

Question

How do water quality factors, such as the pH and various impurities, collectively impact the energy efficiency of proton exchange membrane fuel cells (PEMFC) and can a renewable wind turbine power source generate a comparable energy efficiency to a battery power source when used with a PEMFC to generate hydrogen?

Hypothesis

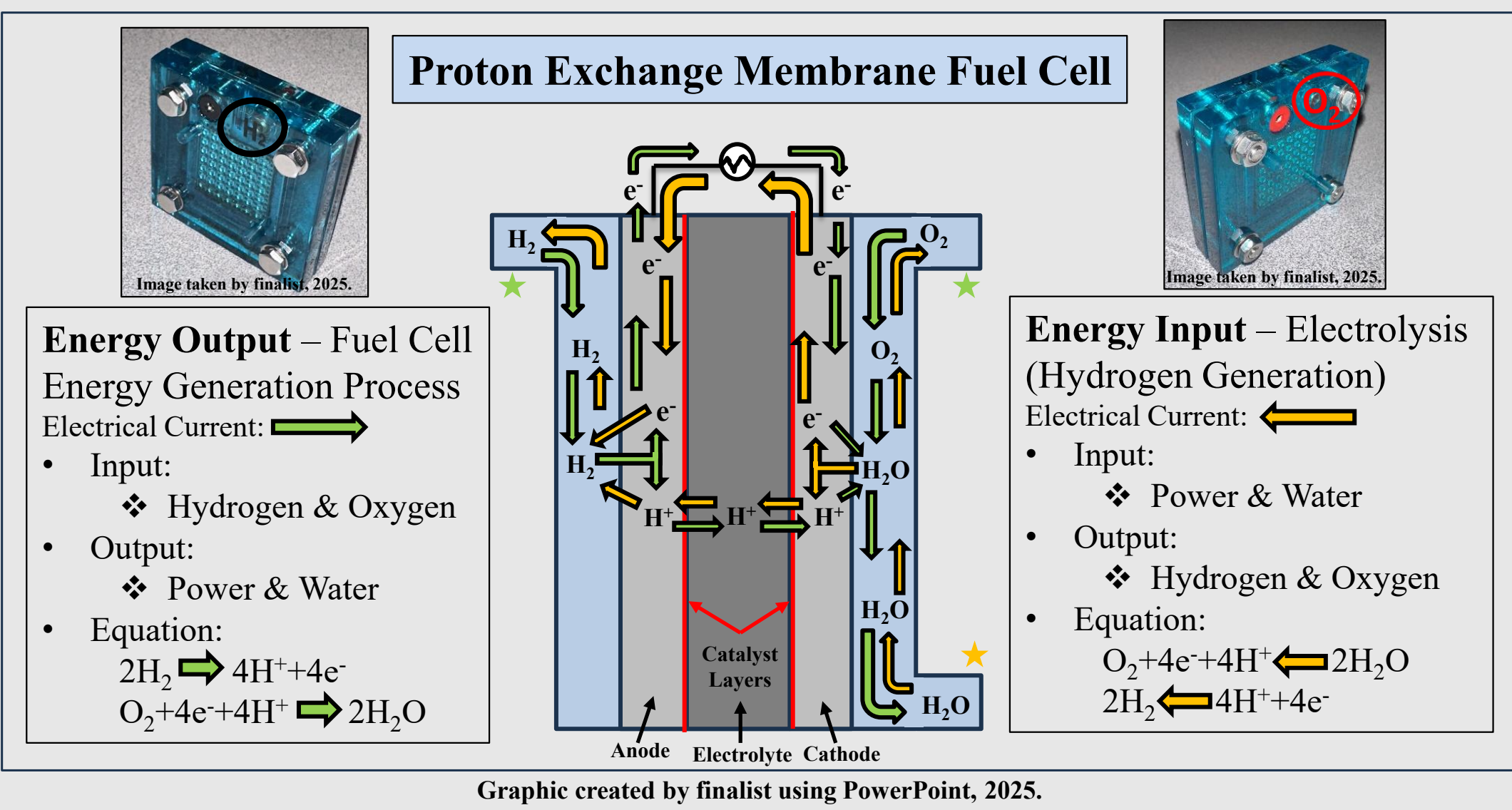
If the pH and water impurity decrease, then the PEMFC energy efficiency will increase. If a wind turbine is used as the external power source instead of a battery to generate hydrogen, then the PEMFC will yield a comparable energy efficiency with no impurities.

