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Construction and Optimisation of Zinc-Copper Galvanic Half-Cells with LED Illuminations

Raminus Samad Khan[1], Tahlia Robertson[1], Kushagr Gowda[1], Yash Makhija[1], Zachary Briscoe[1], Jordan Kambanis[1], Masoomeh Asghar Nejad-Laskoukalayeh[1], Benedict Tai[1], David Alam[1], Thomas Whittle[1] and Gobinath Rajarathnam[1]

[1] School of Chemical and Biomolecular Engineering, University of Sydney, Sydney, New South Wales, Australia

E-mail: rkha0681@uni.sydney.edu.au

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Abstract

This study investigates the construction, performance, and optimisation of galvanic cells using copper-copper ion and zinc-zinc ion half-cells. The experiment aimed to explore electrochemical energy generation through redox reactions and to evaluate how design factors affect cell efficiency. Galvanic half-cells were assembled using 0.1 M and 0.05 M copper (II) sulfate and zinc sulfate solutions as standard electrolytes. Voltage and current outputs were measured with a multimeter, and the ability of each cell to power LEDs of different colours was assessed. Key variables, namely concentration, were systematically varied to determine their influence on electrical performance. The half-cell configuration demonstrated high output due to effective separation of half-reactions and minimal internal resistance. Increasing copper (II) sulfate concentration and decreasing zinc sulfate concentration generally improved performance, while series connections significantly boosted voltage, enabling the illumination of higher-threshold LEDs. The experiment highlighted the principles of electrochemical potential, circuit design, and redox chemistry. Results demonstrated the feasibility of using simple, low-cost materials to generate sufficient electrical energy for practical tasks such as lighting LEDs. This experiment emphasizes the relevance of electrochemical systems in sustainable energy applications and enhances understanding of real-world battery operation and optimisation.

Keywords: galvanic cell, zinc-copper cells, copper electrode, zinc electrode, redox reaction, electrolyte concentration, series and parallel connection

1. Introduction

Batteries are electrochemical devices, where electrical energy is generated from chemical energy by redox reactions at the anode and cathode, spontaneously[1]. Reactions at the anode, the negative electrode, generally take place at lower electrode potentials than at the cathode, the positive electrode. Batteries are closed systems, where the anode and cathode are the charge-transfer medium and are active reactants in the redox reaction. Thus, energy storage and conversion occur in the same compartment[2].

Galvanic cells, or voltaic cells, are the foundational models for electrochemical batteries. These cells generate electricity spontaneously as electrons flow from the anode to the cathode[3]. This principle underpins the design of modern batteries used in portable electronics, electric vehicles, and renewable energy storage systems.

In galvanic cells the process is driven by a reduction in the change in Gibbs free energy, $\Delta_r G < 0$, as concentrations equilibrate[3]. In a typical galvanic cell, such as a zinc-copper system, zinc undergoes oxidation at the anode, releasing electrons and forming Zn^{2+} ions[4]. These electrons travel through an external wire to the cathode, where Cu^{2+} ions in solution are reduced to solid copper; this provides the electron flow of the system. A salt bridge connects the two half-cells, allowing ion transfer to maintain electrical neutrality and complete the internal circuit.

The schematic below illustrates how galvanic cells work, measuring the voltage of the cell using a voltmeter. The zinc anode and copper cathode are immersed in their electrolytes (Cu in Cu^{2+} ions and Zn in Zn^{2+} ions) and connected externally by a conductor and internally by a salt bridge soaked with potassium chloride (KCl) solution. Electron flow from the anode to the cathode generates usable electrical energy measured through the voltmeter, while ion movement through the salt bridge sustains the reaction.

