Technoeconomic Analysis and Comparison of Battery and Hydrogen-based Energy Storage Systems

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Problem Statement

The accelerating global shift toward renewable energy poses significant challenges for ensuring reliable and continuous power supply, given the variability of sources like solar and wind. Rapid growth in electricity demand underscores the urgent need for effective, scalable energy storage solutions to stabilize grids and prevent economic inefficiencies. However, energy storage technologies face unresolved economic, environmental, and technical barriers , raising concerns over integration, raw material sustainability, and end-of-life waste management.

Research Question

Which energy storage technology offers the most environmentally sustainable and cost-effective solution for Canada's renewable energy integration goals?

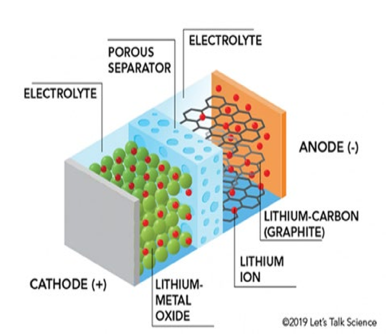
Objectives

- **To quantify the Levelized Cost of Storage (LCoS)** for lithium-ion BESS, hydrogen fuel cells, and hydrogen combustion engines.
- **To assess the life cycle greenhouse gas (GHG) emissions and global warming potential (GWP)** of each technology, considering raw material extraction, production, and operation, following a cradle-to-gate approach.
- **To provide practical recommendations** for policymakers and industry stakeholders to make data-driven decisions regarding renewable energy storage in Canada.

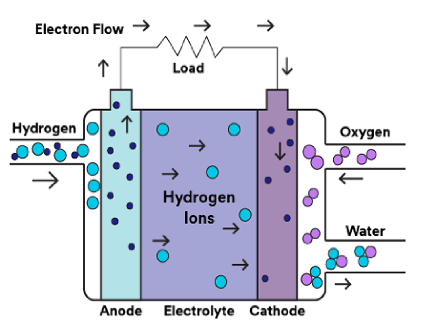
This research project's goal & objective align with the UN Sustainable Development Goals

Literature Review

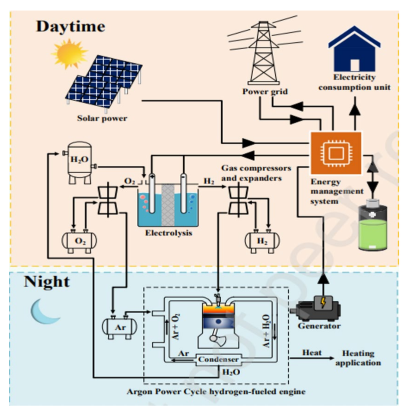
Energy Storage Technologies compared in this research



(PerkinElmer Blog, 2022)



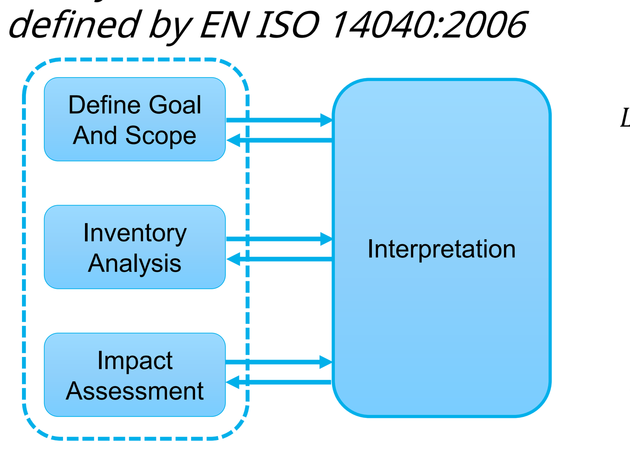
(*Fuel Cells - Hydrogen Technology | 3M UK*, n.d.)



