

Comparative Analysis of Hydrogen Fuel Cell Vehicle Powertrain with Battery Electric, Hybrid, and Gasoline Vehicles

Siddhesh Pimpale

Dana Inc, USA

DOI: <https://doie.org/10.10399/JBSE.2025748774>

Abstract

This study compares the life cycle costs and performance characteristics of various automotive powertrain technologies, including Battery Electric Vehicles, Hybrid Electric Vehicles, Fuel Cell Vehicles, and Internal Combustion Engine vehicles. Hydrogen fuel cell vehicles offer a promising pathway to significantly reduce carbon emissions in the transportation sector. These vehicles utilize hydrogen gas to generate electricity, emitting only water vapor as a byproduct. Compared to gasoline-powered vehicles and Hybrid Vehicles, fuel cell vehicles offer improved environmental performance and contribute to a cleaner, more sustainable transportation future. While challenges remain in terms of infrastructure development and hydrogen production costs, continued advancements in fuel cell technology and supportive policies are paving the way for wider adoption. Hydrogen fuel cell technology has the potential to revolutionize the transportation industry by providing a clean and efficient alternative to traditional internal combustion engines. Unlike gasoline-powered vehicles, fuel cell vehicles produce no harmful tailpipe emissions, making them a more environmentally-friendly option. Moreover, the use of renewable hydrogen as a fuel source further enhances the sustainability of this technology. As research and development continue to drive down costs and improve performance, the widespread adoption of hydrogen fuel cell vehicles could play a crucial role in achieving global climate and emissions reduction goals.

Keywords : Hydrogen fuel cell vehicles, battery electric vehicles, hybrid electric vehicles, internal combustion engine vehicles, carbon emissions, energy efficiency, life cycle cost analysis, hydrogen production, vehicle powertrain comparison, sustainable transportation.

1. Introduction

Owing to the growing environmental concerns and the need to reduce dependency on fossil fuels, the automotive industry has been actively exploring alternative powertrain technologies that can offer improved efficiency, reduced emissions, and greater sustainability. This research paper presents a comprehensive comparative analysis of the performance, characteristics, and environmental impact of hydrogen fuel cell vehicles in relation to battery electric vehicles, hybrid electric vehicles, and traditional gasoline-powered vehicles. The analysis covers a range of factors, including energy efficiency, greenhouse gas emissions, refueling/charging times, and overall sustainability, to provide a holistic understanding of the strengths and limitations of each powertrain technology. This in-depth comparison aims to inform decision-making and guide the continued development and adoption of clean transportation solutions.

Hydrogen fuel cell vehicles have gained significant attention in recent years as a promising solution to address the environmental and energy challenges faced by the transportation sector. As highlighted by recent studies, the use of hydrogen as a fuel source in fuel cell vehicles can offer several advantages over conventional powertrain technologies ([Andriyashin & ИИыпов, 2021](#)). Hydrogen fuel cell vehicles possess the potential for zero direct emissions, enhanced energy efficiency, and lessened reliance on fossil fuels. However, the widespread adoption of hydrogen fuel cell technology is still constrained by various technical and infrastructure-related challenges that need to be addressed. For instance, a study on the "Sizing of the Propulsion System for a Heavy-Duty Fuel Cell Commercial Vehicle" ([Zheng et al., 2021](#)) suggests that the dynamic properties of fuel cells require the integration of additional energy sources, such as battery packs or supercapacitors, to overcome their limitations.

2. Vehicle Powertrain Comparison

When considering energy efficiency and emissions, each powertrain technology exhibits distinct characteristics. Hydrogen fuel cell vehicles are generally more energy-efficient than traditional gasoline vehicles, with the potential to achieve significantly lower greenhouse gas emissions. In contrast, battery electric vehicles are known

for their superior energy efficiency and zero direct emissions, making them an attractive option for sustainable transportation. (Pasini et al., 2013) (Du & Zhan, 2021) On the other hand, hybrid electric vehicles offer a combination of improved efficiency and reduced emissions compared to gasoline-powered vehicles, but may not match the performance of fully electric or hydrogen-powered counterparts. Beyond energy efficiency and emissions, the comparison of these powertrain technologies must also consider other factors, such as refueling/charging times, infrastructure requirements, and overall sustainability.

