



Efficiency of Hydrogen Production

How can the electrolysis of water be augmented by increasing hydrogen ion concentration through adding HCl (increments of 0.1ml of 2 mol/dm³ HCl between 0 and 0.5ml) and increasing the number of electrodes (2 electrodes and 4 electrodes) to increase the efficiency of hydrogen production at scale?

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Introduction

“Hydrogen is easily the most abundant element in the universe”¹; with only one proton it is also the simplest of all the elements², its ion H^+ being just a proton. Hydrogen has many uses, from the production of ammonia for fertiliser to its importance in the production of pharmaceuticals and plastics³. However, one of the most important uses of hydrogen, and the use that will be discussed in this paper is its key role in energy production, specifically, its use in the production of fuels⁴.

There are two ways hydrogen is used in fuel production. The first is its role in removing sulphur in the refinement of oils⁵. Nevertheless, the more interesting use is as a fuel itself. Hydrogen is considered by some a super fuel⁶, as, when used in combustion, it doesn't release any pollutants⁷. When used to power a motor, the chemical reaction of

¹ Royal Society Of Chemistry. n.d. Hydrogen. Accessed September 23, 2018. <http://www.rsc.org/periodic-table/element/1/hydrogen>.

² Royal Society Of Chemistry. n.d. Hydrogen. Accessed September 23, 2018. <http://www.rsc.org/periodic-table/element/1/hydrogen>.

³ Royal Society Of Chemistry. n.d. Hydrogen. Accessed September 23, 2018. <http://www.rsc.org/periodic-table/element/1/hydrogen>.

⁴ Royal Society Of Chemistry. n.d. Hydrogen. Accessed September 23, 2018. <http://www.rsc.org/periodic-table/element/1/hydrogen>.

⁵ Royal Society Of Chemistry. n.d. Hydrogen. Accessed September 23, 2018. <http://www.rsc.org/periodic-table/element/1/hydrogen>.

⁶Hydrogen Solutions. 2017. *Why Hydrogen is the Super Fuel of Our Future*. 2 March. Accessed September 24, 2018. <https://blog.ballard.com/hydrogen-is-the-super-fuel-of-our-future>.

⁷ Royal Society Of Chemistry. n.d. Hydrogen. Accessed September 23, 2018. <http://www.rsc.org/periodic-table/element/1/hydrogen>.

combustion is as follows: $4H_2(g) + 2O_2(g) \xrightarrow{\text{heat}} 2H_2O(l) + \text{energy}$. A fuel with no pollution in an era where fuels are fundamental energy sources, is of extreme value.

Unfortunately, there are problems with the utilisation of hydrogen as a fuel. Firstly, it is highly combustible⁸ increasing the risk of storage. This risk has slowly been decreasing as engineers have found better storage methods for such element. The real problem is the economic unviability of its mass production.

Currently, over 95% of the world's hydrogen is produced through processes involving burning wood and/or fossil fuels⁹. The most common way fossil fuels are used to produce hydrogen is called natural gas reforming¹⁰. This method is the combination of two chemical reactions both of which produce hydrogen. The first one, called steam methane reforming¹¹, is a process in which steam reacts with methane to form carbon monoxide and hydrogen $H_2O(g) + CH_4(g) \rightarrow 3H_2(g) + CO_2(g)$ ¹². This reaction is endothermic and is generally performed with steam between 700°C – 1000°C¹³. The second reaction occurs between the CO produced by the original reaction and the excess H₂O. In a process called water gas shift

⁸ Royal Society Of Chemistry. n.d. Hydrogen. Accessed September 23, 2018. <http://www.rsc.org/periodic-table/element/1/hydrogen>.

⁹ Planete Energies. 2015. Hydrogen Production. 07 January. Accessed September 24, 2018. <https://www.planete-energies.com/en/medias/close/hydrogen-production>.

¹⁰ Planete Energies. 2015. Hydrogen Production. 07 January. Accessed September 24, 2018. <https://www.planete-energies.com/en/medias/close/hydrogen-production>.

¹¹ Office of Energy Efficiency & Renewable Energy. n.d. *Hydrogen Production: Natural Gas Reforming*. Accessed September 24, 2018. <https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming>.

¹² Office of Energy Efficiency & Renewable Energy. n.d. *Hydrogen Production: Natural Gas Reforming*. Accessed September 24, 2018. <https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming>.

¹³ Office of Energy Efficiency & Renewable Energy. n.d. *Hydrogen Production: Natural Gas Reforming*. Accessed September 24, 2018. <https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming>.

reaction, CO and H₂O react to form H₂ and CO₂ in the following manner $H_2O(g) + CO(g) \rightarrow H_2(g) + CO_2(g)$ ¹⁴. This process can also be done with a variety of different fuels, such as ethanol and propane.

The main problem with this method is that it also causes the release of gasses, namely carbon dioxide. This gas has grave effects on the environment and is the major contributor to the greenhouse effect¹⁵, a problem which is currently plaguing the planet. This effect nullifies the desired zero-emission properties of hydrogen as a fuel. Nonetheless, alternative ways of producing hydrogen do exist, one of which is water electrolysis.

Electrolysis is the process by which electricity is utilized to break up chemicals into its components¹⁶. For this process to work, two conditions must be met. Firstly, the component must be in a liquid state, in molten form, or dissolved in a solvent. Secondly, the molten or dissolved liquid must contain ions. The reason for these two conditions to be needed is that ions must be able to flow freely, carrying a charge. To electrolyse the liquid substance, one puts two conductive rods (electrodes) into the liquid and connects them to an energy source. Each electrode either becomes a positive electrode (anode), or a negative electrode (cathode), depending on how they are connected to the energy source. The ions present in the liquid being used can also be categorised into negative ions (anions) and

¹⁴ Office of Energy Efficiency & Renewable Energy. n.d. *Hydrogen Production: Natural Gas Reforming*. Accessed September 24, 2018. <https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming>.

¹⁵ Rohrer, Juerg. 2007. Time for change. 2 December. Accessed September 24, 2018. <https://timeforchange.org/CO2-cause-of-global-warming>.

¹⁶ Song, Kimberly. 2014. Electrolysis. 10 February. Accessed September 24, 2018. [https://chem.libretexts.org/Textbook_Maps/Analytical_Chemistry/Supplemental_Modules_\(Analytical_Chemistry\)/Electrochemistry/Electrolytic_Cells/Electrolysis](https://chem.libretexts.org/Textbook_Maps/Analytical_Chemistry/Supplemental_Modules_(Analytical_Chemistry)/Electrochemistry/Electrolytic_Cells/Electrolysis).

positive ions (cations). Electrons do not flow through the liquid when electrolysis is occurring, instead, the exchange and flow of electrons occur through the flowing on ions in the liquid. Anodes being positively charged attract anions, which flow through the liquid towards the anode; when there, the following half equation occurs¹⁷ $A^- \rightarrow A + e^-$ and the extra electrode flows through the anode. Cathodes being negatively charged attract cations, which flow through the liquid towards the cathode, where the following half equation occurs¹⁸ $C^+ + e^- \rightarrow C$, the electron flowing though the cathode is taken by the cation. These reactions will occur until no ions are left.

Electrolysis of water can be used to break up water into hydrogen and oxygen. The overall reaction¹⁹ is $2H_2O(l) \xrightarrow{\text{electricity}} 2H_2(g) + O_2(g)$, is produced due to water disassociating into H_3O^+ ions and OH^- ions, through a process known as self-ionisation, where one water molecule deprotonates forming H^+ and OH^- ions, the H^+ ions protonates a water molecule to form H_3O^+ ions²⁰ this occurs because water can act as either a Brønsted-Lowry acid or base²¹. These ions act as the cation and anion respectively. At the anode, the

¹⁷ Song, Kimberly. 2014. Electrolysis. 10 Febuary. Accessed September 24, 2018. [https://chem.libretexts.org/Textbook_Maps/Analytical_Chemistry/Supplemental_Modules_\(Analytical_Chemistry\)/Electrochemistry/Electrolytic_Cells/Electrolysis](https://chem.libretexts.org/Textbook_Maps/Analytical_Chemistry/Supplemental_Modules_(Analytical_Chemistry)/Electrochemistry/Electrolytic_Cells/Electrolysis).

¹⁸ Song, Kimberly. 2014. Electrolysis. 10 Febuary. Accessed September 24, 2018. [https://chem.libretexts.org/Textbook_Maps/Analytical_Chemistry/Supplemental_Modules_\(Analytical_Chemistry\)/Electrochemistry/Electrolytic_Cells/Electrolysis](https://chem.libretexts.org/Textbook_Maps/Analytical_Chemistry/Supplemental_Modules_(Analytical_Chemistry)/Electrochemistry/Electrolytic_Cells/Electrolysis).

¹⁹Nave, R. n.d. Electrolysis of Water. Accessed September 24, 2018. <http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/electrol.html>.

²⁰ Flowers, Paul. 2016. *Self-Ionization of Water and the pH Scale*. 8 Febuary. Accessed September 24, 2018. [https://chem.libretexts.org/Textbook_Maps/General_Chemistry/Map%3A_General_Chemistry_\(Petrucci_et_al.\)/16%3A_Acids_and_Bases/16.3%3A_Self-Ionization_of_Water_and_the_pH_Scale](https://chem.libretexts.org/Textbook_Maps/General_Chemistry/Map%3A_General_Chemistry_(Petrucci_et_al.)/16%3A_Acids_and_Bases/16.3%3A_Self-Ionization_of_Water_and_the_pH_Scale).