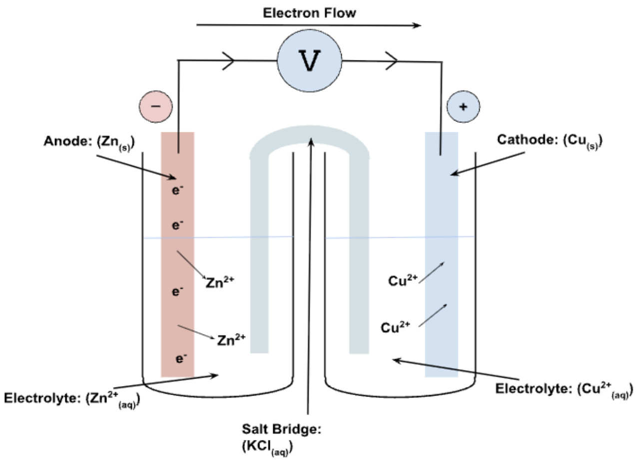

Figure 1: *Schematic diagram of a zinc-copper galvanic cell*

From an engineering standpoint, battery design involves optimising materials, reaction kinetics, and system integration, minimizing costs whilst maximizing efficiency and safety. Applications of electrochemistry are widespread in society, ranging from consumer electronics to automobiles, medical electronics and space travel. Electrode and electrolyte materials must be chosen by engineers for their conductivity, stability, cost, and environmental impact. Through thermodynamic properties such as cell potential and Gibbs free energy, energy output is determined, while kinetic factors influence charge and discharge[5]. Engineers must also address thermal management, mechanical durability, and safety, especially in large-scale or high-performance applications. Innovations such as lithium-ion, solid-state, and flow batteries have emerged and been optimised by the work of chemical engineers in combination with other engineering disciplines. Through this study we aim to explore how galvanic cells can be optimised to improve performance and efficiency, emulating how batteries are optimised industrially by chemical engineers.

2. Methods

2.1 Materials and Reagents

Copper (Cu) and Zinc (Zn) foils (cut to 3 cm × 6 cm) were used as electrodes. Initially, 0.1 M aqueous electrolyte solutions were prepared using distilled water, copper (II) sulfate ($CuSO_4$), zinc sulfate ($ZnSO_4$) solutions. Cotton rope strips were used to prepare salt bridges and spacers. Centrifuge tubes served as individual half-cell containers. Electrical measurements were taken using a digital multimeter. Alligator clips and insulated wires facilitated connections. Light-emitting diodes (LEDs) of different colours (green, blue, white, yellow, red) were used for output tests.

2.2 Preparation of Electrodes and Electrolytes

Copper and zinc foils were abraded with fine sandpaper to ensure a clean, reactive surface for the half-cell. Electrolyte solutions were prepared at 0.1 M and 0.05 M concentrations. Salt bridges were created by soaking cotton rope strips in 0.1 M potassium chloride (KCl) solution.

2.3 Construction of Galvanic Cells

Two centrifuge tubes were used as the basis of the half-cells. One was filled to two-thirds capacity with 0.1 M $CuSO_4$ and the other with 0.1 M $ZnSO_4$. A sanded copper electrode was placed in the $CuSO_4$ solution (cathode), and a sanded zinc electrode in the $ZnSO_4$ solution (anode). The half-cells were connected using the salt bridge prepared by cotton rope strips soaked in 0.1 M KCl. Electrodes were connected to a multimeter using alligator clips to measure electrical output. This process was repeated with different combinations of concentrations of $CuSO_4$ and $ZnSO_4$ to make four galvanic cells.

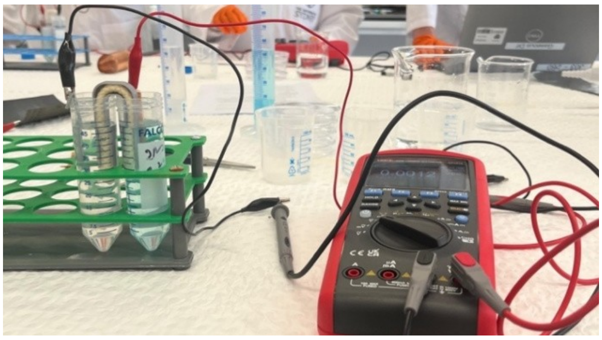

Figure 2: *Zinc-Copper Galvanic Cell Experimental Setup*

2.4 Series and Parallel Configurations

The galvanic cells were connected in series to find the optimal configuration to illuminate different LEDs. Voltage across the terminal ends and current in the circuit were measured for each successful configuration using a digital multimeter. The galvanic cells were not connected in parallel as it would not yield enough electromotive force (E.M.F.) to illuminate the LEDs.

2.5 Data Collection

Two forms of data collection were carried out. The first was electrical measurements, where voltage was measured under open-circuit conditions and the short-circuit current was measured by switching the multimeter to current mode. The second data collection was qualitative, LED lighting. Each cell configuration (series, parallel) was connected to a circuit containing one LED at a time, in the sequence: green → blue → white → yellow → red. LEDs were observed for illumination, and the results were recorded

2.6 Investigation of Variable Parameters: Electrolyte Concentration

Electrolyte concentrations of $CuSO_4$ or $ZnSO_4$ solutions varied as both the electrolytes were prepared with 0.1 M and 0.05 M concentrations. Multiple galvanic cells were constructed using the modified parameter while keeping other conditions constant. Voltage and current outputs were measured for each variation.

