Research Journal of Recent Sciences ISSN 2277-2502
Vol. **15(1),** 11-15, January **(2026)** *Res. J. Recent Sci.*

Sustainability Assessment of Hydrogen Fuel Cell Vehicles versus Fossil Fuel Vehicles: A Canadian Perspective

Md Faiz Ur Rehman Saquib[1,2*], Syed Kumail Ameer[1], Pranshu Munjial[1] and Osama Aly[1]
[1]Faculty of Graduate Studies, University of Calgary, Canada
[2]Department of Petrochemical Engineering, Dr. Babasaheb Ambedkar Technological University, Lonere, Maharashtra, India
saquibmohd6117@gmail.com

Available online at: www.isca.in, www.isca.me
Received 30th November 2025, revised 12th December 2025, accepted 30th December 2025

Abstract

Transportation is a primary driver of Canada's greenhouse gas emissions, contributing nearly 27% to the national total. To meet the ambitious Net-Zero 2050 targets, a paradigm shift from conventional internal combustion vehicles (ICVs) to cleaner propulsion technologies is imperative. This study presents a comparative sustainability assessment of Hydrogen Fuel Cell Vehicles (HFCVs) within the specific energy context of Alberta. Utilizing a scenario-based approach, we integrated Life Cycle Analysis (LCA) and Fuel Cycle Assessment with multidimensional indicators—environmental, economic, and social—aligned with the Triple Bottom Line. The findings demonstrate that HFCVs significantly reduce tailpipe emissions and noise pollution while improving energy efficiency, thereby supporting the decarbonization of the transport sector. However, the sustainability of HFCVs is heavily dependent on the hydrogen production pathway; currently, natural gas reforming offers lower emissions and superior cost-effectiveness compared to electrolysis, given Alberta's fossil-fuel-intensive electricity grid. Techno-economic analyses highlight reduced operational costs and potential for job creation, while social metrics suggest improvements in accessibility and public health. These insights underscore the necessity for robust infrastructure development, targeted policy interventions, and strategic investment in the hydrogen economy to accelerate adoption. Future work will focus on dynamic modelling to guide evidence-based decisions for Canada's sustainable mobility transition.

Keywords: Hydrogen Fuel Cell Vehicles, Sustainability Metrics, Life Cycle Analysis, Emission Mitigation, Alberta Energy Transition, Triple Bottom Line, Hydrogen Economy, Net-Zero 2050.

Introduction

In recent years, the frequency of catastrophic events linked to climate change has escalated, transforming what was once considered a peripheral concern into a global emergency. The world is witnessing environmental disasters at an alarming scale. Data indicates that climate-related events in regions such as India, Pakistan, and Southeast Asia have tripled over the past two decades. For instance, the 2020 bushfire season in Australia was unprecedented, resulting in 10 million hectares burned[1], while droughts in Africa have intensified, causing severe crop and livestock losses. More recently, Storm Daniel caused massive flooding in Libya, claiming over 4,300 lives with thousands still missing[2]. These events serve as stark warnings, necessitating immediate and serious mitigation strategies. Under the Paris Agreement, 195 countries, including Canada, pledged to limit global temperature rise to below 2 degrees Celsius[3]. This commitment is particularly relevant to Canada, which ranked as the 11th largest GHG-emitting nation in 2020[4]. In the effort to combat climate change, research into alternatives to fossil fuels has accelerated. However, replacing the current energy paradigm requires more than just technological feasibility; it demands a holistic evaluation based on the "triple bottom line" balancing social, environmental, and economic impacts[5,6].

Key questions arise: Is the alternative accessible to the general public? Does it genuinely reduce environmental pollution? Is the transition economically viable?

This paper compares the sustainability of Hydrogen Fuel Cell Vehicles (HFCVs) against conventional Internal Combustion Vehicles (ICVs) powered by fossil fuels. By analyzing these technologies through the lens of the triple bottom line, we highlight the potential of HFCVs as a sustainable alternative for Canada's transportation sector.

