electrolyser.

- Turn the pump on and set to the desired flow rate. The flow rate may need to be set higher initially to provide sufficient suction to draw the water, but then can be reduced to the desired level.
- Allow the system to run for several minutes to stabilize. Then place the “L”-shaped glass tube containing the gas output valve into the inverted cylinder to begin measuring the volume of gas produced. Record the water volume level before and after the experiment to determine the volume of gas produced over the measured period of time.