²¹Flowers, Paul. 2016. *Self-Ionization of Water and the pH Scale*. 8 Febuary. Accessed September 24, 2018. [https://chem.libretexts.org/Textbook_Maps/General_Chemistry/Map%3A_General_Chemistry_\(Petrucci_et_al.\)/16%3A_Acids_and_Bases/16.3%3A_Self-Ionization_of_Water_and_the_pH_Scale](https://chem.libretexts.org/Textbook_Maps/General_Chemistry/Map%3A_General_Chemistry_(Petrucci_et_al.)/16%3A_Acids_and_Bases/16.3%3A_Self-Ionization_of_Water_and_the_pH_Scale).

half equation is $4OH^-(aq) \rightarrow 2H_2O(l) + O_2(g) + 4e^-$, while the half equation at the anode is $2H_3O^+(aq) + 2e^- \rightarrow 2H_2O(l) + H_2(g)$. This process is dependent on the self-ionisation of water into H_3O^+ ions and OH^- ions, a rare event that with pure water happens in about 1 in 500 million moles²². The reason for this is that the reaction $H_2O(l) + H_2O(l) \rightleftharpoons H_3O^+(aq) + OH^-(aq)$ heavily favours the reverse reaction.

The rarity of the self-ionisation of water makes the reaction very slow and current methods of initiating such reaction are energetically inefficient as too much energy is lost in the process²³. The time and expense of this process makes it less economically viable than natural gas reforming, using current technology. This reality is slowly changing as both catalysts and new materials for electrodes are being discovered²⁴.

One way to increase the efficiency and speed of the electrolysis of water would be to push the equilibrium self-ionisation reaction of water, $H_2O(l) + H_2O(l) \rightleftharpoons H_3O^+(aq) + OH^-(aq)$, towards the right. One alternative would be to use temperature to push the equilibrium, as the reaction is endothermic²⁵, therefore, increasing temperature would push the reaction forward. This could be useful, however, for electrolysis and the self-ionisation of water to work, the H_2O molecules must be in liquid state, this sets the limit to how high the temperature can be increased. Although the boiling point can be elevated by increasing

²²Biology Corner. n.d. *Acids and Bases*. Accessed September 24, 2018. https://www.biologycorner.com/worksheets/acids_bases_coloring.html.

²³Bandarenka, Dr. Aliaksandr S. 2016. *Efficiency of water electrolysis doubled*. 10 March. Accessed September 24, 2018. <https://www.tum.de/en/about-tum/news/press-releases/detail/article/32998/>.

²⁴Bandarenka, Dr. Aliaksandr S. 2016. *Efficiency of water electrolysis doubled*. 10 March. Accessed September 24, 2018. <https://www.tum.de/en/about-tum/news/press-releases/detail/article/32998/>.

²⁵Clark, Jim. 2014. THE IONIC PRODUCT FOR WATER, Kw. December. Accessed September 27, 2018. <https://www.chemguide.co.uk/physical/acidbaseeqia/kw.html>.

the pressure, the amount of energy required to do so would be more than the energy saved in the process.

An alternative solution, and the one which will be explored in this paper, would be to increase H^+ ion concentration through adding acids to the water to increase the de-ionisation of water. This concept replaces water as the chemical causing the de-ionisation of water and replaces it with an acid. For the purposes of this paper, the acid in question will be hydrochloric acid HCl. In replacing water with HCl, the de-ionisation equation becomes²⁶ $H_2O(l) + HCl(aq) \rightleftharpoons H_3O^+(aq) + Cl^-(aq)$. This reaction has its equilibrium almost completely to the right, the reason for this is that HCl is a very strong acid, meaning it has a large disassociation constant²⁷. The strength of an acid referring to its ease to let go of hydrogen ion, means that HCl is very willing to do so, and its disassociation reaction $HCl(aq) \rightleftharpoons H^+(aq) + Cl^-(aq)$, lies heavily on the right, so much so, that it is considered that HCl is completely ionized²⁸. As H^+ ions react almost instantly with water to form H_3O^+ ions, $H_2O(l) + HCl(aq) \rightleftharpoons H_3O^+(aq) + Cl^-(aq)$ has an equilibrium which lies heavily to the right. The question is to identify to what extent HCl affects the efficiency of electrolysis.

²⁶Flowers, Paul. 2016. *Self-Ionization of Water and the pH Scale*. 8 Febuary. Accessed September 24, 2018. [https://chem.libretexts.org/Textbook_Maps/General_Chemistry/Map%3A_General_Chemistry_\(Petrucchi_et_al.\)/16%3A_Acids_and_Bases/16.3%3A_Self-Ionization_of_Water_and_the_pH_Scale](https://chem.libretexts.org/Textbook_Maps/General_Chemistry/Map%3A_General_Chemistry_(Petrucchi_et_al.)/16%3A_Acids_and_Bases/16.3%3A_Self-Ionization_of_Water_and_the_pH_Scale).

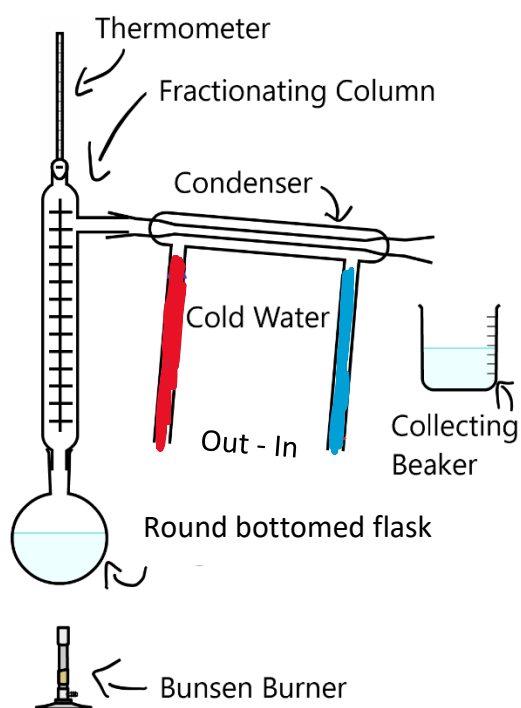
²⁷ Boundless Chemistry. n.d. Strength of Acids. Accessed September 27, 2018. <https://courses.lumenlearning.com/boundless-chemistry/chapter/strength-of-acids/>.

²⁸ Boundless Chemistry. n.d. Strength of Acids. Accessed September 27, 2018. <https://courses.lumenlearning.com/boundless-chemistry/chapter/strength-of-acids/>.

Research Question

How can the electrolysis of water be augmented by increasing hydrogen ion concentration through adding HCl (increments of 0.1ml of 2 mol/dm³ HCl between 0 and 0.5ml) and increasing the number of electrodes (2 electrodes and 4 electrodes) to increase the efficiency of hydrogen production at scale?

To answer the research question, I designed a three-part experiment to find ways of minimizing the energy used to electrolyse water and form hydrogen. Before beginning any of the experiments a water distillation system had to be set up as so.



The procedure was as followed:

- 1) Fill round-bottomed flask up to halfway
- 2) Place antibumping granules into round-bottomed flask
- 3) Turn on water passing through the condenser tube
- 4) Light Bunsen burner

5) Collect pure water in a beaker

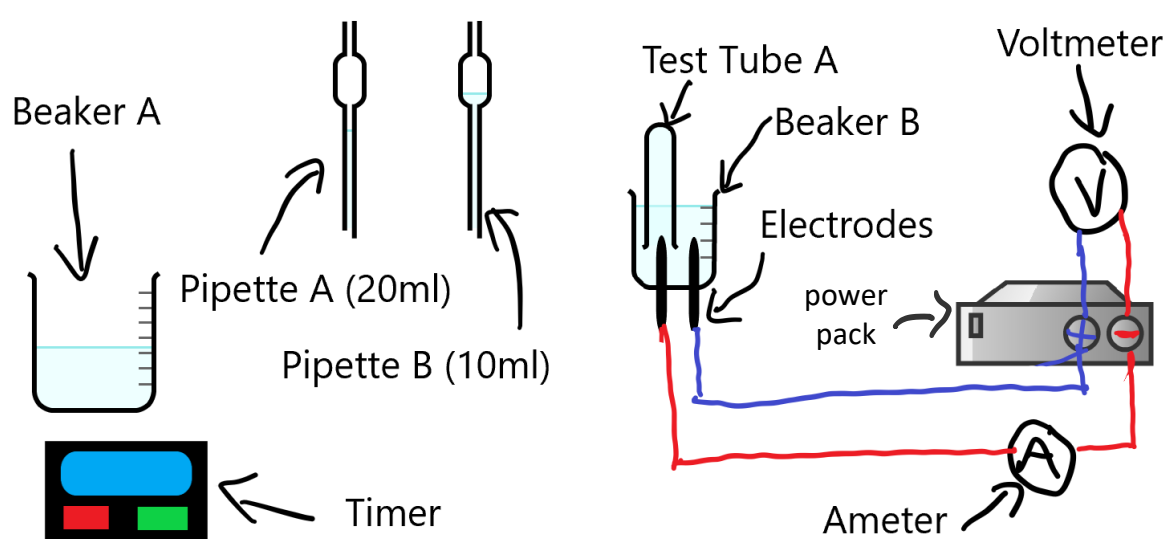
Pure water would slowly gather in the beaker. Once the flask began to run out of water, the Bunsen burner would be removed and steps 1 through 4 would be repeated. This could be left running while other experiments take place.