Methodology

To address Canada's reliance on ICVs, three primary strategies were identified: enhancing public transit, adopting Battery-Electric Vehicles (BEVs), and deploying Hydrogen Fuel Cell Vehicles (HFCVs). While public transit aims to reduce personal vehicle use, safety concerns cited by 27% of Canadians and perceived unreliability have hindered its growth[7,8]. Similarly, while BEVs offer emission reductions, adoption is stalled by "range anxiety," high purchase costs, and insufficient charging infrastructure, with 63% of Canadians unlikely to purchase an EV as their next vehicle[9].

Consequently, this study focuses on the third approach: HFCVs. These vehicles utilize hydrogen combustion to produce zero tailpipe emissions and offer high energy efficiency (10–60%) compared to ICVs (20%)[10]. Crucially, HFCVs address the limitations of BEVs by offering rapid refueling (less than five minutes) and driving ranges comparable to conventional fossil fuel cars[11]. Comparative studies on vehicle registrations and usage patterns further support the need for this transition[12–14].

Sustainability Indicators: To provide a comprehensive evaluation, we selected a set of sustainability indicators that extend beyond basic economic metrics. These indicators, detailed in Table-1, acknowledge the interlinked nature of sustainability parameters for example, traffic congestion impacts economic productivity, environmental air quality, and social well-being[15,16]. Methodologies for rating vehicle environmental performance were also reviewed to ensure robust selection[17].

Results and Discussion

Environmental Performance: To determine the environmental impact, we reviewed Streamlined Life Cycle Assessments (SLCA) of light-duty vehicles. For conventional diesel and CNG cars, the vehicle operation stage is the primary contributor to environmental degradation[18]. Further studies on hydrogen transport options confirm these findings[19].

In contrast, HFCVs exhibit negligible tailpipe emissions. However, the environmental burden shifts to fuel cycles specifically hydrogen production. Our analysis indicates that in Alberta, the method of hydrogen production is the decisive factor. Figure-1 illustrates that HFCVs using hydrogen produced via electrolysis (Scenario 2) currently generate higher GHG emissions during the usage stage than gasoline cars, due to Alberta's carbon-intensive electricity grid[20,21]. Similar lifecycle impacts have been observed in other power-to-gas systems[22,23].

Table-1: Proposed sustainability indicators for vehicle evaluation[15].

Goal	Indicator	Description
Environment	GHG emissions/capita	Includes Fuel Cycle (feedstock, production, distribution) and Vehicle Cycle (material, operation, disposal).
	Air & Noise pollution	Impact on local air quality (NOx, SOx, PM) and acoustic environment.
Technology	Fuel frequency	Time required to refuel the vehicle.
	Maintenance frequency	Frequency of parts/fluids replacement over vehicle lifetime.
	Engine power	Maximization of vehicle power and efficiency.
Energy	Life cycle energy	Energy consumed during manufacturing, fueling, and operation.
Economy	Life cycle cost	Total cost of ownership: purchase, operation, and maintenance.
	Subsidies	Portion of costs covered by government incentives/taxpayers.
Users	Global availability	Vehicle uptime and availability for daily use.
	Fueling opportunities	Density and accessibility of fueling or charging infrastructure.

Table-2: LCA emissions contribution by stage for Diesel and CNG cars[18].

Life Cycle Stage	Diesel Contribution (%)	CNG Contribution (%)
Vehicle Production	15-20%	15-20%
Fuel Supply	10-15%	10-15%
Vehicle Operation	65-75%	65-75%
End of Life	<5%	<5%

Scenario Analysis for Alberta: We analyzed three distinct scenarios for the adoption of light-duty vehicles in Alberta: i. Current Scenario: Continued reliance on gasoline vehicles. ii. Scenario 1: Replacing 1% of ICVs with HFCVs using Hydrogen from Natural Gas (SMR). iii. Scenario 2: Replacing 1% of ICVs with HFCVs using Hydrogen from Electrolysis.