Purpose

- To demonstrate how variations in water quality affect fuel cell energy efficiency, this project tested a combination of pHs and impurities to analyze their effects on the energy efficiency of a proton exchange membrane fuel cell (PEMFC).
- To test various power sources for hydrogen generation, this project used both a wind turbine and a battery to observe their differences during electrolysis and compare their PEMFC energy efficiencies.

Background Research

- A fuel cell converts the chemical energy of hydrogen or other fuels into electricity through a pollution free process. They are similar to batteries but don't run down or need recharging.
- Invented by Sir William Grove approximately 180 years ago, fuel cells emerged when he demonstrated that electrolysis, the process of splitting water into hydrogen and oxygen, could be reversed to create an electric current by recombining the hydrogen and oxygen.
- Fuel cells consist of two electrodes - an anode (negatively charged) and a cathode (positively charged) - sandwiched around an electrolyte, a material that allows specific particles to move between sides of the fuel cell while blocking others.
- In a proton exchange membrane fuel cell (PEMFC), hydrogen is supplied to the anode, and oxygen is fed to the cathode. A catalyst layer at the anode splits the hydrogen molecules into electrons and protons which take separate paths to the cathode: the electrons flow through an external circuit, generating an electricity, while the protons pass through the electrolyte to the cathode. Here, the protons combine with the returning electrons from the circuit and supplied oxygen to complete a process that produces water.
- A PEMFC can also function as an electrolyzer when an external power source reverses the electric current, producing hydrogen and oxygen by splitting water.



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Variables

Independent Variable (IV)		Constant (C)	Dependent Variable (DV)
Water pH	Acidic (pH 3)	* Ambient temperature * Water temperature * Time between each reading * Multimeter setting * Water level in the graduated cylinders * Amount of impurities	PEMFC Energy Efficiency Energy Output per ml of Hydrogen + Energy Input per ml of Hydrogen Energy per ml of hydrogen = Energy (W-s) ÷ Hydrogen Volume (ml) Total Energy (W-s) = Power (W) × Time (sec) Power (W) = Voltage (V) × Current (amp) Current (amp) = Voltage drop (V) ÷ 0.33 (Ω)
	Neutral (pH 7) - Control		
	Alkaline (pH 11)		
Impurity	None - Control		
	Salt (12 g)		
	Sugar (16 g)		
Power Source	Salt (12 g) & Sugar (16 g)		
	Battery - Control		
Wind Turbine	Wind Turbine		

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Factors Affecting Fuel Cell Energy Efficiency