Additionally, ambient pressure and temperature were taken using a barometer and thermometer at the beginning of the day on which the experiments took place.

Experiment 1

The first part of the experiment consisted of testing different types of water to which there was easy access. This experiment was designed to show that there is a link between the impurities in water and the efficiency of electrolysis. As ions are used to carry charges in the process of electrolysis, I suspect that higher the concentrations of impurities in water will result in higher ion concentration, resulting in more efficient electrolysis.

The experiment is set up as so:



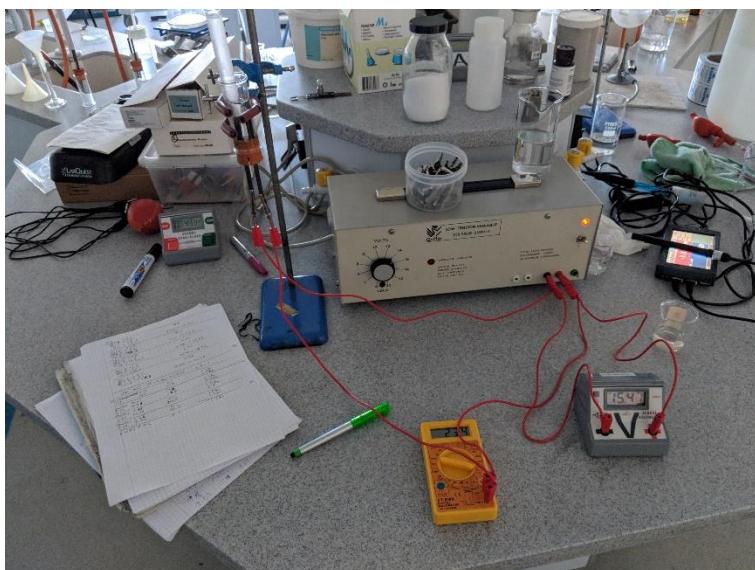


Figure 1 Experiment Setup

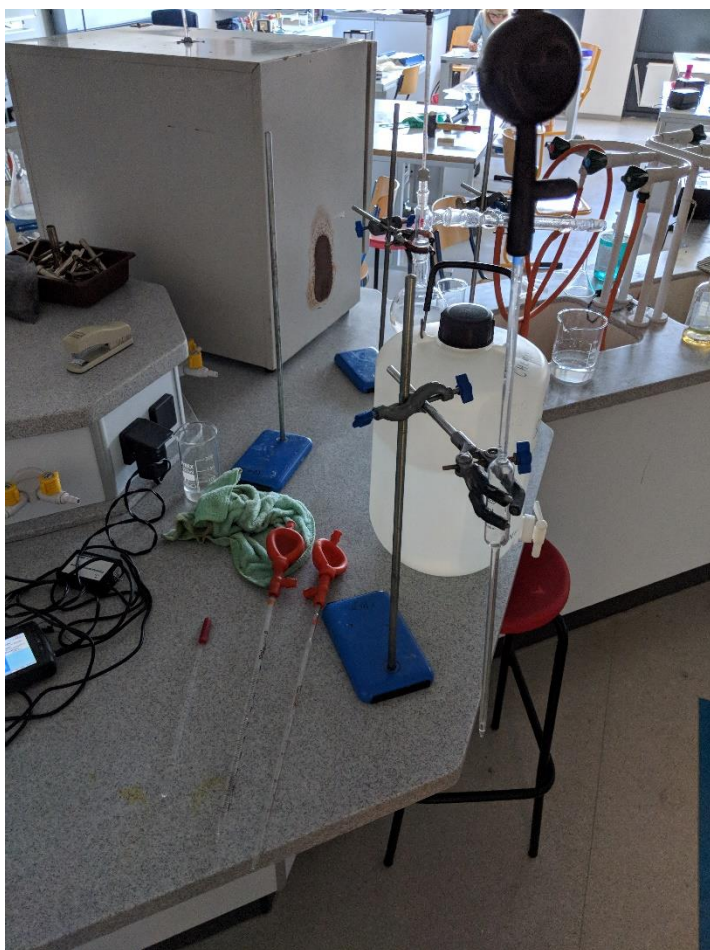


Figure 2 Pipet Setup

The procedure was as followed:

- 1) Fill Beaker A with 170 ml of distilled water
- 2) Fill pipet A and B with the distilled water in beaker A
- 3) Fill test tube A with pipet A
- 4) Use the remaining distilled water in pipets A and B fill beaker B
- 5) Place test tube A into beaker B surrounding the cathode
- 6) Measure volume of air in test tube A
- 7) Turn on power pack switch and start timer
- 8) Measure voltage and current
- 9) Wait around five minutes
- 10) Turn off power pack and switch off timer
- 11) Measure the new volume of gas in test tube A

This experiment was repeated 5 times to reduce random errors, and was repeated with “de-ionized water” and “tap water”. The data gathered is shown in tables 1 - 3.

Table 1

	Tap Water				
	Test				
Measurement	Test 1	Test 2	Test 3	Test 4	Test 5
Initial Volume (ml)	2.2	1.8	1.8	1.8	2.5
Final Volume (ml)	3.0	2.8	2.6	3.0	5.0
Initial Voltage (V)	0.7	0.55	0.68	0.71	0.68
Voltage (V)	17.41	17.41	17.42	17.45	17.39
Initial Current (mAmps)	0	0	0	0	0
Current (mAmps)	2.1	2.0	2.1	2.0	2.0
Times (s)	306	339	340	357	473

Table 2

	De-Ionized Water				
	Test				
Measurement	Test 1	Test 2	Test 3	Test 4	Test 5
Starting Volume (ml)	2.0	4.8	2.3	1.1	1.5
Final Volume (ml)	2.2	5.4	2.8	1.6	2.1
Initial Voltage (V)	0.46	0.75	0.76	0.67	0.8
Voltage (V)	17.56	17.63	17.61	17.6	17.63
Initial Current (mAmps)	0	0	0	0	0
Current (mAmps)	1.0	1.1	0.9	1.0	1.0
Time (s)	335	443	326	305	429

Table 3

	Distilled Water				
	Test				
Measurement	Test 1	Test 2	Test 3	Test 4	Test 5
Initial Volume (ml)	2.3	1.6	1.7	1.4	1.5
Final Volume (ml)	2.3	1.6	1.7	1.4	1.5
Initial Voltage (V)	0.18	0.15	0.25	0.17	0.24
Voltage (V)	17.6	17.66	17.66	17.7	17.73
Initial Current (mAmps)	-0.1	-0.1	-0.1	-0.1	-0.1
Current (mAmps)	2.0	1.5	1.7	1.9	2.4
Times (s)	327	365	322	316	302

This data was then processed to create tables 4 – 6 by processing data in the following way:

- Change in Volume = Final Volume – Initial Volume
- Moles of Hydrogen = (Change in Volume * Pressure)/(8.314 * Temperature)

- Power = Current * Voltage
- Energy = Power * time
- Joules per mol = Energy/ Moles of Hydrogen

Table 4

	Tap Water		
	Processing		
Measurement	Value	Absolute Error	% Error
Temperature (K)	301	0.1	0.03%
Pressure (Pa)	201900	50	0.02%
Initial Volume (ml)	2.2	0.05	2%
Final Volume (ml)	3.0	0.05	2%
Initial Voltage (V)	0.70	0.005	0.7%
Voltage (V)	17.41	0.005	0.03%
Initial Current (Amps)	0.0000	0.00005	0%
Current (Amps)	0.0021	0.00005	2%
Times (s)	363	0.5	0.1%
Change in Volume (ml)	0.8	0.10	13%
Moles of hydrogen (mol)	60	8	13%
Power (W)	0.040	0.001	2%
Energy (J)	13	0.3	3%
Joules per mole of H ₂ (J/mol)	0.2	0.03	15%

Table 5

	De-Ionized Water		
	Processing		
Measurement	Value	Absolute Error	% Error
Temperature (K)	301	0.1	0.03%
Pressure (Pa)	201900	50	0.02%
Initial Volume (ml)	2.0	0.05	3%

Final Volume (ml)	2.2	0.05	2%
Initial Voltage (V)	0.46	0.005	1.1%
Voltage (V)	17.56	0.005	0.03%
Initial Current (Amps)	0.0000	0.00005	0%
Current (Amps)	0.0010	0.00005	5%
Times (s)	368	0.5	0.1%
Change in Volume (ml)	0.2	0.1	50%
Moles of hydrogen (mol)	20	8	50%
Power (W)	0.020	0.001	5%
Energy (J)	6.0	0.3	5%
Joules per mole of H ₂ (J/mol)	0.4	0.2	55%

Table 6

	Distilled Water		
	Processing		
Measurement	Value	Absolute Error	% Error
Temperature (K)	301	1	0.03%
Pressure (Pa)	201900	50	0.02%
Initial Volume (ml)	2.3	0.05	2%
Final Volume (ml)	2.3	0.05	2%
Initial Voltage (V)	0.18	0.005	3%
Voltage (V)	17.60	0.005	0.03%
Initial Current (Amps)	-0.0001	0.00005	50%
Current (Amps)	0.0020	0.00005	3%
Times (s)	326	0.5	0.2%
Change in Volume (ml)	0.0	0.1	0%
Moles of hydrogen (mol)	0	0	0.06%
Power (W)	0.040	0.001	3%
Energy (J)	11	0.3	3%
Joules per mole of H ₂ (J/mol)	N/A	N/A	3%

As no moles of hydrogen were detected to have been produced, the joules per mole of H_2 creates a division by 0 error. Nevertheless, as any change was too small to detect, the number of moles too were very small, hence, the value of the joules per mole would be very large. With this and the data from tables 4 – 5, the joules per mole can be seen to decrease with the presence of more impurities in the water. Referring to the research question, this experiment suggests that the electrolysis of water will become more efficient as ion concentration increases.