2.7 Data Analysis

Voltage and current data were analysed to determine trends related to cell configuration (single, series, parallel), parameter variation (electrolyte concentration), and LED illumination threshold. Trends were graphed to show relationships between variables. Observations on LED illumination were linked to measured output values to determine minimum requirements for successful operation.

2.8 Equations and Standard Potentials

The net reaction of a copper-zinc galvanic cell is,

$$Zn_{(s)} + Cu^{2+}_{(aq)} \rightarrow Zn^{2+}_{(aq)} + Cu_{(s)}$$

Oxidation at anode (Zn^{2+}/Zn half-cell):

$$Zn_{(s)} \rightleftarrows Zn^{2+}_{(aq)} + 2e-$$

Reduction at cathode (Cu^{2+}/Cu half-cell):

$$Cu^{2+}_{(aq)} + 2e- \rightleftarrows Cu_{(s)}$$

The theoretical cell potential, E^{o}_{cell}, is calculated as,

$$E^{o}_{cell} = E^{o}_{cathode} - E^{o}_{anode}$$

Where, $E^{o}_{cathode}$, standard reduction potential of cathode (Cu^{2+}/Cu), is +0.34V and E^{o}_{anode}, standard reduction potential of anode (Zn^{2+}/Zn), is −0.76V [6].

Thus, $E^{o}_{cell} = +0.34\ V - (-0.76\ V) = +1.10\ V$ [7].

2.9 Safety and Waste Disposal

All chemical handling was performed with gloves and safety goggles. Toxic solutions such as $CuSO_4$ were disposed of in heavy metal waste containers. Direct skin contact with $ZnSO_4$ was avoided. Electrical testing was conducted using insulated wires and connectors.

3. Results and Discussion

3.1 Results

Table 1: *Cell potential with different combinations of electrolyte concentrations*

Battery	[$CuSO_4$] (M)	[$ZnSO_4$] (M)	Cell Potential, E_{cell}, (V)
A	0.10	0.10	1.0652
B	0.10	0.05	1.0707
C	0.05	0.05	1.0545
D	0.05	0.10	1.0480

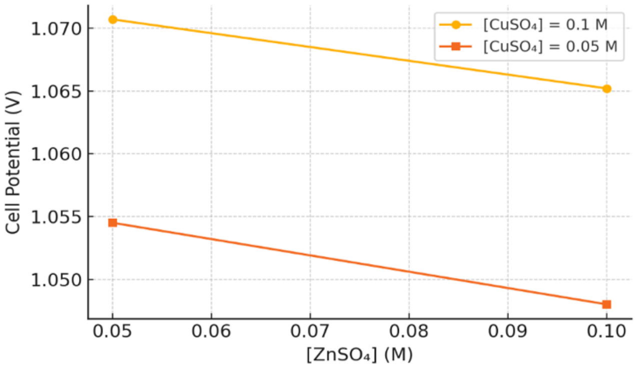

Figure 3: *Graph of how the cell potential varies with different combinations of electrolyte concentrations (Generated by AI using the raw data from the experiment)*

Table 2: *Electromotive Forces across the circuit for Different LEDs*

Colour of LED	Wavelength of LED (nm)	Series Connection of Batteries	E.M.F. (V)
Red	622.5	A + B	2.1296
Yellow	592.5	A + B	2.1323
White	550.0	A + B + C	3.1689
Blue	462.5	A + B + C	3.1857
Green	522.5	A + B + C	3.1887

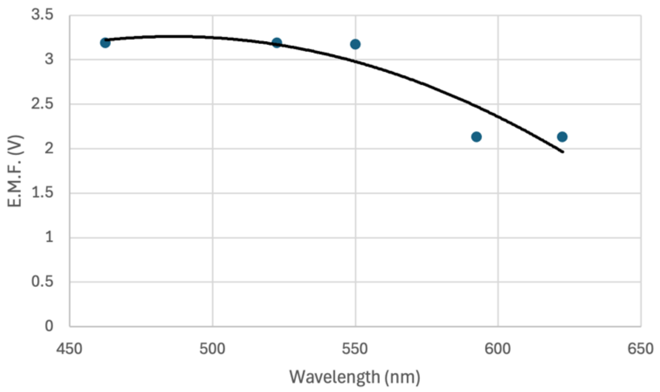

Figure 4: *Graph of how the E.M.F.varies across different wavelengths*

Table 3: *Current in the circuit for Different LEDs*

Colour of LED	Wavelength of LED (nm)	Series Connection of Batteries	Current (mA)
Red	622.5	A + B	19.831
Yellow	592.5	A + B	19.350
White	550.0	A + B + C	19.953
Blue	462.5	A + B + C	19.880
Green	522.5	A + B + C	19.802