Procedure

Fuel Cell Preparation and Setup

- Retrieve all necessary materials
- Prepare 12 solutions in beakers by mixing distilled water with various amounts of white distilled vinegar, household bleach, salt, and sugar to get multiple pHs and impurities
 - ❖ **pH 7 – Neutral**
 - Neutral Solution (Control): 250 ml of distilled water
 - Salt: dissolve 12 g of table salt into the neutral solution
 - Sugar: dissolve 16 g of sugar into the neutral solution
 - Salt and Sugar: dissolve 12 g of table salt and 16 g of sugar into the neutral solution
 - ❖ **pH 3 – Acidic**
 - Acidic Solution: 2.5 ml of white distilled vinegar mixed with 250 ml of distilled water
 - Follow the same additions as Ph 7, using the acidic solution: 12 g salt, 16 g sugar, and both
 - ❖ **pH 11 – Alkaline**
 - Alkaline Solution: 15 ml of household bleach mixed with 250 ml of distilled water
 - Follow the same additions as the neutral solution, using the alkaline solution: 12 g salt, 16 g sugar, and both
- Attach the two ~5 cm rubber tubes to the hydrogen and oxygen sides of the PEMFC
- Securely place the two 60 ml graduated cylinders into the base
- Securely place the two 30 ml cones into the graduated cylinders
- Connect the ~20 cm rubber tubes from the cones to the hydrogen and oxygen sides of the PEMFC
- Use the syringe filled with one of the prepared solutions to fill the oxygen side of the PEMFC through the ~5 cm rubber tube
- Pour the same solution as step 7 into the graduated cylinders, ensuring the liquid level is exactly at the halfway mark
- Connect the positive terminal of the battery power source (red) to the left side of the resistor (A)
- Connect a cable from the right side of the resistor (B) to the positive terminal (red) on the oxygen side of the PEMFC
- Connect the negative terminal of the battery (black) directly to the negative terminal (black) on the hydrogen side of the PEMFC
- Connect the positive and negative terminals of Multimeter 1 to the appropriate terminals of the battery
- Connect the positive and negative terminals of Multimeter 2 to the left side (A) and right side (B) of the resistor, respectively
- Set both multimeters to the 1.5 V setting
- Turn on the battery for electrolysis and immediately start the stopwatch
- Every 30 seconds, record the hydrogen volume, oxygen volume, voltage across the battery, and voltage drop across the resistor
- When the hydrogen volume reaches 30 ml, turn off the battery and record the time, hydrogen volume, oxygen volume, voltage across the battery, and voltage drop across the resistor
- Reset the stopwatch
- Energy Output - Fuel Cell Energy Generation Process**
- Reconnect the positive and negative terminals of Multimeter 2 to the right side (B) and left side (A) of the resistor, respectively
- Reconnect all cables connected to the battery to the appropriate terminals of the motor
- Start the stopwatch immediately once the cables are connected to the motor
- Every 30 seconds, record the hydrogen volume, oxygen volume, voltage across the motor, and voltage drop across the resistor
- Once the motor stops moving, record the time, hydrogen volume, oxygen volume, voltage across the motor, and voltage drop across the resistor
- Turn off both multimeters
- Cleanup**
- Disconnect all cables and rubber tubes in the setup
- Detach the cones and graduated cylinders from each other and the base
- Empty the solution from the cones and graduated cylinders
- Rinse the cones and graduated cylinders thoroughly
- Use the syringe to push air through the PEMFC and rubber tubes to remove any reminiscences of the solution
- Repetition**
- Repeat steps 3-29 with a different solution each time until all have been tested
- Repeat steps 2-30 for the second and third trials of all solutions
- Wind Turbine Experimentation**
- Assemble the wind turbine power source
- Position the wind source (~ 33 km/hr wind speed) ~5 cm away, directly facing the wind turbine
- Repeat steps 2-31, only using the neutral, acidic, and alkaline solutions with no impurities and the wind turbine as the power source for electrolysis instead of the battery



Image taken by finalist, 2024.