(Wang et al., 2025)

Methodology

Life-cycle assessment framework defined by EN ISO 14040:2006



Life-cycle Costing for LCoS defined by Viswanathan et al., 2022

$$LCOS = \frac{[(FCR \times CAPEXPV) + O\&MFixed]}{AH} + \left(\frac{Energy\ Cost}{Overall\ RTE}\right)$$

Financial Cost + ECC

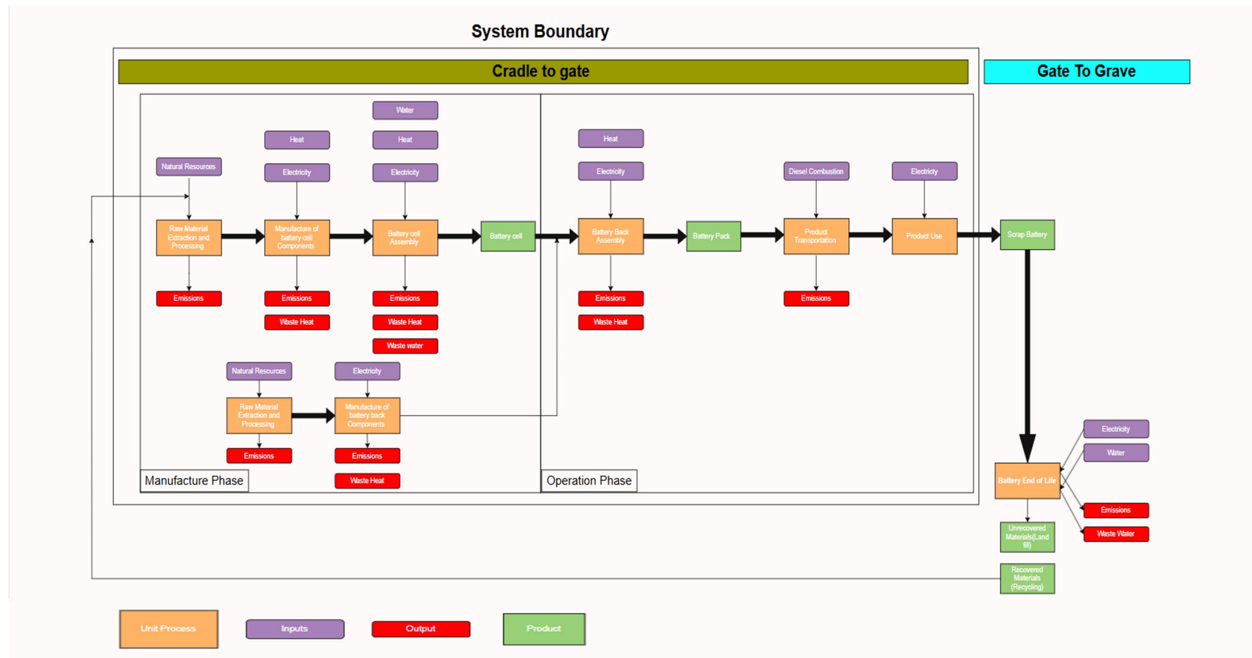
FCR: Fixed Charge Rate (%),

$CAPEXP_{PV}$: Present value of capital expenditures ($/kW), **$O\&M_{fixed}$**: Annual fixed operation and maintenance costs ($/kW-year).

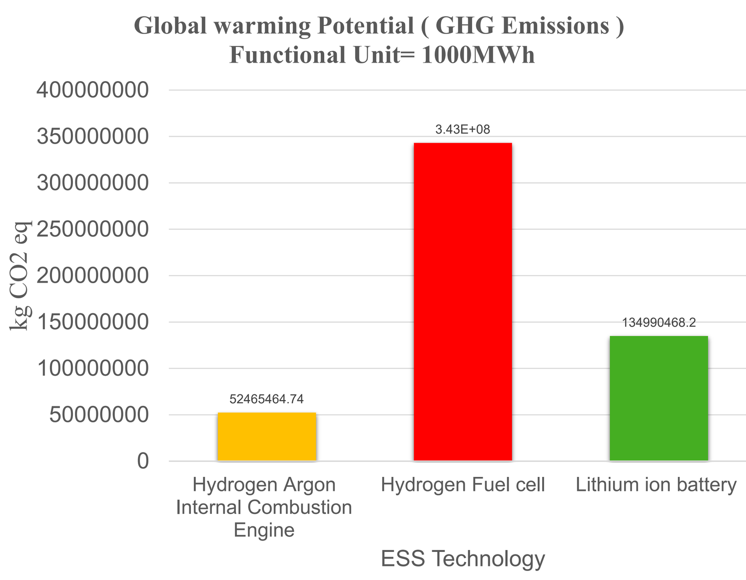
AH: Annual hours discharged (h/year),

ECC: Electricity charging cost ($/kWh-discharge), inclusive of efficiency losses.