2.1. Battery Electric Vehicles

As a pioneering technology in the shift towards sustainable mobility, battery electric vehicles have gained considerable traction in recent years, primarily due to their ability to operate without producing any direct emissions and their remarkable energy efficiency, which can translate to lower operational costs for consumers (Hassan et al., 2023) (Zheng et al., 2021) (Andriyashin & Илйпов, 2021). One key challenge commonly associated with battery electric vehicles is the relatively long charging times required to fully replenish the onboard battery, which can be a significant inconvenience for drivers, especially when undertaking longer journeys.

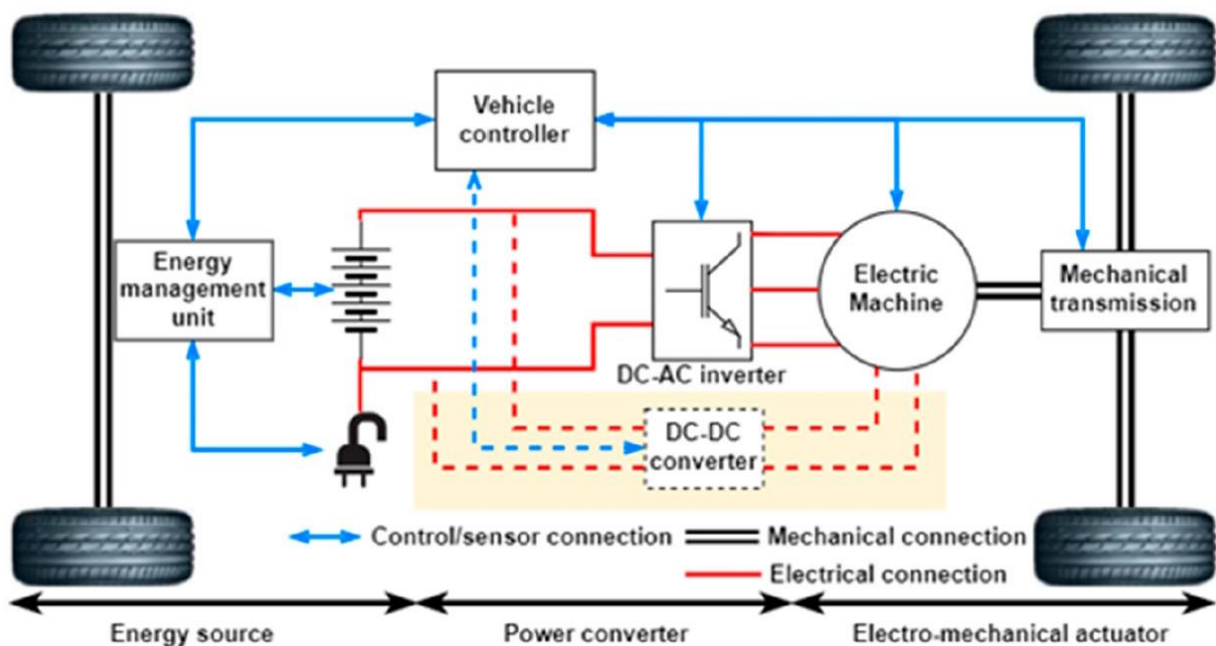


figure 1. battery electric vehicle architecture and its primary components.

2.2. Hybrid Vehicles

Hybrid electric vehicles, which combine an internal combustion engine with an electric motor and battery, offer a compromise between the benefits of electric propulsion and the convenience of traditional gasoline-powered vehicles. These vehicles have the potential to provide improved fuel efficiency and reduced emissions compared to their purely gasoline-powered counterparts, while also addressing the range limitations associated with battery electric vehicles.

Hybrid electric vehicles come in a variety of powertrain configurations, such as series, parallel, plug-in hybrid, and range extender designs, as shown in Figures 2.