Experiment 2

To answer the second part of my research question. How can the electrolysis of water be augmented by increasing the number of electrodes (2 electrodes to 4 electrodes) to increase the efficiency of hydrogen production? I designed a second experiment testing the effect of the number of electrodes being used to electrolyse water. As increasing the number of electrodes increases the surface area of the electrodes, this should make it easier for current to flow through ions, as a large area of reaction will be available for H^+ and OH^- ions to react, total reactions should increase, hence the efficiency should increase.

For this experiment I had to custom design a stopper with which to hold 4 electrodes as none were available, this was quite difficult as the carbon electrodes were very brittle and snapped under the pressure of me pushing them into small incisions made into the stopper.

The experiment was set up as follows:

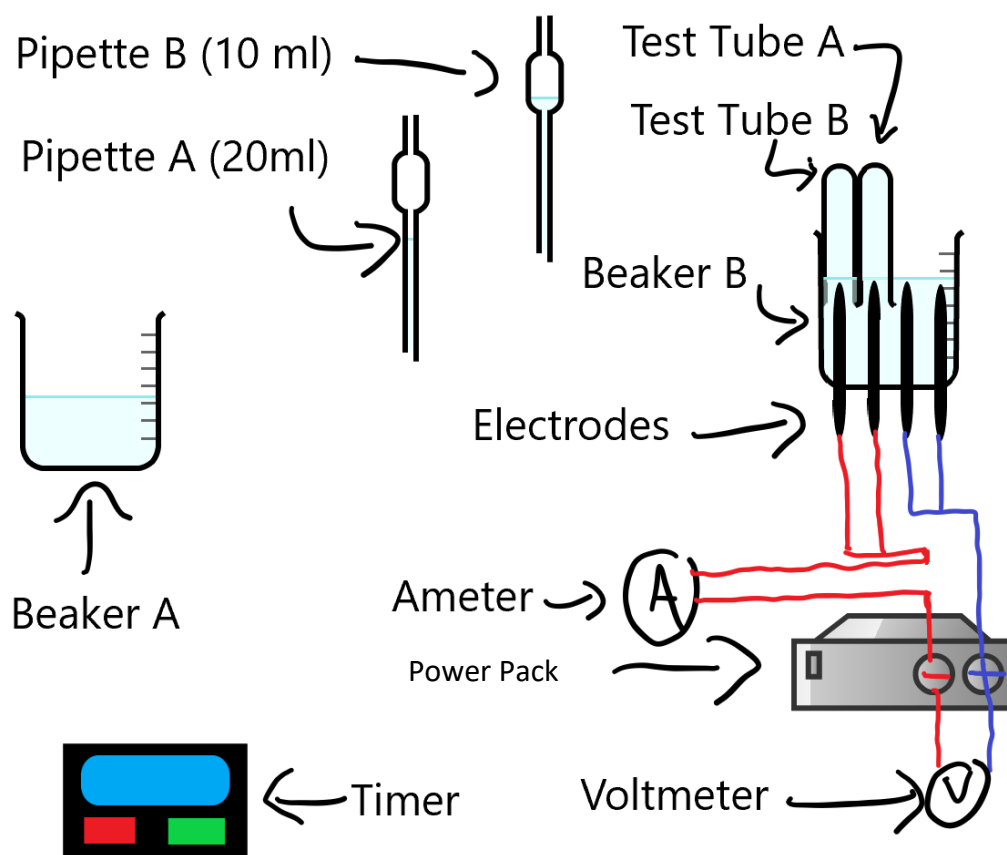


Figure 3

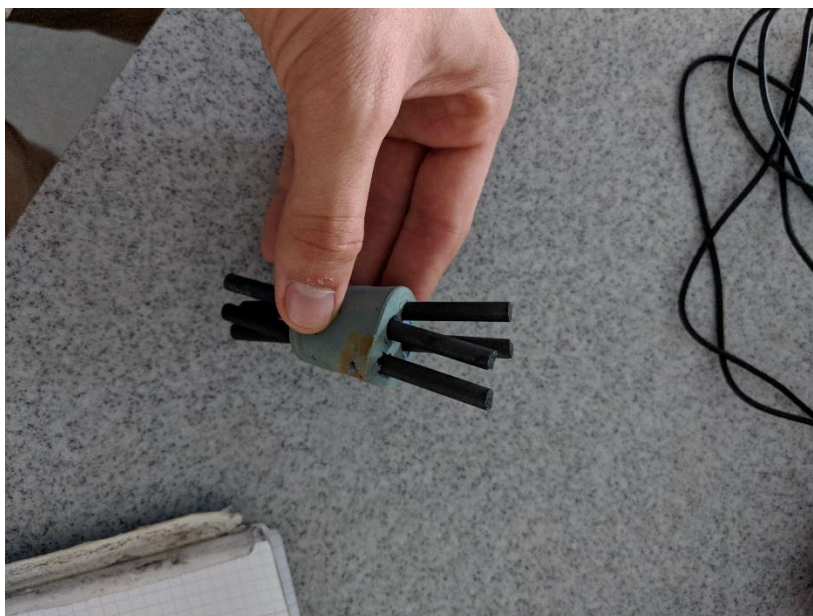


Figure 4 Custom built electrode stopper

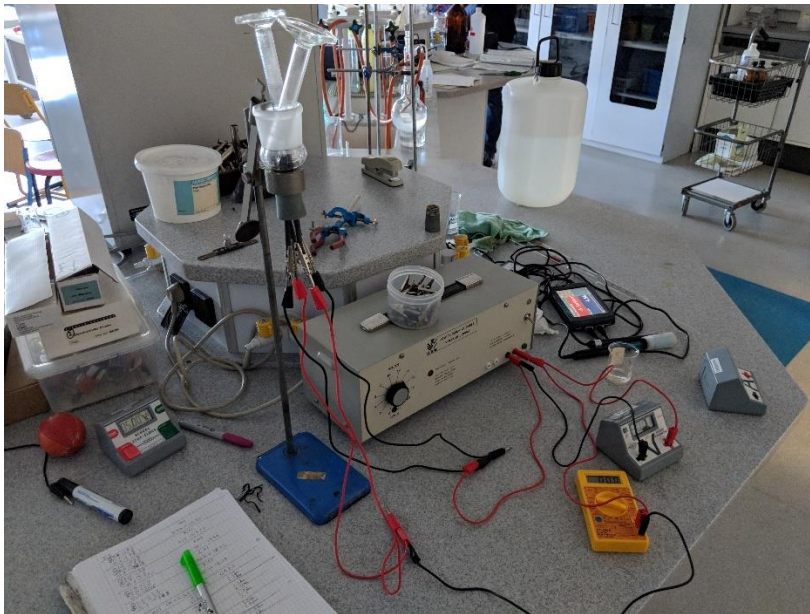


Figure 5 Experiment Setup

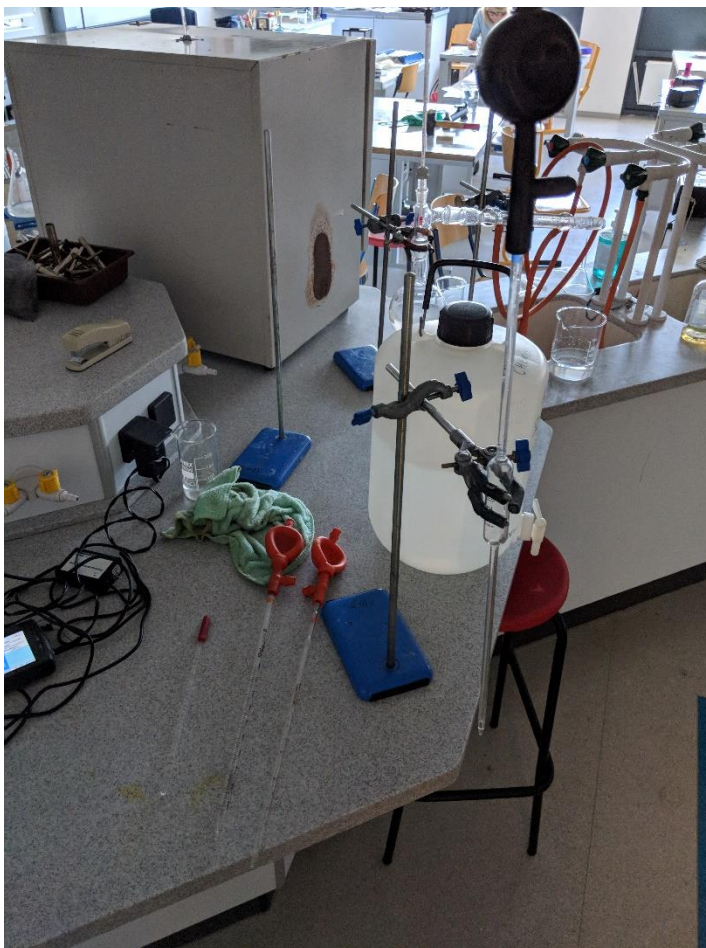


Figure 6 Pipet Setup

The procedure was as follows:

- 1) Fill beaker A 350 ml of water
- 2) Fill pipettes A and B with water in beaker A
- 3) Fill test tubes A and B with water
- 4) Use remaining water in pipettes A and B to fill beaker B
- 5) Fill pipet A and B with water in Beaker A
- 6) Use water in pipets A and B to fill beaker B
- 7) Place test tubes A and B into beaker B surrounding their respective cathodes as shown in the diagram
- 8) Measure volume of air in test tubes A and B
- 9) Turn on power pack switch and start timer
- 10) Measure voltage and current
- 11) Wait around 5 – 6 minutes
- 12) Turn off power pack and switch off timer
- 13) Measure the new volume of gas in test tubes A and B

This experiment was repeated 5 times to reduce random errors, and was repeated with “de-ionized water” and “tap water”. The data gathered is shown in tables 7 - 9.