System Boundary



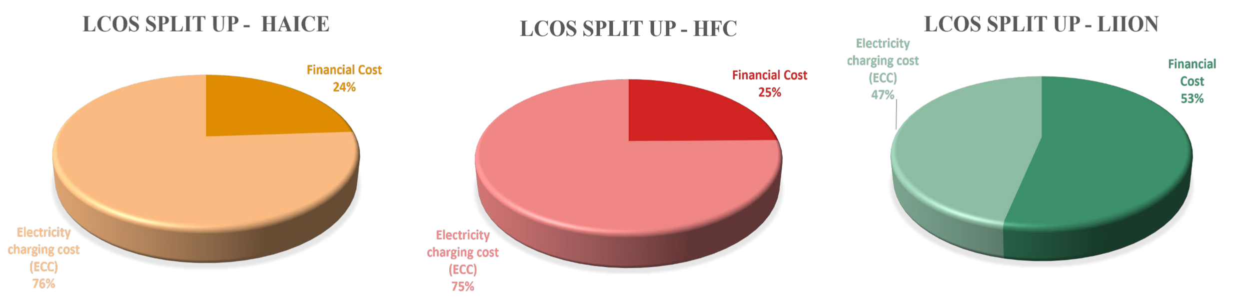
Results & Interpretation

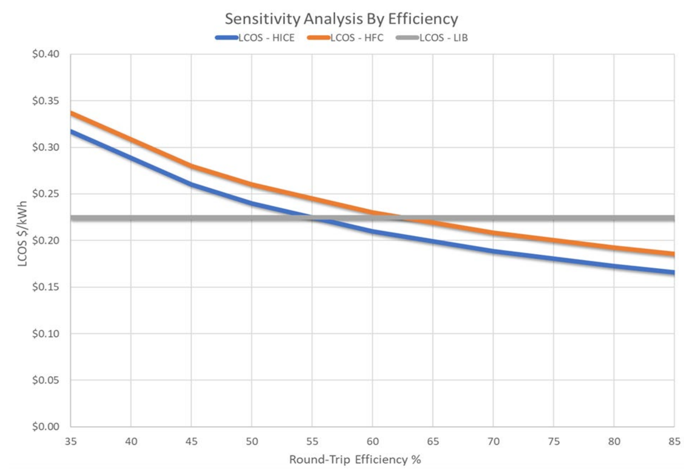


HAICE shows the lowest manufacturing emissions and avoids NOx pollutants from hydrogen combustion, while fuel cells and lithium-ion batteries have higher GWP due to material intensity, especially platinum-group metals and battery metals. Operational emissions are negligible except in hydrogen-based systems, where GWP depends on hydrogen production methods and system efficiency.

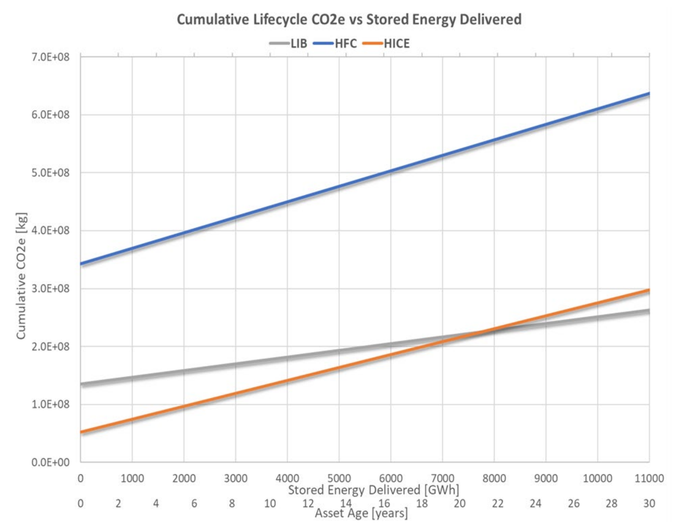
Energy Storage Technology	Levelized Cost of Storage
Hydrogen Argon Internal Combustion Engine (HAICE)	$0.292/kWh
Hydrogen Fuel Cell (HFC)	$0.318/kWh.
Lithium-ion Battery (LIB)	$0.223/kWh