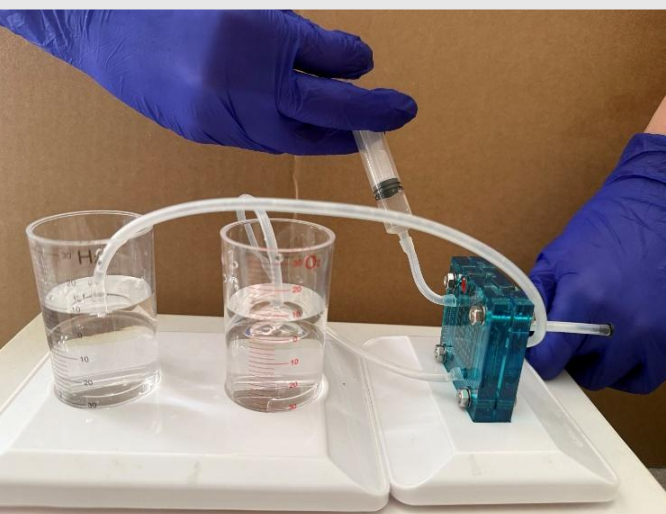


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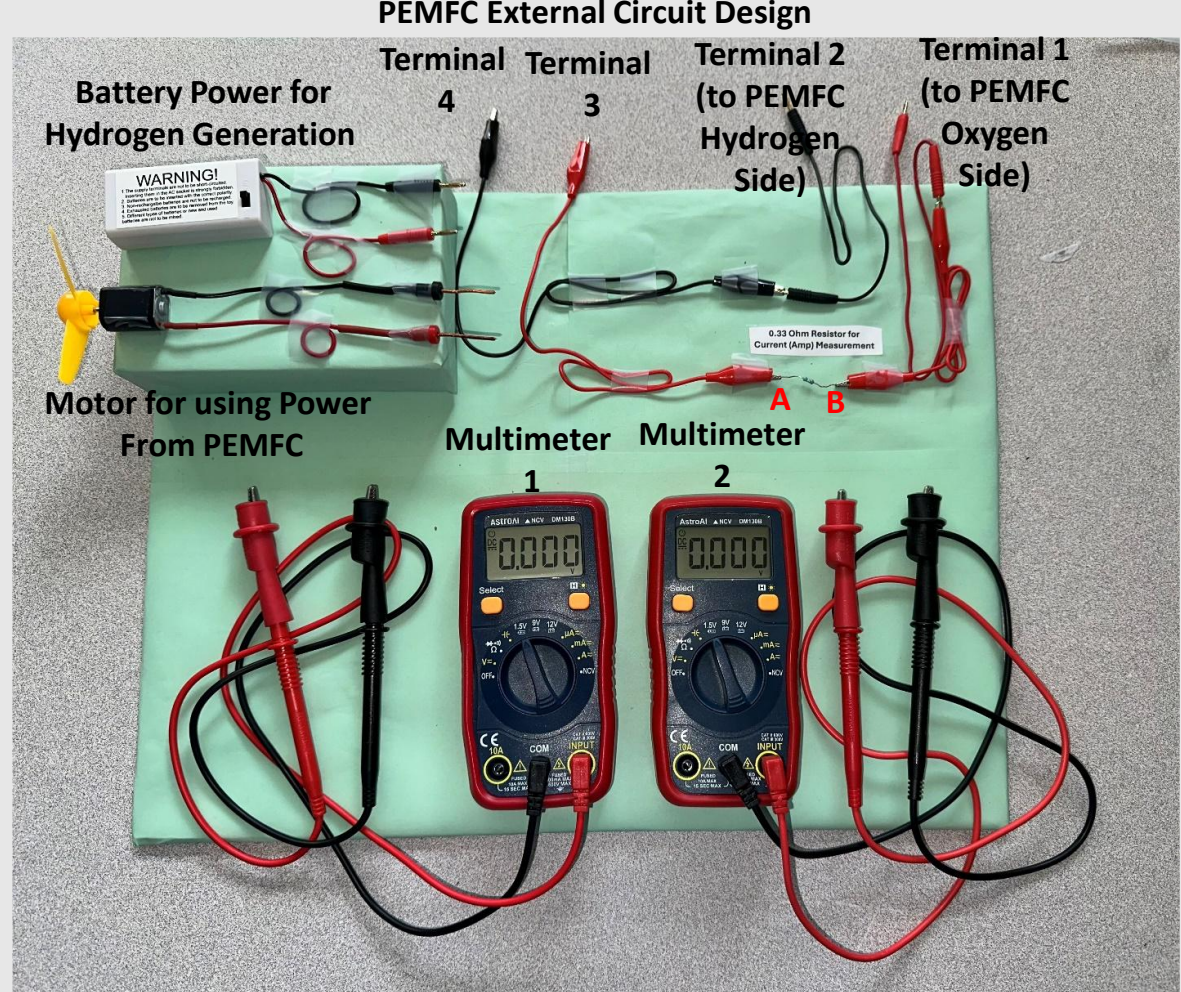
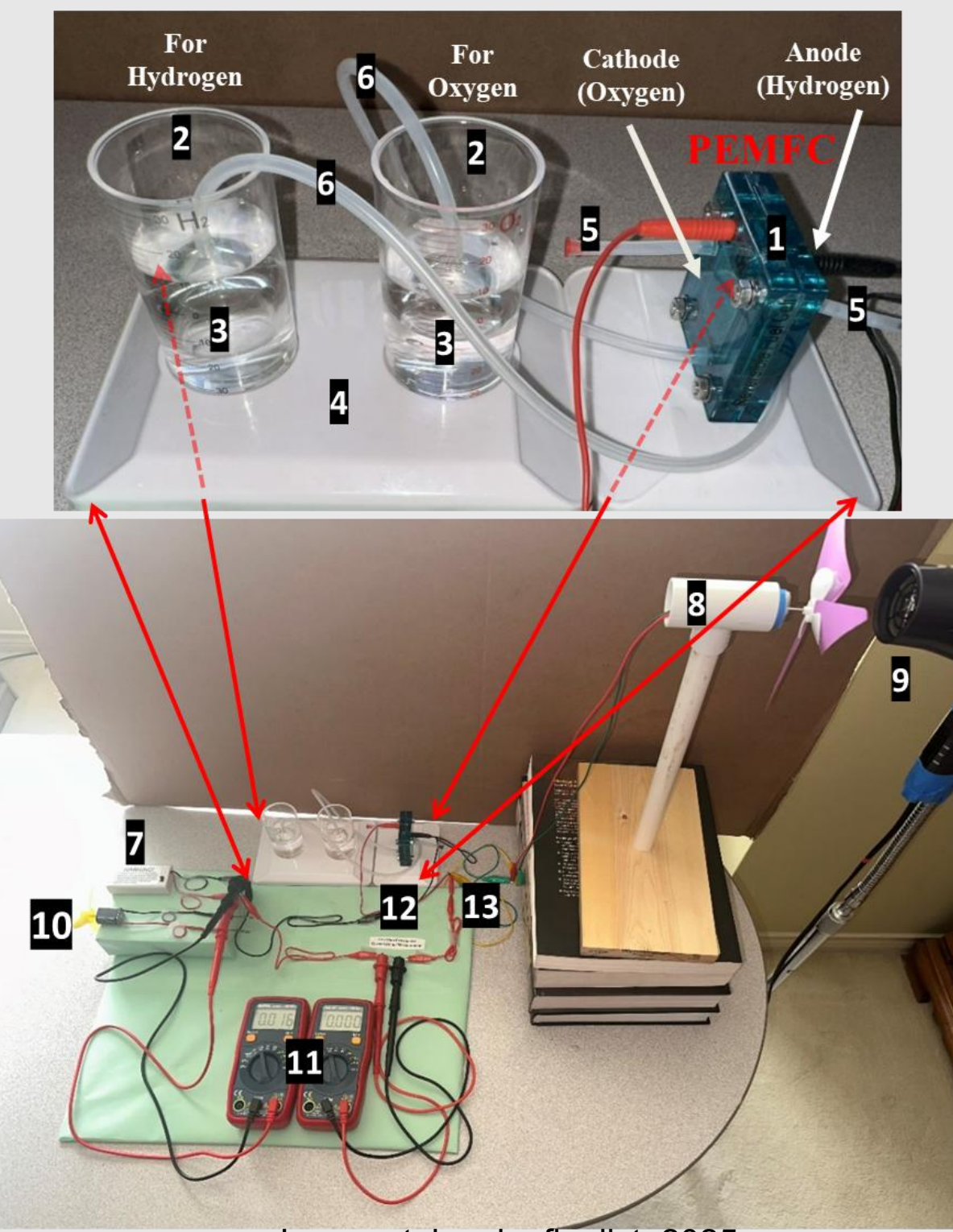