Table 7

	Tap Water with 2 Diodes					
	Test					
Measurement	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Initial Volume 1 (ml)	3.1	1.0	2.7	1.0	1.5	1.1
Final Volume 1 (ml)	5.6	2.9	4.4	2.2	2.7	2.6
Initial Volume 2 (ml)	2.1	5.5	1.0	2.2	5.1	2.5
Final Volume 2 (ml)	4.4	6.11	2.8	4.0	7.0	4.3
Initial Voltage (V)	0.6	0.74	0.57	0.83	0.82	0.74

Voltage (V)	14.89	14.88	14.9	14.9	14.88	14.9
Initial Current (mAmps)	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
Current (mAmps)	116.5	111.7	111.9	113.4	107.9	110.8
Times (s)	447	319	312	302	322	325

Table 8

	De-Ionised Water with 2 Diodes				
	Test				
Measurement	Test 1	Test 2	Test 3	Test 4	Test 5
Initial Volume 1 (ml)	0.4	1.6	3.0	1.4	2.2
Final Volume 1 (ml)	5.2	2.4	3.8	2.3	3.2
Initial Volume 2 (ml)	1.1	4.6	5.4	2.0	2.7
Final Volume 2 (ml)	1.7	5.3	6.3	3.0	3.6
Initial Voltage (V)	0.55	0.65	0.58	0.69	0.56
Voltage (V)	15.22	15.27	15.34	15.32	15.34
Initial Current (mAmps)	-0.2	-0.2	-0.2	-0.2	-0.2
Current (mAmps)	56.1	50.3	55.3	50.6	54.5
Times (s)	301	302	302	383	345

Table 9

	Distilled Water with 2 Diodes				
	Test				
Measurement	Test 1	Test 2	Test 3	Test 4	Test 5
Initial Volume 1 (ml)	1.2	3.2	3.3	3.2	1.2
Final Volume 1 (ml)	1.2	3.2	3.3	3.2	1.2
Initial Volume 2 (ml)	1.8	1.8	7.9	3.5	3.5
Final Volume 2 (ml)	1.8	1.8	7.9	3.5	3.5
Initial Voltage (V)	0.3	0.36	0.43	0.37	0.41
Voltage (V)	15.51	15.54	15.48	15.5	15.47
Initial Current (mAmps)	-0.1	-0.1	-0.1	-0.1	-0.1

Current (mAmps)	8.7	7.8	9.5	9.3	8.3
Times (s)	332	321	317	310	322

This data was then processed in a similar fashion to that in the first experiment, taking the extra variables into account, to produce tables 10-12 by processing data in the following way:

- Initial Volume = Initial Volume 1 + Initial Volume 2
- Final Volume = Final Volume 1 + Final Volume 2
- Change in Volume = Final Volume – Initial Volume
- Moles of Hydrogen = (Change in Volume * Pressure)/(8.314 * Temperature)
- Power = Current * Voltage
- Energy = Power * time
- Joules per mol = Energy/ Moles of Hydrogen

Table 10

	Tap Water		
	Processing		
Measurement	Value	Absolute Error	% Error
Temperature (K)	301	0.1	0.03%
Pressure (Pa)	201900	50	0.02%
Initial Volume (ml)	4.8	0.05	1.0%
Final Volume (ml)	8.2	0.05	0.6%
Initial Voltage (V)	0.72	0.005	0.7%
Voltage (V)	14.89	0.005	0.03%
Initial Current (Amps)	-0.0002	0.00005	25%

Current (Amps)	0.1120	0.00005	0.05%
Times (s)	338	0.5	0.1%
Change in Volume (ml)	3.4	0.1	3%
Moles of hydrogen (mol)	270	8	3%
Power (W)	1.668	0.001	0.08%
Energy (J)	564	1	0.2%
Joules per mole of H ₂ (J/mol)	2.1	0.07	3%

Table 11

	De-Ionized Water		
	Processing		
Measurement	Value	Absolute Error	% Error
Temperature (K)	301	0.1	0.03%
Pressure (Pa)	201900	50	0.02%
Initial Volume (ml)	4.9	0.05	1.0%
Final Volume (ml)	7.4	0.05	0.7%
Initial Voltage (V)	0.61	0.005	0.8%
Voltage (V)	15.30	0.005	0.03%
Initial Current (Amps)	-0.0002	0.00005	25%
Current (Amps)	0.0534	0.00005	0.09%
Times (s)	327	0.5	0.2%
Change in Volume (ml)	2.5	0.1	4%
Moles of hydrogen (mol)	200	8	4%
Power (W)	0.816	0.001	0.1%
Energy (J)	267	0.7	0.3%
Joules per mole of H ₂ (J/mol)	1.3	0.06	4%

Table 12

	De-Ionized Water
	Processing

Measurement	Value	Absolute Error	% Error
Temperature (K)	301	0.1	0.03%
Pressure (Pa)	201900	50	0.02%
Initial Volume (ml)	6.1	0.05	0.8%
Final Volume (ml)	6.1	0.05	0.8%
Initial Voltage (V)	0.37	0.005	1.3%
Voltage (V)	15.50	0.005	0.03%
Initial Current (Amps)	-0.0001	0.00005	50%
Current (Amps)	0.0087	0.00005	0.6%
Times (s)	320	0.5	0.2%
Change in Volume (ml)	0.0	0.1	0%
Moles of hydrogen (mol)	0	0	0.1%
Power (W)	0.14	0.001	0.6%
Energy (J)	43	0.3	0.8%
Joules per mole of H ₂ (J/mol)	N/A	N/A	0.8%

Interestingly, this shows that the extra electrodes made the electrolysis less efficient, increasing the amount of energy required to create a mole of Hydrogen. This is not what I had originally expected, although looking into it, it probably has something to do with the fact that, as each electrode pair was set up in parallel, the current passing through each pair was lower than in the first experiment, hence by Faraday's laws of Electrolysis relating yield and current, hydrogen yield would drop. More relevant is the relationship between the two experiments. Shown in Table 13 is the relationship.

Table 13

	Joules per mole of H ₂ (J/mol)		Ratio of Exp 2: Exp 1
Type of water	Experiment 1	Experiment 2	

Tap Water	0.2	2.1	10:1
De-Ionized Water	0.4	1.3	3:1

Looking at table 13, the rate at which adding electrodes made the production of hydrogen less efficient appears to increase the more efficient the original method is, or how impure the water used is.

Relating back to the research question, increasing the number of electrodes from 2 to 4, not only makes the electrolysis of water, less efficient, the rate at which it does so increase as the ion concentration in water increases. Testing this for more accurate concentration of ions would be an interesting way of exploring this phenomenon.

Experiment 3

Since using a basic two electrode method for producing hydrogen from electrolysing water is more efficient than using multiple sets of electrodes, the third experiment will build on that model. This experiment addresses the first part of the research question, how can the electrolysis of water be augmented by increasing hydrogen ion concentration through adding HCl (increments of 0.1ml of 2 mol/dm³ HCl between 0 and 0.5ml), to increase the efficiency of hydrogen production?

This experiment builds upon the first experiment but controls the addition of ions into the water. As previously shown, there is an inverse correlation between energy supplied and moles of hydrogen produced, as efficiency must be positive (neither the energy nor the moles of hydrogen produced can be negative), the relationship is probably in

the form $C \propto \frac{1}{eff}$ where C is the concentration of ions and eff is the efficiency of electrolysis.