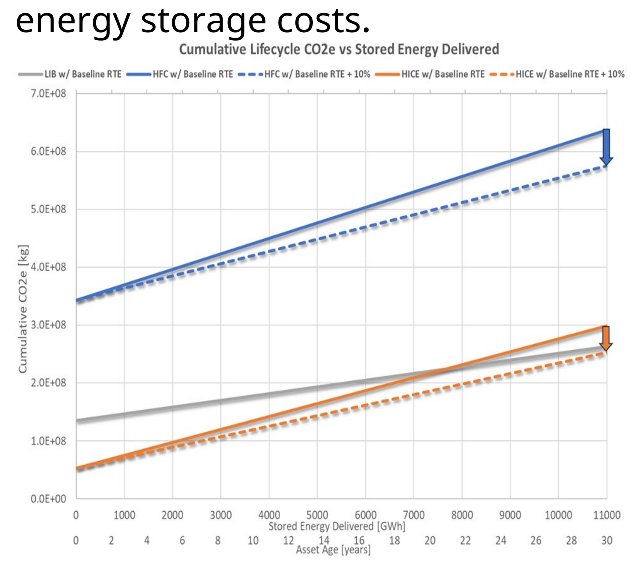
Lithium-ion batteries (LIB) have the lowest levelized cost of storage (LCoS), with balanced contributions from capital and electricity charging costs. Hydrogen-based systems show much higher charging costs due to low round-trip efficiencies, especially in fuel cells (HFC), whereas HAICE's lower financial costs shift the burden further onto charging expenses.

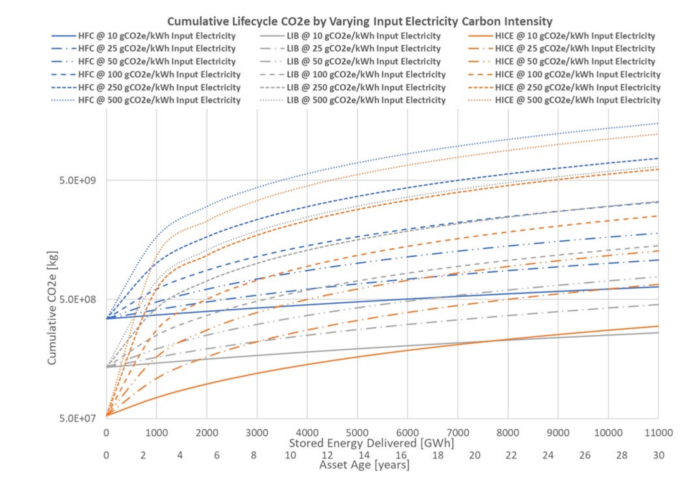




A sensitivity analysis varying round-trip efficiency (RTE) at a fixed electricity price of 9 cents/kWh found that hydrogen fuel cells (HFC) reach cost parity with lithium-ion batteries (LIB) at about 62% RTE, while hydrogen-argon internal combustion engines (HICE) do so at 55% RTE. These break-even points guide R&D by highlighting efficiency targets needed for competitive energy storage costs.