The results (Table-3) demonstrate that introducing just 1% of HFCVs significantly lowers total emissions. How- ever, Scenario 1 (Natural Gas) currently outperforms Scenario 2 (Electrolysis) in terms of GHG reduction? This counter-intuitive finding results from the high carbon footprint of Alberta's electricity used for electrolysis[24,25]. There- fore, the immediate pathway for HFCV adoption in Alberta should leverage the province's abundant natural gas re-serves[26] while transitioning the grid to renewable.

Economic Benefits: Transitioning to electric drive vehicles offers compelling economic advantages: i. Reduced Operational Costs: EVs and HFCVs offer superior efficiency. The energy cost per mile for an EV is approximately \$0.03–\$0.05, compared to \$0.10–\$0.15 for gasoline vehicles[6,27]. ii. Maintenance Savings: With fewer moving parts, electric drive trains reduce maintenance burdens. Annual maintenance costs for ICEVs average \$800–\$1,200, whereas EVs can reduce this by nearly 50% over a 10-year period[28]. iii. Job Creation: The shift to zero-emission vehicles is a catalyst for economic growth. Estimates suggest that by 2030, the transition could generate approximately 200,000 new jobs in Canada across manufacturing, infrastructure, and technology sectors[29].

Social and Stakeholder Analysis: The shift to HFCVs impacts stakeholders differently. As detailed in Table-4, while consumers initially face higher costs, the long-term benefits include reduced noise pollution and better health outcomes.

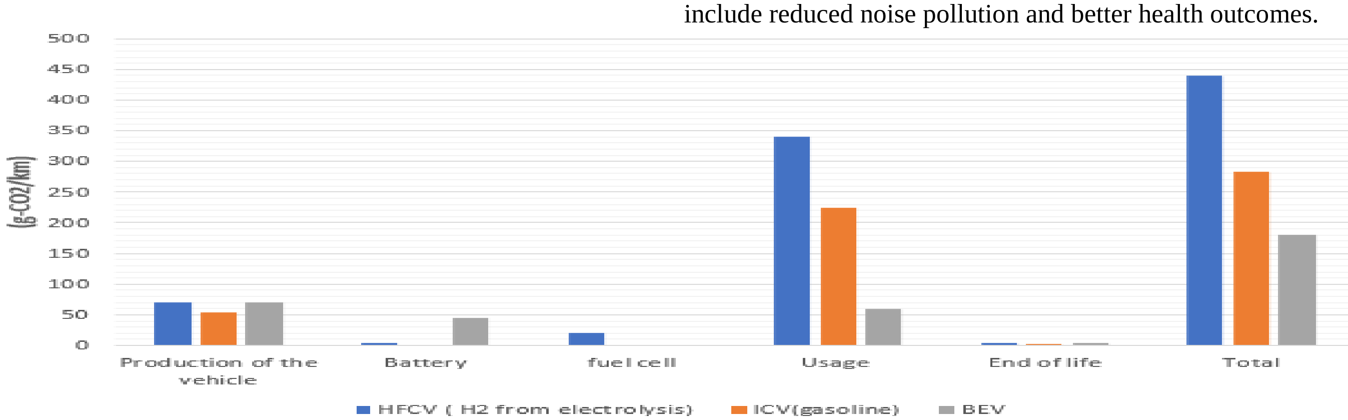

Figure-1: Comparative GHG emissions for HFCV, ICV, and BEV usage stages[20].

Table-3: Comparison of GHG, CO, and NOx emissions across current and proposed scenarios.

Parameter	Current Scenario (Gasoline)	Scenario 1 (HFCV via SMR)	Scenario 2 (HFCV via Electrolysis)
GHG Emissions (MT CO_2eq)	High	Moderate (Reduced)	High (Grid Dependent)
NOx Emissions (tons/yr)	High	Low	Low
CO Emissions (tons/yr)	High	Negligible	Negligible
Overall Efficiency	20-25%	40-50%	30-40%

Table-4: Effects on stakeholders: Current Paradigm vs. HFCV Adoption.