The experiment was set up as follows:

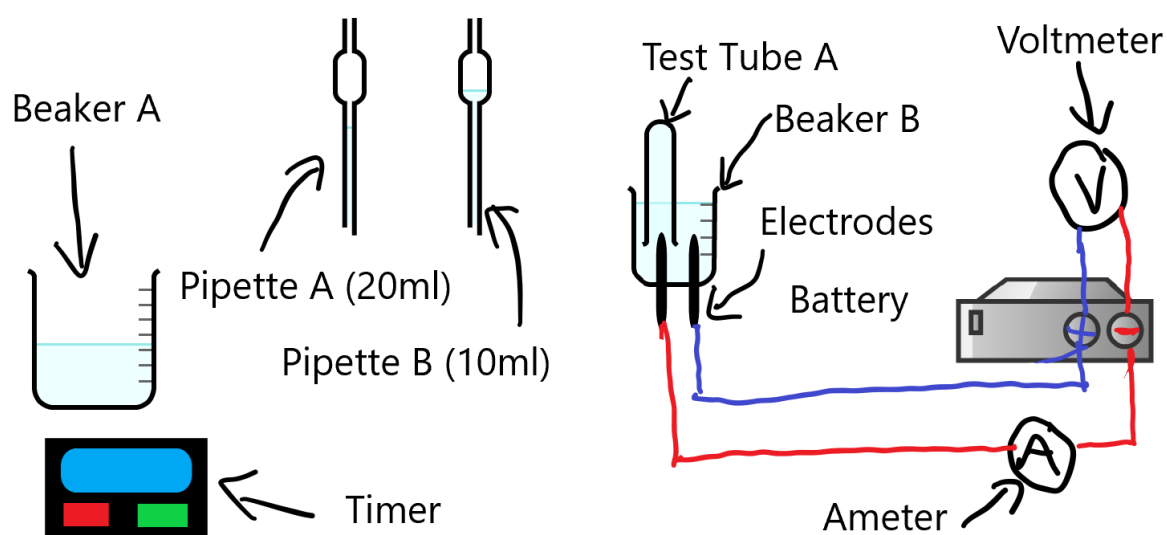


Figure 7

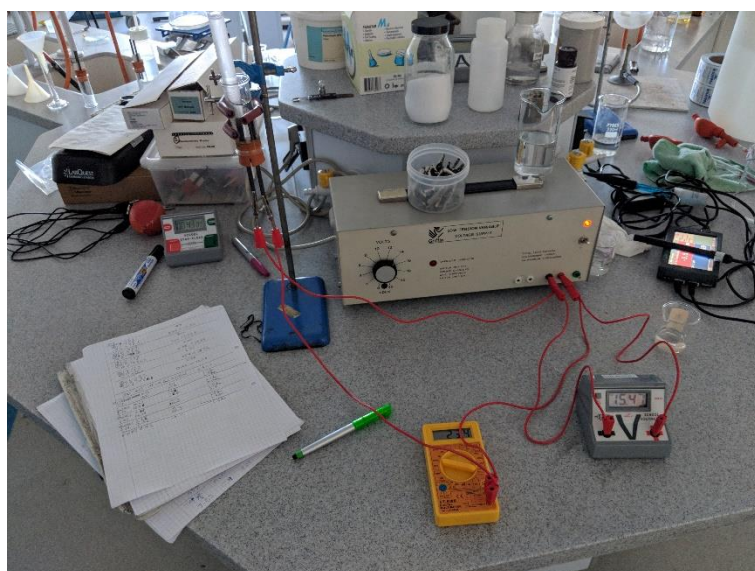


Figure 8 Experiment Setup

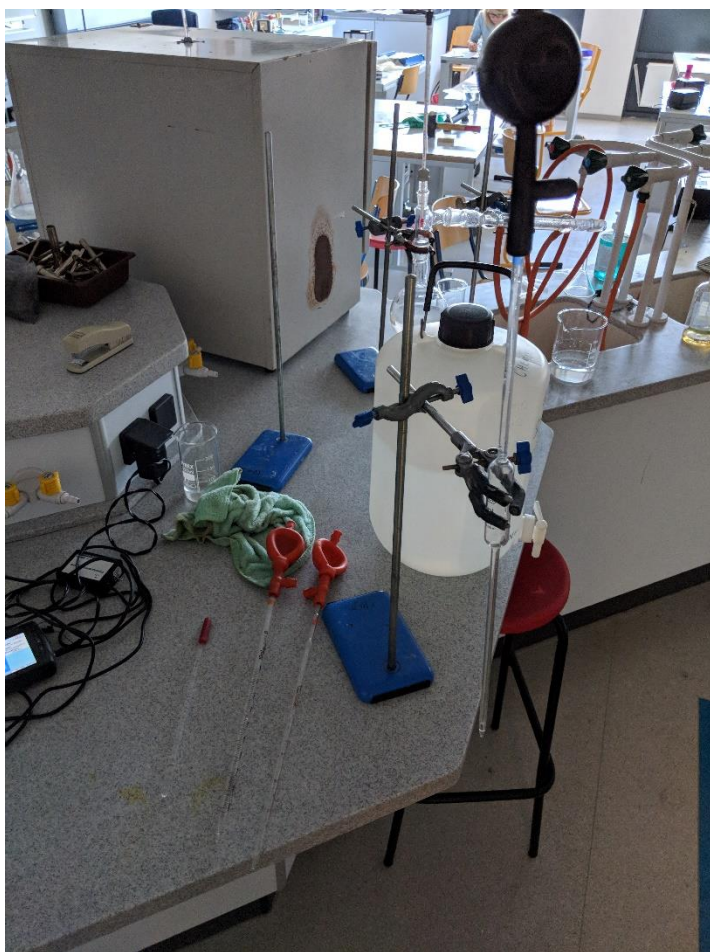


Figure 9 Pipet Setup

The procedure was as follows:

- 1) Fill Beaker A with 170 ml of distilled water using a measuring cylinder
- 2) Add 0.1 ml of 2 mol/dm³ HCL in Beaker A using Pipet C
- 3) Stir solution with glass rod
- 4) Fill pipettes A and B with solution in beaker A
- 5) Fill test tube A with pipet A
- 6) Use the remaining solution in pipets A and B fill beaker B
- 7) Place test tube A into beaker B surrounding the cathode as specified in appendix A
- 8) Measure volume of air in test tube A
- 9) Turn on power pack switch and start timer

- 10) Measure voltage and current
- 11) Wait around 5-6 minutes
- 12) Turn off power pack and switch off timer
- 13) Measure the new volume of gas in test tube A

This experiment was repeated 5 times to reduce random errors and was then repeated using 0.1 to 0.5 M of 2 mol/dm³ HCl in 0.1 ml increments. The data gathered is shown in tables 14 - 18.

Table 14

	Distilled Water with 0.1ml of 2 mol/dm ³ HCl				
	Test				
Measurement	Test 1	Test 2	Test 3	Test 4	Test 5
Initial Volume (ml)	1.3	1.6	1.1	2.4	1.7
Final Volume (ml)	1.8	2.1	1.8	3.0	2.4
Initial Voltage (V)	0.34	0.41	0.37	0.53	0.52
Voltage (V)	17.25	17.23	17.2	17.43	17.38
Initial Current (mAmps)	-0.1	-0.1	-0.1	-0.2	-0.2
Current (mAmps)	19.3	19.6	19.8	22.7	25.5
Times (s)	319	322	349	364	323

Table 15

	Distilled Water with 0.2ml of 2 mol/dm ³ HCl				
	Test				
Measurement	Test 1	Test 2	Test 3	Test 4	Test 5
Initial Volume (ml)	1.2	1.0	1.7	1.3	1.0
Final Volume (ml)	3.0	2.7	4.0	3.9	3.3
Initial Voltage (V)	0.66	0.67	0.68	0.67	0.84
Voltage (V)	16.91	16.89	16.9	16.85	16.82

Initial Current (mAmps)	-0.1	-0.2	-0.2	-0.3	-0.2
Current (mAmps)	55.6	55.2	61.4	62.5	62.7
Times (s)	322	300	341	348	342

Table 16

	Distilled Water with 0.3ml of 2 mol/dm ³ HCl				
	Test				
Measurement	Test 1	Test 2	Test 3	Test 4	Test 5
Initial Volume (ml)	1.6	1.5	1.7	1.2	1.3
Final Volume (ml)	4.7	4.5	4.2	4.1	4.1
Initial Voltage (V)	0.27	0.73	0.83	0.77	0.89
Voltage (V)	16.19	16.2	16.27	16.29	16.4
Initial Current (mAmps)	-0.1	-0.3	-0.3	-0.2	-0.4
Current (mAmps)	88.2	86.8	81.9	86.5	83.5
Times (s)	327	327	310	310	308

Table 17

	Distilled Water with 0.4ml of 2 mol/dm ³ HCl				
	Test				
Measurement	Test 1	Test 2	Test 3	Test 4	Test 5
Initial Volume (ml)	0.47	0.84	0.5	0.52	0.78
Final Volume (ml)	6.3	6.2	6.5	6.8	5.8
Initial Voltage (V)	0.47	0.84	0.5	0.52	0.78
Voltage (V)	15.85	15.86	15.97	16.02	16.05
Initial Current (mAmps)	-0.2	-0.3	-0.2	-0.1	-0.2
Current (mAmps)	137.5	132.2	133	123.9	124.3
Times (s)	314	309	311	395	300

Table 18

	Distilled Water with 0.5ml of 2 mol/dm ³ HCl
--	---

	Test				
Measurement	Test 1	Test 2	Test 3	Test 4	Test 5
Initial Volume (ml)	1.4	1.2	1.2	1.4	1.1
Final Volume (ml)	10.1	8.1	10.4	8.7	9.2
Initial Voltage (V)	0.36	0.91	0.79	0.9	1.02
Voltage (V)	15.14	15.3	15.2	15.12	15.16
Initial Current (mAmps)	-0.2	-0.2	-0.2	-0.2	-0.3
Current (mAmps)	190.2	178.3	192.2	193.2	189.1
Times (s)	399	340	445	325	357