Image taken by finalist, 2024.

Materials/Setup

- Proton Exchange Membrane Fuel Cell (PEMFC)
- 2 60 ml Graduated Cylinders
- 2 30 ml Cones
- Base for Graduated Cylinders
- 2 ~5 cm Rubber Tubes
- 2 ~20 cm Rubber Tubes
- Battery Power Source (2 AA Batteries)
- Wind Turbine Power Source
- Wind Source
- Motor
- 2 Multimeters
- 0.33 Ω Resistor
- 3 Cables with Alligator Clips
- 250 ml Beakers
- Distilled Water
- White Distilled Vinegar
- Household Bleach
- Salt
- Sugar
- pH Meter
- Syringe
- Measuring Spoon
- Stopwatch



Images taken by finalist, 2025.

Methodology for Assessing PEMFC Energy Efficiency

- ❖ **Calculate the Average Current (Amp):**
 - Using Ohm's Law, the average current is calculated by dividing the average voltage drop (measured by Multimeter 2) across the resistor which is 0.33 Ω.
 - **Formula:** Current (amp) = Voltage Drop (V) ÷ 0.33 (Ω)
- ❖ **Calculate the Average Power (W):**
 - The average electrical power is calculated by multiplying the average voltage (measured by Multimeter 1) across the power source (like the battery or wind turbine) for the power input or average voltage across the motor for the power output by the average current.
 - **Formula:** Power (W) = Voltage (V) × Current (amp)
- ❖ **Calculate the Total Energy (W-s):**
 - The total energy in the system is determined by multiplying the average power by the time it took to generate the set amount of hydrogen for the energy input or the time it took for the motor to stop moving for the energy output.
 - **Formula:** Energy (W-s) = Power (W) × Time (sec)
- ❖ **Calculate the Average Energy per ml of Hydrogen:**
 - The energy per ml of Hydrogen is determined by dividing the total energy by the volume of hydrogen generated for the energy input or the hydrogen consumed for the energy output.
 - **Formula:** Energy per ml of hydrogen = Energy (W-s) ÷ Hydrogen Volume (ml)

$$PEMFC \text{ Energy Efficiency} = \frac{\text{Energy Output per ml of Hydrogen}}{\text{Energy Input per ml of Hydrogen}}$$