Stakeholder	Current (Fossil Fuel Dependency)	Future (HFCV Adoption)
Consumers	Rising fuel costs, exposure to noise and pollution	Faster refueling, extended range, silent operation
Local Communities	Deteriorating air quality and living conditions	New employment opportunities, improved public health
Manufacturers	High investment required to meet emission regulations with old tech	Access to government incentives for green technology innovation
Hydrogen Producers	Limited demand (industrial use only)	Surge in demand requiring infrastructure expansion

Table-5: Short-term and Long-term impacts of HFCV adoption.

Impacts	Item	Short Term	Long Term
Environment	GHG Emissions	Reduction by 66 M-CO_2-eq/yr	Reduction by approx. 400 M-CO_2-eq by 2030
	NOx Emissions	Reduction by 35 ton/yr	Reduction by approx. 250 ton/yr
Economic	Mfg Cost	High due to low production volume	Decreases significantly with economies of scale
	Fuel Cost	Moderate; infrastructure developing	Affordable; comparable to conventional fuels
Social	Accessibility	Limited; relies on early investment	Widespread and equitable access
	Safety	Public concern over high-pressure storage	Addressed through education and mature safety tech

Table-5 summarizes the short- and long-term implications. While short-term barriers like cost and accessibility exist, the long-term trajectory points toward significant environmental restoration and economic stability[30].

Conclusion

This study confirms that while HFCVs offer a robust solution for reducing tailpipe emissions and noise pollution, their overall sustainability is intrinsically linked to the energy source used for hydrogen production. In the context of Alberta, producing hydrogen via Natural Gas reforming (Scenario 1) currently presents a more environmentally favorable and cost-effective pathway than electrolysis, due to the carbon intensity of the local power grid. Techno- economic analysis highlights significant benefits, including reduced operational costs and job creation. However, social barriers such as accessibility and safety perceptions remain. To realize the full potential of HFCVs, Canada must prioritize infrastructure development and implement targeted policies that support the growth of a hydrogen economy.

Acknowledgement

The authors acknowledge the support of Dr. Sathish Ponnurangam and the Faculty of Graduate Studies, University of Calgary, for their guidance in the ENGG 682 Sustainability Engineering course.

References

1. Oxfam International (2018). 5 natural disasters that beg for climate action. Retrieved November 29, 2023.
2. UNICEF (2023). *Devastating floods in Libya: Two months after massive storm, families are still reeling*. Retrieved November 29, 2023.
3. Cadman, T. (2018). The United Nations framework convention on climate change. In *The Palgrave handbook of contemporary international political economy* (pp. 359-375). London: Palgrave Macmillan UK.
4. Government of Canada (2023). *Environment and natural resources: Global greenhouse gas emissions*. Retrieved November 27, 2023.
5. Government of Canada (2023). *Environment and natural resources: Net-zero emissions by 2050*. Retrieved November 24, 2023.
6. Natural Resources Canada (2016). *Links between fuel consumption, climate change, our environment and health*. Government of Canada.
7. Ipsos (2023). Over a Quarter (27%) of Canadians Do Not Feel Safe Taking Public Transit Alone.
8. Cross P. (2023). Governments keep pushing public transit Canadians don't want. *Financial Post*.
9. Sutter H. M. (2023). Canadians less keen to buy EVs, despite government policy push: Study. *BNN Bloomberg*.
10. US Department of Energy (2023). Fuel Cells: Hydrogen and Fuel Cell Technologies Office.
11. Global, T. W. I. (2023). What are the pros and cons of hydrogen fuel cells.
12. Government of Canada (2022). Transportation Data Information Hub: Vehicle Registrations, 2021.
13. Statistics Canada (2023). Vehicle registrations, by type of vehicle and fuel type.
14. Think Insure (2022). *Average KMs Per Year by Canadian Drivers*.
15. L. K. Mitropoulos and P. D. Prevedouros (2016). Incorporating sustainability assessment in transportation planning: an urban transportation vehicle-based approach. *Transport Reviews*, 36(5), 623–644. https://doi.org/10.1080/03081060.2016.1174363
16. G. Santos and K. Ribeiro (2013). The use of sustainability indicators in urban passenger transport during the crisis period in Portugal. *Current Opinion in Environmental Sustainability*, 5(2), 209–214. https://doi.org/10.1016/j.cosust.2013.04.010
17. M. Batista, F. Freire, and C. Silva (2015). Vehicle environmental rating methodologies: Overview and application to light-duty vehicles in Portugal. *Renewable and Sustainable Energy Reviews*, 45, 611–620.