This data in conjunction with table 3, was then processed in a similar fashion to that in the first experiment, taking into account the extra values, to produce tables 19 – 24 by processing the data in the following way:

- Change in Volume = Final Volume – Initial Volume
- Moles of Hydrogen = (Change in Volume * Pressure)/(8.314 * Temperature)
- Power = Current * Voltage
- Energy = Power * time
- Joules per mol = Energy/ Moles of Hydrogen
- Mol of HCL = Volume of 2 mol/dm³ HCl / 1000 * 2
- Concentration of HCl = Mol of HCl / Volume of Water

Table 19

	Distilled Water with 0.0 ml of 2 mol/dm ³ HCl		
	Processing		
Measurement	Value	Absolute Error	% Error

Temperature (K)	301	0.1	0.03%
Pressure (Pa)	201900	50	0.02%
Volume of 2 mol/dm ³ HCl (ml)	0	0	0%
Volume of Water (ml)	30	1	3%
Initial Volume (ml)	2.3	0.05	2%
Final Volume (ml)	2.3	0.05	2%
Initial Voltage (V)	0.18	0.005	3%
Voltage (V)	17.60	0.005	0.03%
Initial Current (Amps)	-0.0001	0.00005	50%
Current (Amps)	0.0020	0.00005	3%
Times (s)	327	0.5	0.2%
Change in Volume(ml)	0.0	0.1	0%
Moles of Hydrogen (mol)	0	0	0.06%
Power (W)	0.040	0.001	3%
Energy (J)	12	0.3	3%
Joules per mol of H ₂ (J/mol)	0	0	3%
Moles of HCL (mol)	0	0	0%
Moles of H ₂ per Joule	N/A	N/A	N/A

Table 20

	Distilled Water with 0.1 ml of 2 mol/dm ³ HCl		
	Processing		
Measurement	Value	Absolute Error	% Error
Temperature (K)	301	0.1	0.03%
Pressure (Pa)	201900	50	0.02%
Volume of 2 mol/dm ³ HCl (ml)	0.1	0.01	10%
Volume of Water (ml)	30	1	3%
Initial Volume (ml)	1.3	0.05	4%
Final Volume (ml)	1.8	0.05	3%
Initial Voltage (V)	0.34	0.005	1.5%

Voltage (V)	17.25	0.005	0.03%
Initial Current (Amps)	-0.0001	0.00005	50%
Current (Amps)	0.0193	0.00005	0.3%
Times (s)	319	0.5	0.2%
Change in Volume (ml)	0.5	0.1	20%
Moles of Hydrogen (mol)	40	8	20%
Power (W)	0.33	0.001	0.3%
Energy (J)	110	0	0.4%
Joules per mol of H ₂ (J/mol)	3	0	21%
Moles of HCL (mol)	0.0002	0.00002	10%
Concentration of HCL (mol/dm ³)	0.0067	0.0009	13%

Table 21

Measurement	Distilled Water with 0.2 ml of 2 mol/dm ³ HCl		
	Processing		
Measurement	Value	Absolute Error	% Error
Temperature (K)	301	0.1	0.03%
Pressure (Pa)	201900	50	0.02%
Volume of 2 mol/dm ³ HCl (ml)	0.2	0.01	5%
Volume of Water (ml)	30	1	3%
Initial Volume (ml)	1.2	0.05	4%
Final Volume (ml)	3.0	0.05	2%
Initial Voltage (V)	0.66	0.005	0.8%
Voltage (V)	16.91	0.005	0.03%
Initial Current (Amps)	-0.0001	0.00005	50%
Current (Amps)	0.0556	0.00005	0.09%
Times (s)	322	0.5	0.2%
Change in Volume (ml)	1.8	0.1	6%
Moles of Hydrogen (mol)	150	8	6%

Power (W)	0.940	0.001	0.1%
Energy (J)	303	0.8	0.3%
Joules per mol of H ₂ (J/mol)	2.1	0.01	0.3%
Moles of HCL (mol)	0.0004	0.00002	5%
Concentration of HCL (mol/dm ³)	0.013	0.001	8%

Table 22

	Distilled Water with 0.3 ml of 2 mol/dm ³ HCl		
	Processing		
Measurement	Value	Absolute Error	% Error
Temperature (K)	301	0.1	0.03%
Pressure (Pa)	201900	50	0.02%
Volume of 2 mol/dm ³ HCl (ml)	0.3	0.01	3%
Volume of Water (ml)	30	1	3%
Initial Volume (ml)	1.6	0.05	3%
Final Volume (ml)	4.7	0.05	1.1%
Initial Voltage (V)	0.27	0.005	1.9%
Voltage (V)	16.19	0.005	0.03%
Initial Current (Amps)	-0.0001	0.00005	50%
Current (Amps)	0.0882	0.00005	0.06%
Times (s)	327	0.5	0.2%
Change in Volume (ml)	3.1	0.1	3%
Moles of Hydrogen (mol)	250	0	0.06%
Power (W)	1.43	0.001	0.09%
Energy (J)	467	1	0.2%
Joules per mol of H ₂ (J/mol)	1.87	0.006	0.3%
Moles of HCL (mol)	0.0006	0.00002	3%
Concentration of HCL (mol/dm ³)	0.020	0.001	7%

Table 23

	Distilled Water with 0.4 ml of 2 mol/dm ³ HCl		
	Processing		
Measurement	Value	Absolute Error	% Error
Temperature (K)	301	0.1	0.03%
Pressure (Pa)	201900	50	0.02%
Volume of 2 mol/dm ³ HCl (ml)	0.4	0.01	3%
Volume of Water (ml)	30	1	3%
Initial Volume (ml)	0.5	0.05	11%
Final Volume (ml)	6.3	0.05	0.8%
Initial Voltage (V)	0.47	0.005	1%
Voltage (V)	15.85	0.005	0.03%
Initial Current (Amps)	-0.0002	0.00005	25%
Current (Amps)	0.1375	0.00005	0.04%
Times (s)	314	0.5	0.2%
Change in Volume (ml)	5.8	0.1	1.7%
Moles of Hydrogen (mol)	470	0	1.8%
Power (W)	2.179	0.0015	0.07%
Energy (J)	684	1.6	0.2%
Joules per mol of H ₂ (J/mol)	1.5	0	2%
Moles of HCL (mol)	0.0008	0.00002	3%
Concentration of HCL (mol/dm ³)	0.027	0.002	6%

Table 24

	Distilled Water with 0.5 ml of 2 mol/dm ³ HCl		
	Processing		
Measurement	Value	Absolute Error	% Error
Temperature (K)	301	0.1	0.03%
Pressure (Pa)	201900	50	0.02%
Volume of 2 mol/dm ³ HCl (ml)	0.5	0.01	2%

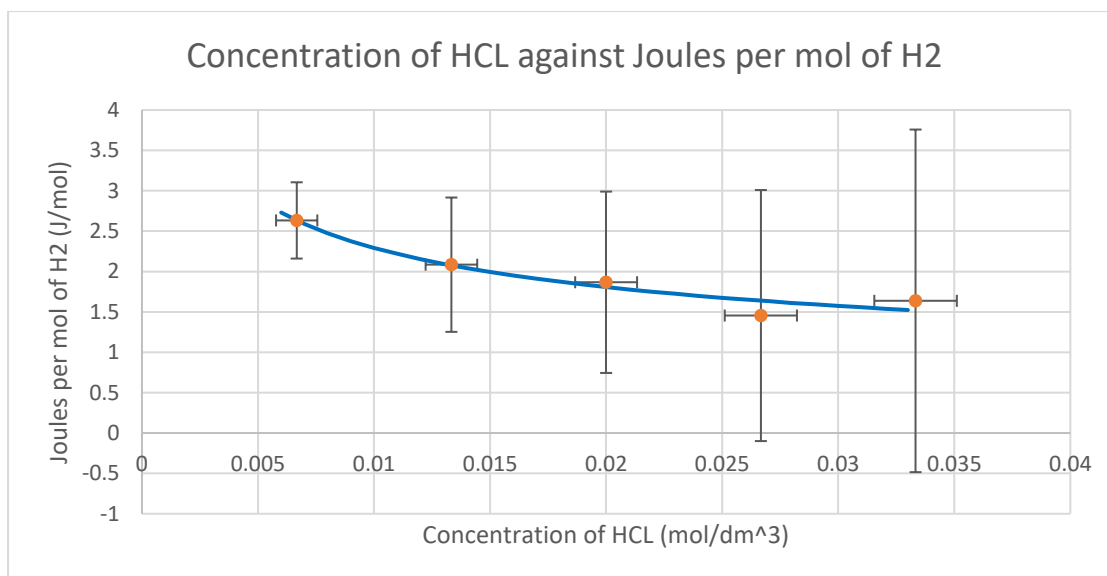
Volume of Water (ml)	30	1	3%
Initial Volume (ml)	1.4	0.05	4%
Final Volume (ml)	10.1	0.05	0.5%
Initial Voltage (V)	0.36	0.005	1.4%
Voltage (V)	15.14	0.005	0.03%
Initial Current (Amps)	-0.0002	0.00005	25%
Current (Amps)	0.1902	0.00005	0.03%
Times (s)	399	0.5	0.1%
Change in Volume (ml)	8.7	0.1	1.2%
Moles of Hydrogen (mol)	700	0	1.2%
Power (W)	2.880	0.0017	0.06%
Energy (J)	1149	2.1	0.2%
Joules per mol of H ₂ (J/mol)	1.6	0	1.4%
Moles of HCL (mol)	0.001	0.00002	2%
Concentration of HCL (mol/dm ³)	0.033	0.002	5%

With these values, one can graph the concentration of HCl, against the Joules consumed per mol of H₂ produced. These values can be shown in table 25.