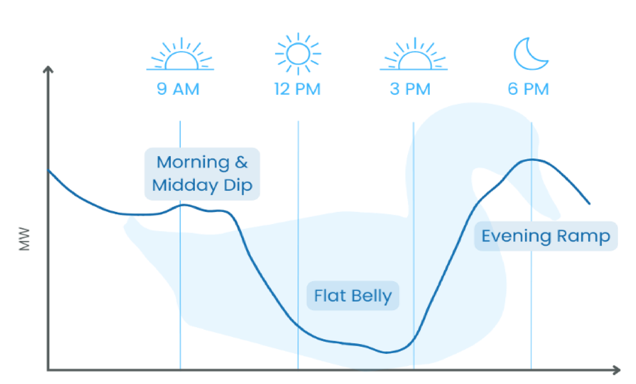


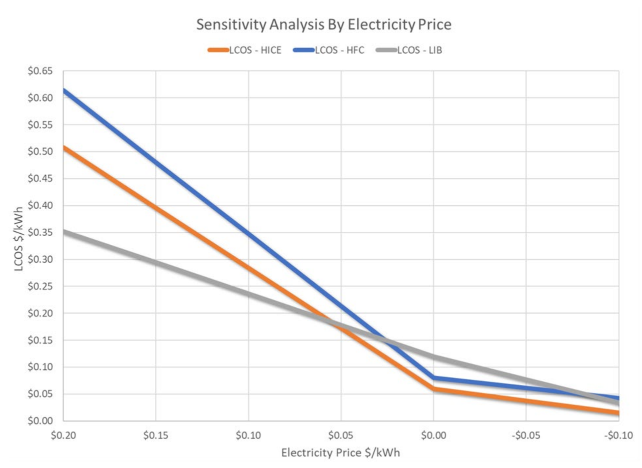


Life cycle CO2 emissions show HFC systems have the highest emissions due to construction intensity and low RTE, while HICE starts lowest but surpasses LIB emissions after ~20 years; improving HICE efficiency can maintain lower emissions long-term. Emissions for all technologies rise with input electricity carbon intensity, but LIB's higher RTE results in slower cumulative emissions growth compared to hydrogen systems reliant on electrolysis.

Sensitivity Analysis

Understanding the duck curve (Oliveira, 2023)





Renewable energy, especially solar and wind, causes electricity prices to drop sharply or turn negative during midday when generation exceeds demand, a pattern known as the "duck curve." This price fluctuation significantly impacts energy storage costs and market dynamics.

Sensitivity analysis shows lithium-ion batteries have the lowest cost at high electricity prices due to high efficiency, but as prices fall below 5 cents/kWh, hydrogen systems—especially HAICE—become equally or more cost-effective. In low or negative price scenarios, capital costs dominate, making hydrogen storage more economical for storing excess renewable energy despite lower efficiency.

Conclusion

This research finds that the Hydrogen Argon Internal Combustion Engine (HAICE) has the lowest construction-phase GHG emissions among the three energy storage technologies studied. Operational emissions depend entirely on the carbon intensity of the input electricity and round-trip efficiency (RTE), with HAICE adding negligible direct emissions. Hydrogen fuel cells (HFC) suffer from high construction emissions and low RTE. Lithium-ion batteries (LIB) have the lowest levelized cost of storage (LCoS) under fixed electricity prices due to higher RTE, but optimized HAICE can achieve lower LCoS, especially when electricity prices are low or negative. HAICE also offers better scalability compared to HFC, enhancing cost and environmental feasibility in low-carbon systems.

Works Cited

- *Fuel Cells - Hydrogen Technology | 3M UK*. (n.d.). MMM-ext. https://www.3m.co.uk/3M/en_GB/hydrogen-technology-uk/applications/fuel-cells/
- *ISO 14040:2006*. (n.d.). ISO. https://www.iso.org/standard/37456.html
- Oliveira, T. (2023, October 10). *Understanding the duck curve*. https://synertics.io/blog/72/understanding-the-duck-curve#:~:text=The%20duck%20curve%20illustrates%20the,when%20electricity%20demand%20typically%20dips
- PerkinElmer Blog. (2022, July 27). *The Lithium Battery Paradox: Energy vs. Environment | PerkinElmer Blog*. https://blog.perkinelmer.com/posts/the-lithium-battery-paradox-energy-vs-environment/
- *THE 17 GOALS | Sustainable Development*. (n.d.). https://sdgs.un.org/goals
- Viswanathan, V., Mongird, K., Franks, R., Li, X., & Sprenkle, V. (2022). 2022 Grid Energy Storage Technology Cost and Performance Assessment. In *Pacific Northwest National Laboratory*. Department of Energy. https://www.pnnl.gov/sites/default/files/media/file/ESGC%20Cost%20Performance%20Report%202022%20PNNL-33283.pdf
- Wang, Chenxu and Deng, Jun and DIBBLE, Robert W. and Li, Liguang, A Novel Hydrogen Energy Storage System: On-Site Hydrogen and Oxygen Production from Excess Renewable Power; Followed by Power Regeneration Employing an Argon Power Cycle Hydrogen-Fueled Engine with a Net Indicated Thermal Efficiency to 70% (Gross Ite Over 64%). Available at SSRN: https://ssrn.com/abstract=5081962 or http://dx.doi.org/10.2139/ssrn.5081962