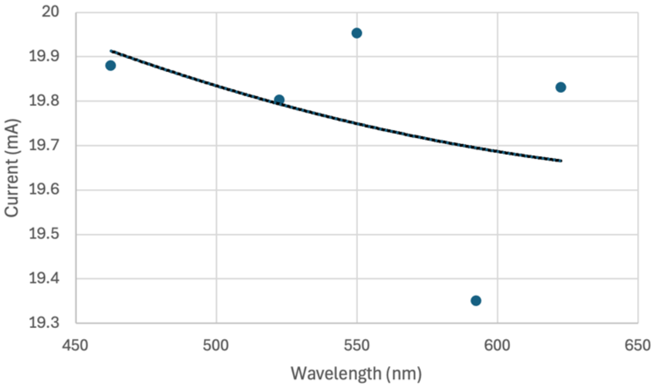

Figure 5: *Graph of how the current varies across different wavelengths*

Table 4: *Power output by the series connection of batteries for illuminating different LEDs*

Colour of LED	Wavelength of LED (nm)	Series Connection of Batteries	Power Output (mW)
Red	622.5	A + B	42.232
Yellow	592.5	A + B	41.260
White	550.0	A + B + C	63.229
Blue	462.5	A + B + C	63.332
Green	522.5	A + B + C	63.142

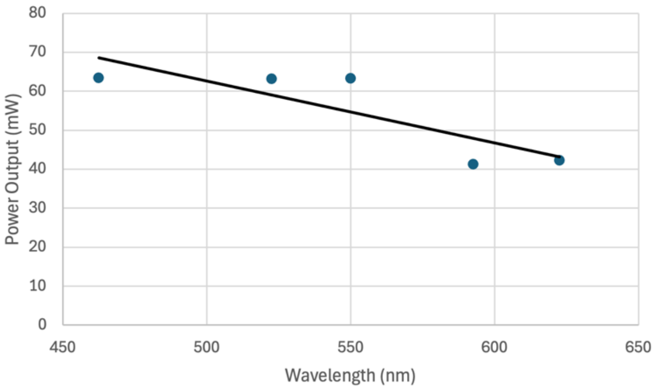

Figure 6: *Graph of how the power output varies across different wavelengths*

Table 5: *Energy output in 5 seconds and specific power for illuminating different LEDs*

Colour of LED	Wavelength of LED (nm)	Series Connection of Batteries	Energy Output in 5 seconds (mJ)	Specific Power (Wm^{-2})
Red	622.5	A + B	211.16	23.462
Yellow	592.5	A + B	206.30	22.922
White	550.0	A + B + C	316.15	35.127
Blue	462.5	A + B + C	316.66	35.184
Green	522.5	A + B + C	315.71	35.079

3.2 Discussion

Electrical measurements of galvanic cells are a direct method to evaluate their electrochemical performance by quantifying voltage, current, and power output under varying conditions, such as electrolyte concentration. At an electrolyte concentration of 0.1 M $CuSO_4$ and 0.1 M $ZnSO_4$ produced a cell potential of +1.0652 V which is in line with the theoretical value of +1.10 V, thus confirming that the fundamental electrochemical reaction being conducted is

$$Zn_{(s)} + Cu^{2+}_{(aq)} \longrightarrow Zn^{2+}_{(aq)} + Cu_{(s)}$$

In the galvanic cell, oxidation occurs at the zinc anode as zinc is oxidised to Zn^{2+} ions following the half-cell equation, $Zn_{(s)} \rightleftarrows Zn^{2+}_{(aq)} + 2e-$, and reduction at the copper cathode as Cu2+ ions are reduced to copper following the half-cell equation, $Cu^{2+}_{(aq)} + 2e- \rightleftarrows Cu_{(s)}$.