https://doi.org/10.1016/j.rser.2015.01.040

18. C. Wulf, M. Kaltschmitt, and P. Zapp (2018). Life Cycle Assessment of hydrogen transport and distribution options. *Journal of Cleaner Production*, 199, 431–443. https://doi.org/10.1016/j.jclepro.2018.07. 180

19. S. B. Walker, M. Fowler, and P. Ahmadi (2015). Comparative life cycle assessment of power-to-gas generation, storage and use in various application pathways. *Journal of Energy Storage*, 4, 135–148. https://doi.org/ 10.1016/j.est.2015.09.008

20. P. Ahmadi and E. Kjeang (2015). Comparative life cycle assessment of hydrogen fuel cell passenger vehicles in different Canadian provinces. *International Journal of Hydrogen Energy*, 40(38), 12905–12917. https://doi. org/10.1016/j.ijhydene.2015.07.147

21. M. Kannangara, F. Bensebaa, and Y. Zhang (2021). An adaptable life cycle greenhouse gas emissions assessment framework for light-duty vehicles. *Journal of Cleaner Production*, 289, 128394. https://doi.org/10.1016/ j.jclepro.2021.128394

22. A. Valente, D. Iribarren, and J. Dufour (2020). Using harmonised life-cycle indicators to explore the role of hydrogen in the environmental performance of fuel cell electric vehicles. *International Journal of Hydrogen Energy*, 45(47), 25758–25765. https://doi.org/10.1016/ j.ijhydene.2020.06.280

23. J. C. Koj, C. Wulf, and P. Zapp (2019). Environmental impacts of power-to-X systems - A review of techno-logical performance levels and assessment methods. *Renewable and Sustainable Energy Reviews*, 112, 865–879. https://doi.org/10.1016/j.rser.2019.06.029

24. P. Cuda, I. Dincer, and G. F. Naterer (2012). Hydrogen utilization in various transportation modes and their life cycle environmental impacts. *International Journal of Hydrogen Energy*, 37(1), 581–594. https://doi.org/ 10.1016/j.ijhydene.2011.10.027

25. J. J. Hwang (2013). Sustainability study of hydrogen pathways for fuel cell vehicle applications. *Renewable and Sustainable Energy Reviews*, 19, 220–229. https://doi.org/10.1016/j.rser.2012.11.033

26. Alberta Energy Regulator (2023). Emerging Resources – Hydrogen.

27. Green Learning (2022). Electrical Energy Calculator – Alberta.

28. E. Shahraeeni, S. Ahmed, and K. Malek (2015). Life cycle emissions and cost of transportation systems: A case study on hydrogen fuel-cell-based transport in British Columbia. *Journal of Natural Gas Science and Engineer- ing*, 25, 80–92. https://doi.org/10.1016/j.jngse.2015.03.029

29. P. Ahmadi and E. Kjeang (2017). Realistic simulation of fuel economy and life cycle metrics for hydrogen fuel cell vehicles. *International Journal of Energy Research*, 41(5), 714–727. https://doi.org/10.1002/ er.3672.

30. P. Ahmadi and A. Khoshnevisan (2022). Dynamic simulation and lifecycle assessment of hydrogen fuel cell electric vehicles considering degradation of the fuel cell stack. *International Journal of Hydrogen Energy*, 47(58), 24445–24460. https://doi.org/10.1016/j.ijhydene.2022. 06.215.