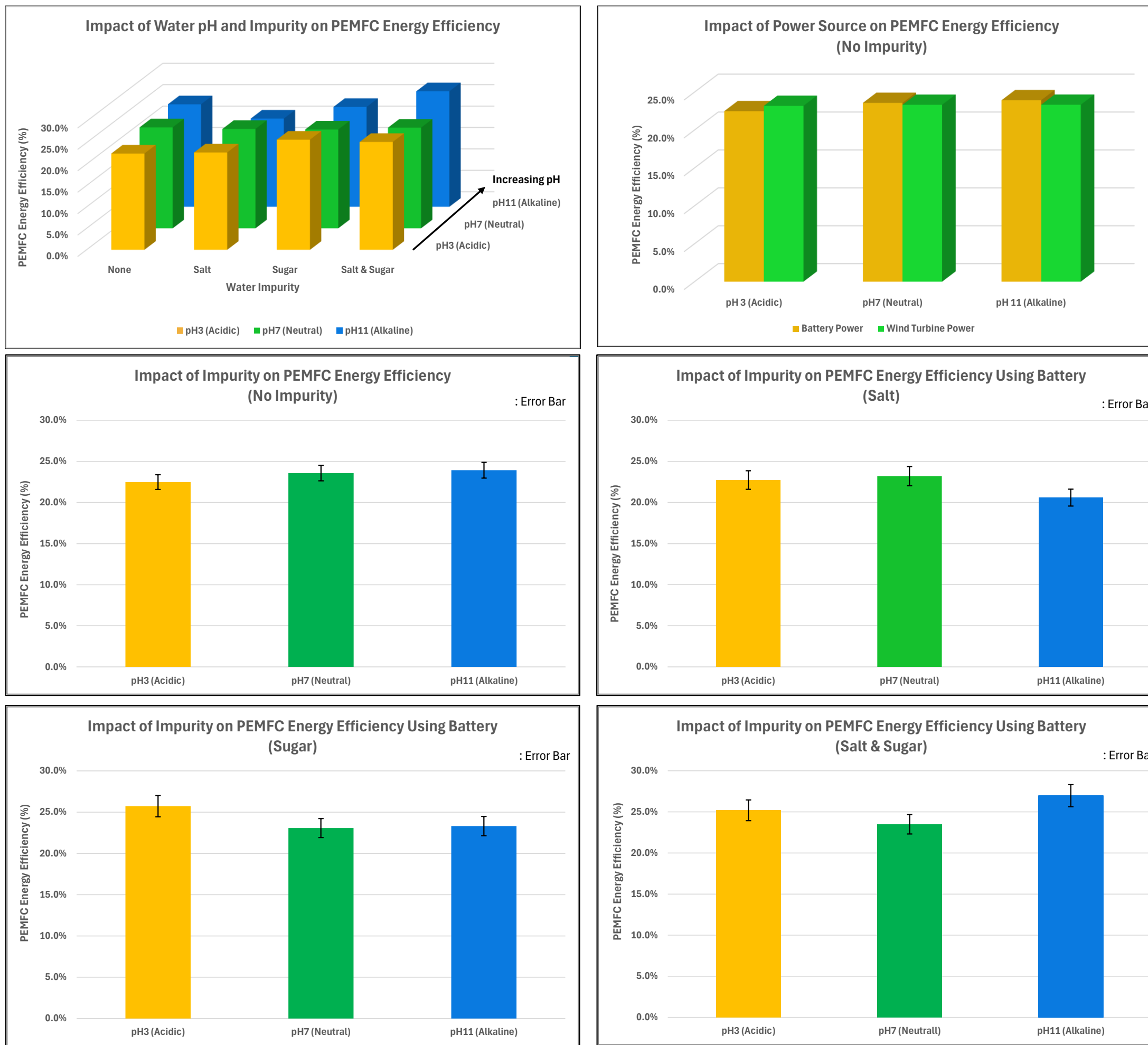
Results

Calculated PEMFC Energy Efficiency								
Experiment Details			Energy Input - Hydrogen Generation		Energy Output - Fuel Cell Energy Generation		PEMFC Energy Efficiency	
Power Source	pH	Impurity	Average Input Voltage (Volt)	Average Input Current (Amp)	Average Energy Input per ml Hydrogen (W-s)	Average Output Voltage (Volt)		Average Output Current (Amp)
Battery	pH 3 (Acidic)	None	2.398	0.542	9.863	0.471	0.187	22.48%
	pH 3 (Acidic)	Salt	2.341	0.511	9.427	0.495	0.179	22.73%
	pH 3 (Acidic)	Sugar	2.310	0.505	9.507	0.481	0.176	25.72%
	pH 3 (Acidic)	Salt & Sugar	2.288	0.490	9.468	0.491	0.169	25.19%
	pH 7 (Neutral)	None	2.297	0.496	9.640	0.456	0.178	23.57%
	pH 7 (Neutral)	Salt	2.295	0.473	9.526	0.461	0.172	23.20%
	pH 7 (Neutral)	Sugar	2.239	0.434	8.720	0.481	0.167	23.07%
	pH 7 (Neutral)	Salt & Sugar	2.230	0.439	9.128	0.453	0.158	23.49%
	pH 11 (Alkaline)	None	2.305	0.473	9.506	0.471	0.157	23.93%
	pH 11 (Alkaline)	Salt	2.303	0.474	10.660	0.440	0.152	20.59%
	pH 11 (Alkaline)	Sugar	2.239	0.443	9.110	0.481	0.148	23.31%
	pH 11 (Alkaline)	Salt & Sugar	2.098	0.396	8.411	0.430	0.155	26.97%
Wind Turbine	pH 3 (Acidic)	None	1.567	0.028	3.545	0.392	0.200	23.18%
	pH 7 (Neutral)	None	1.545	0.031	3.360	0.268	0.133	23.32%
	pH 11 (Alkaline)	None	1.549	0.029	3.572	0.385	0.184	23.33%

Table created by finalist, 2024.

- The PEMFC energy efficiencies ranged from around 21% to 27%.
- The variation in energy efficiencies mainly resulted from a broader range of energy inputs (electrolysis) rather than energy outputs (fuel cell energy generation process).
- Overall, impurities had the greatest impact at pH 11, resulting in the widest range of energy efficiencies, and the least impact at pH 7, where efficiencies stayed within 23%.
- Although the wind turbine power source provided a lower input voltage (1.5 V), the energy efficiencies still remained comparable to the battery (2.3 V), at around 23% with no impurities.

Graphs



Graphs created by finalist using Excel, 2024.

Conclusions

- With no impurities, the energy efficiency increases as the pH increases.
- Salt has a minimal impact on the energy efficiency at lower pHs but sharply decreases efficiency at higher pHs.
- Sugar generally improves energy efficiency especially at lower pHs.
- Salt and sugar combined at higher pHs achieve greater energy efficiencies.
- Impurities have the greatest impact at higher pHs and the least impact at neutral pHs.
- Wind turbines can produce comparable energy efficiencies to a battery and function as effective external power sources for electrolysis.

Salt and sugar combined at higher pHs is recommended to improve PEMFC energy efficiencies, and wind turbines can serve as reliable and renewable power sources for electrolysis.

Error Analysis

- Human error may have introduced small inconsistencies when measuring the amount of impurities and preparing the solutions.
- The graduated cylinders have a measurement scale with 2 ml increments, which limit the precision of volumetric readings.
- The hydrogen and oxygen tubes may have retained traces of air bubbles, potentially affecting the accuracy of the experiment slightly.
- To mitigate these issues, more advanced equipment could be used to maintain greater control and accuracy in the future.

Applications

- Studying the factors affecting fuel cell energy efficiency can lead to improvements in performance, reductions in cost, and advancements in the commercial development of fuel cell technology.
- When parried with electrolysis, fuel cells create a clean energy cycle capable of powering diverse applications across multiple sectors.
- Fuel cells are particularly useful in the transportation industry, but they also hold potential for residential and industrial power generation, as well as for long term energy storage in reversible systems.

Future Research

This project could be expanded by exploring:

- A wider variety of impurities and pHs, to analyze how they impact the PEMFC energy efficiency and performance.
- Various solution temperatures to determine their influence.
- Other types of fuel cells such as PAFC (Phosphoric Acid Fuel Cells), MCFC (Molten Carbonate Fuel Cells), and SOFC (Solid Oxide Fuel Cells) to compare their energy efficiencies with a PEMFC.
- The durability of a fuel cell under real-world conditions over time.