3.2.1 Effect of Electrolyte Concentration

Systematic variation of electrolyte concentrations of 0.05 M and 0.1 M shows that changing $CuSO_4$ and $ZnSO_4$ concentrations affected cell potential and current output. This observation is consistent with the Nernst equation, where due to Le Chatelier's principle, a higher concentration of Cu^{2+} ions shifts the equilibrium to favour the reduction pathway (https://link.springer.com/article/10.1007/bf02645347).

$$E_{cell} = E°_{cell} - \frac{RT}{nF} \ln([Zn^{2+}] / [Cu^{2+}])$$

The Nernst equation[8] shown above mathematically describes the relationship between the cell potential, temperature, and the concentrations of the involved ionic species. Thus, it shows the nonlinear impact of concentration changes on voltage output[9].

The Nernst equation[10] contains a natural logarithm. As a result, small changes in the concentration of electrolytes have a nonlinear but significant effect on the cell potential[11]. Thus, if the [Cu^{2+}] decreases, the cell potential read by the multimeter will be lower as the cathode has fewer available ions to reduce, hence the reduction pathway becomes less favourable and thus the cell potential drops. This is evidenced by the data, as in both the galvanic cells with the [Cu^{2+}] being 0.05 M, the E_{cell} values are lower than the E_{cell} values of the galvanic cells where [Cu^{2+}] was 0.1 M, with the latter being 1.0480V at its lowest, and the former at 1.0707V at its highest. However, with reference to the Nernst equation, lower Zn^{2+} ion concentration makes the oxidation reaction more thermodynamically stable, as this favours the oxidation pathway, thus raising the cell potential.

3.2.2 Connecting Cells in Series and Parallel Configurations

The effects of connecting multiple cells in series and parallel were also examined. When cells are connected in series, cell potentials add linearly to give the electromotive force (E.M.F.) across the circuit[12]. Three galvanic cells in a series connection yielded an electromotive force (E.M.F.) of approximately 3.19 V, which was sufficient to illuminate LEDs with higher forward voltage thresholds such as white, blue, and green. This is evidenced by higher threshold LEDs such as white, blue, and green requiring three galvanic cells for activation, whereas red and yellow LEDs were illuminated by two cells connected in series. This is in line with their known forward voltages ranging from 2.0 V to 2.2 V for red and yellow LEDs and 3.0 V to 3.2 V for white, blue and green LEDs.

While not tested in this experiment, cells may also be connected in parallel. This, in essence, will result in the electromotive force (E.M.F.) of the circuit to be the same as the cell with the highest cell potential[13]. However, it will increase the current capacity greatly, thus improving runtime. However, parallelly connecting three cells with E.M.F. values of approximately 1.10 V will not be sufficient to power the LEDs due to their forward voltages ranging from 2.0 V to 3.2 V.

It is important to mention that current measurements were consistently conducted at the conclusion of each trial, as initiating current flow earlier would result in the immediate depletion of the cell, thereby preventing further experimentation. This rapid discharge is characteristic of series circuits, where the same current flows through each cell, leading to increased total energy consumption. In such configurations, there exists only a single path for the electric current, which imposes a uniform and continuous load across all cells. By contrast, in parallel circuits, the total current is distributed among the individual branches[14], thereby reducing the load experienced by each cell and extending the overall runtime of the battery system. This distinction arises from fundamental circuit behaviour, wherein parallel arrangements reduce effective resistance and distribute current more efficiently as current is divided amongst cells[15], reducing the load on the battery, resulting in slower depletion rates.

3.2.3 Trends Observed in the Recorded and Calculated Data and Battery Performance Analysis

While both the electromotive force (E.M.F.) across the circuit and current in the circuit are observed to have a nonlinear decreasing trend, the shape of the best-fit curve for both their trends are very different. However, the trends are difficult to observe as the red and yellow LEDs had the same forward voltage ranges, the white, blue and green LEDs had the same forward voltage ranges, and all the LEDs had the same maximum current.

However, the power output by the series connection of the batteries shows a linear decreasing trend across the wavelengths.

To evaluate the performance of the constructed battery systems, specific power and energy output in 5 seconds were calculated and analysed. Specific power refers to the rate at which energy is delivered per unit area of the electrode. In the highest-performing configuration (white LED, three cells in series), a specific power of approximately 35.13 W/m^2 was recorded, along with an energy output of 316.15 mJ over 5 seconds. These values, while shy in performance to commercial batteries, demonstrate the cell's capability to deliver targeted power outputs for low-energy applications.