Table 25

Concentration of HCL (mol/dm ³)	Joules per mol of H ₂ (J/mol)
0.0067	2.6
0.013	2.1
0.020	1.9
0.027	1.5
0.033	1.6

This is represented visually in graph 1:



Graph 1

100% pure water theoretically would contain no ions at all, this means that theoretically regardless of the energy put into the water H₂ would be created. Taking this into account and the general appearance of the data points, it became clear that there was some sort of inverse correlation. Using a custom-made python script²⁹ a trendline with the function: $y = \frac{0.474}{x^{0.342}}$. This trendline is shown in graph 1.

The final correlation of $\frac{J}{\text{Mol of H}_2} = \frac{0.474}{[\text{HCl}]^{0.342}}$ reveals a correlation where to decrease the amount of joules used to generate a mol of hydrogen by a factor of 1, one has to increase the concentration of HCl exponentially by a factor of almost 3. To answer the third part of my research question, how can the electrolysis of water be augmented to increase the efficiency of hydrogen production at scale? the economic viability of this experiment will be considered. On an industrial scale, revenues and costs are very important, and finding the

²⁹ Appendix A

ideal concentration of HCl to maximize profit is of utmost importance. Assuming scaling does not change the nature of this process of electrolysis, one can use the correlation to find the economically most viable way to produce hydrogen in large quantities.

To calculate the ratio, I will assume that my HCl solution will occupy a volume of v dm³. As the HCl solution is electrolysed, necessary product will be added to the solution to keep the concentration of HCl at a constant level. Using an energy of j , and c moles of HCl, the correlation discovered in experiment 3 can be rewritten as: $\frac{j}{n} = \frac{0.474}{(\frac{c}{v})^{0.342}}$ where n is the Mol of H₂. This can be re written as: $n = j \frac{(\frac{c}{v})^{0.342}}{0.474}$. This is the amount of H₂ which will be produced given the constants j , c , and v .

The half-equation of electrolysis of water at the cathode, where hydrogen forms, is $2H_3O^+ + 2e^- \rightarrow 2H_2O + H_2$. At the anode, the half equation of electrolysis is $2Cl^- \rightarrow Cl_2 + 2e^-$. As both reactions either use or produce 2 electrons, the ratio of H₃O⁺ ions to Cl⁻ ions used in the electrolysis of water are 1:1. As water and HCl form ions through the reaction $H_2O + HCl \rightleftharpoons H_3O^+ + Cl^-$, the ratio of H₂O to H₃O⁺ ions and HCl to Cl⁻ ions are both 1:1. Additionally, the H₃O⁺ ions react to form water at the cathode, as for every mol of water electrolysed, one mole of water is formed, the water used in electrolysis will on its own replenish itself through the reaction. The HCl, however, would need to be replenished at a ratio of 2 Mol of HCl for each Mol of H₂.

In order to use the correlation found in experiment 3, pure water would have to be used. Any large-scale producer would, therefore, have to distil water, which costs about

€0.004 per litre³⁰. As the cost of water in around the world averages out to about €0.00048³¹ per litre is minimal compared to the cost of purifying water, it can be ignored. 1 mol of HCl costs about €1³². The average cost of electricity around the world is €0.13 per kWh³³ or €3.6E-8 per Joule.

Using this information, the cost of producing H₂ is revealed to be:

$$Cost = 4 * 10^{-3}V + 3.6 * 10^{-8}J + 1 * 2j \frac{(\frac{C}{V})^{0.342}}{0.474}$$

Hydrogen sells for about €12.04 per kg of H₂³⁴ or €0.005972 per Mol of H₂. This leads to the conclusion that revenue from hydrogen production can be detailed as:

$$Revenue = 4.972 * 10^{-3} * j \frac{(\frac{C}{V})^{0.342}}{0.474}$$

Together this creates the profit function at:

$$Profit = Revenue - Cost$$

$$Profit = 4.972 * 10^{-3} * j \frac{(\frac{C}{V})^{0.342}}{0.474} - 4 * 10^{-3}V + 3.6 * 10^{-8}j + 1 * 2j \frac{(\frac{C}{V})^{0.342}}{0.474}$$

³⁰ Timmons, Mark. 2012. De-ionization 101. 30 August. Accessed September 21, 2018. <https://www.uswatersystems.com/blog/2012/08/de-ionization-101/>.

³¹ Sabatelle, Joseph. 2004. Price Of Water. Accessed November 28, 2018. <https://hypertextbook.com/facts/2004/JosephSabatelle.shtml>.

³² Right Price Chemicals. 2018. HYDROCHLORIC ACID, REAGENT GRADE (ACS) - 37%. 21 September. Accessed September 21, 2018. <http://www.rightpricechemicals.com/purchase-hydrochloric-acid-online-37.html>.

³³ Global Energy Prices. n.d. Electricity prices around the world. Accessed September 21, 2018. <https://www.globalenergyprices.com/en/electricity-prices/>.

³⁴ California Fuel Cell Partnership. n.d. Cost to refill. Accessed September 21, 2018. <https://cafcp.org/content/cost-refill>.

Which can be simplified to:

$$Profit = j \frac{\left(\frac{c}{v}\right)^{0.342}}{0.474} (-1.995028) - 4 * 10^{-3}V - 3.6 * 10^{-8}j$$

Unfortunately, this formula reveals that this production, regardless of the values of j, c, and v, the profit will always be negative.

Evaluation

As with any small-scale experiment trying to explain a process which will occur on a large scale, my experiment does not account for the effects of scaling. This means that the correlation found in experiment 3 is most likely not the same as what would occur when everything was brought to production scale.

As I progressed through the experiments, I realized that there was a small initial current and voltage at the beginning of every trial, these can be seen in my raw data. The reason for these may have been that the electrodes were acting somewhat like capacitors storing small amounts of energy. At first, I tried waiting for these to disappear before continuing my experiment, but due to time constraints, I wasn't able to do it for most of my trials.

Another variable I didn't control was time. When I started the experiment, my thought was to use a range of times to get a better dispersion of variables. As time only increased the energy being put through the system, I assumed that when I found the efficiency through dividing Mol of hydrogen by energy consumed it would all cancel out. However, I did not account for how the increased energy would affect the temperature and

hence the production of hydrogen. This although minor on the small scale when scaled up could have a large impact on output.

For the second experiment, I had to create my own equipment to hold 4 electrodes instead of 2. I made it by hand drilling holes into a cork and pushing electrodes through the holes. Although it worked well, it wasn't high quality, and there may have been anomalies in the way it worked which may have been the reason for the inefficiency found in the results of experiment 2.

I did account for most variables. I always used the same amount of solution for every trial of each experiment. I kept the test tube collecting hydrogen at the cathode exposing the same amount of the electrode. I utilize the same source of water for all my experiments. The same set of electrodes were used for each of the experiments, and they were all carbon electrodes meaning they did not react.

Conclusion

Although this specific experiment proved to be unviable on a large scale, it did show that electrolysis can be made to be more efficient. Something which could be interesting to analyse more in depth, would be to further explore the effects observed in the second experiment, normally one might think that increasing electrodes would increase the surface area of the electrodes increasing the efficiency, while the opposite effect was found in my experience, and although it can be explained by decreased current, that doesn't quite explain why the decrease in efficiency is greater the more ion concentration present in the water.

Overall, adding HCl to water, does make it more efficient, however it is still not economically viable, given current technological standards. Nonetheless, this does not bring electrolysis off the table, other factors such as different electrodes, catalysts, and different pressures, may be used to make electrolysis more efficient, and economically viable³⁵. Additionally, other routes are being explored to increase the efficiency of hydrogen production without producing carbon emissions. One such concept is that of photocatalysts, which uses photons to release electrons from the surface of the catalyst reducing the hydrogen in the water³⁶.

³⁵ Bandarenka, Dr. Aliaksandr S. 2016. *Efficiency of water electrolysis doubled*. 10 March. Accessed September 24, 2018. <https://www.tum.de/en/about-tum/news/press-releases/detail/article/32998/>.

³⁶ Kobe University. 2017. Photocatalyst makes hydrogen production 10 times more efficient. 18 May. Accessed September 29, 2018. <https://phys.org/news/2017-05-photocatalyst-hydrogen-production-efficient.html>.

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Appendix A

```
import scipy
import scipy.optimize
from sys import argv
x = [float(k) for k in argv[1].split(',')]
y = [float(k) for k in argv[2].split(',')]

def trendlineFit(x, y):
    expDet = scipy.optimize.curve_fit(lambda t,a,b: a/(t**b), x, y)
    outFunction = f"y = {str(expDet[0][0])} / x^{str(expDet[0][1])}"
    return outFunction

print(trendlineFit(x, y))
```