3.2.4 Zinc-Copper Galvanic Cells in Engineering Context

Design and testing of copper-zinc galvanic cells presents implications for broad real-world applications, such as developing cost-effective yet sustainable energy storage solutions. Such simple cells exemplify the challenges encountered in scaling up electrochemical systems. For example, low energy density, relatively short lifespan due to reactant depletion, and limitations in voltage output from single cells to name a few. However, the results also highlight the advantages of reconfigurability, where stacking and arranging cells in series or parallel configurations improves performance.

In resource-limited or remote settings, such as off-grid locations, galvanic cells offer a compelling option due to the accessibility of the materials as well as its ease of assemblance. In industrial settings, however, cost-performance trade-offs are a crucial consideration. Whilst zinc-copper galvanic cells may not outperform lithium-ion electrochemical technologies on energy density or life cycle, they are however low cost, environmentally friendly[16], and have safer operation conditions which make them more ideal for temporary applications, such as low-power environmental sensors or single-use diagnostic devices. The combination of safety, environmental sustainability and abundant reserve make these energy storage systems highly advantageous for the environment[17].

From a sustainability perspective, using recyclable metals like copper and zinc and aqueous electrolytes poses less environmental risk than organic solvents to align these systems with greener energy production. Further research could optimize systems by exploring biodegradable electrolytes, waste-metal sourcing, or integration with renewable inputs. Moreover, zinc and copper can be recycled in economically feasible methods[18] to further improve its economic efficiency.

3.2.5 Possible Improvements in the Cell Design

Possible improvements in the zinc-copper galvanic cell can be brought about by significantly improving the specific energy by optimizing the electrode-to-electrode ratio and reducing internal resistance through better separation and increased ionic conductivity[19] and by increasing the energy density of the cell by increasing electrode thickness[20]. Further trial and error can be performed to find the optimal electrolyte configurations with different liquids as electrolytes with salt and other compounds to obtain optimal energy output[21].

Additionally, the zinc-copper galvanic cell can be improved by using optimised electrode configurations with accordance to their electrode architecture and improved fabrication strategies[22]. Furthermore, zinc-copper cells can be made rechargeable using a cation-exchange membrane to separate the half-cells with a sodium-based background electrolyte[23] or using electrolytes made from hydrogels[24] while increasing the output voltage of the cells by inserting two pairs of both cathodes and anodes in one volume of the electrolyte[25].

Such metrics are crucial in engineering design, particularly when selecting battery types for portable medical or environmental monitoring devices. As observed, even simple aqueous-based electrochemical cell designs can be tuned through their variable concentration and configurations to meet specific voltage and power requirements.

4. Conclusion

This experiment successfully demonstrated the principles of galvanic cell operation using copper and zinc electrodes, with variable electrolyte concentrations and cell configurations. The results followed expected trends, such as higher voltages from series connections and variable concentrations on output, thus reflecting how chemical potential and circuit design interplay in real world electrochemical systems.

Moreover, series connections significantly increased cell voltage, illuminating LEDs with higher voltage requirements. In contrast, changes in electrolyte concentration influenced cell voltage in a non-linear manner, small increases in Cu^{2+} ion concentration led to voltage gains, whereas small increases in Zn^{2+} ion concentration suppressed voltage, staying consistent with the Nernst equation. Power values reached over 35 W/m^2 in the most efficient configuration, suggesting feasibility of such cells for low-power applications.

These findings are relevant for developing accessible and sustainable battery technologies that prioritize safety, low cost, and reconfigurability. Further improvements could explore more materials, higher electrode surface areas, and hybrid integration of cells with renewable energy systems. The experiment reinforces the role of electrochemical engineering in tackling modern energy challenges and provides a foundation for future innovation in battery design.

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Authorship Statement

Raminus Samad Khan conducted the experiment, recorded the raw data, prepared the results, research and writing cell design improvements, incorporated all sections of the article, and performed complete article modeling; Tahlia Robertson conducted the experiment, research on the experiment, and writing the abstract and methods; Kushagr Gowda conducted the experiment, research and writing the discussion; Yash Makhija conducted the experiment, research and writing the discussion and the conclusion; Zachary Briscoe conducted the experiment, research and writing the introduction; Benedict Tai, Jordan Kambanis and Masoomeh Asghar Nejad-Laskoukalayeh provided task direction and project assistance; Dr Thomas Whittle designed the experiment; Dr David Alam facilitated project resources and guidance on conceptual direction; and Dr. Gobinath Rajarathnam ideated conceptual direction, research and writing guiding frameworks, and direct project supervision.

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