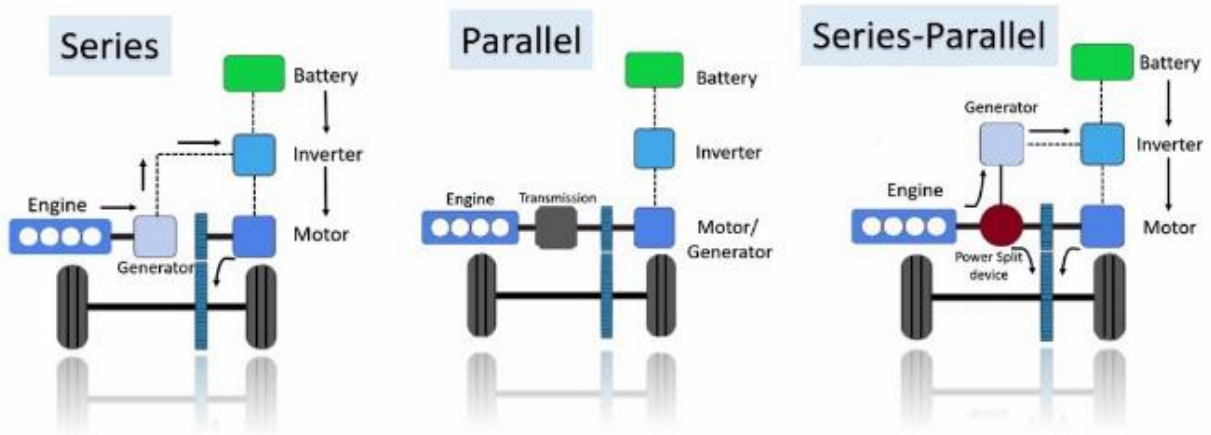


figure 2. hybrid vehicle powertrain architectures.

2.3. Hydrogen Fuel Cell Electric Vehicles

Hydrogen fuel cell vehicles, which utilize hydrogen as the primary energy source to generate electricity and power electric motors, present several advantages over other powertrain technologies. These vehicles offer the potential for zero direct emissions when hydrogen is produced using renewable resources, as well as rapid refueling times and extended driving ranges. (Franceschi et al., 2021). However, the widespread adoption of hydrogen fuel cell technology is still limited by the availability of refueling infrastructure, as well as the relatively higher costs associated with the production and storage of hydrogen. (Gogate, 2018)

Figure 3 below illustrates the standard architecture of a hydrogen fuel cell vehicle, which uses hydrogen produced from wind power.

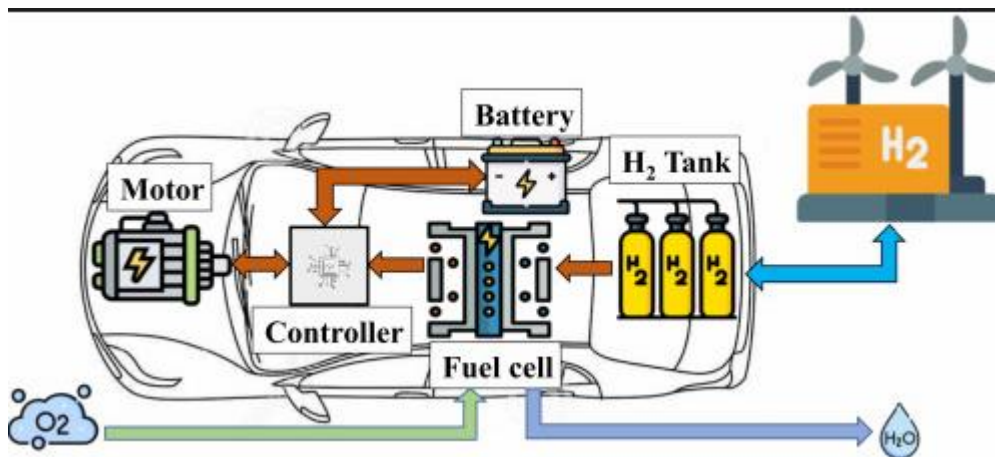


figure 3. hydrogen fuel cell vehicle architecture.

2.4. Gasoline Vehicles

Traditional gasoline-powered vehicles, despite their widespread adoption, face significant challenges in terms of energy efficiency and environmental impact. As highlighted in (Gogate, 2018), these vehicles are heavily reliant on non-renewable energy sources, have relatively low efficiency, and generate harmful exhaust emissions. In recent years, automakers have made efforts to improve the efficiency of gasoline engines, such as through the use

of turbochargers, direct injection, and cylinder deactivation technologies. Figure 4 depicts common Gasoline Vehicle powertrain architecture.

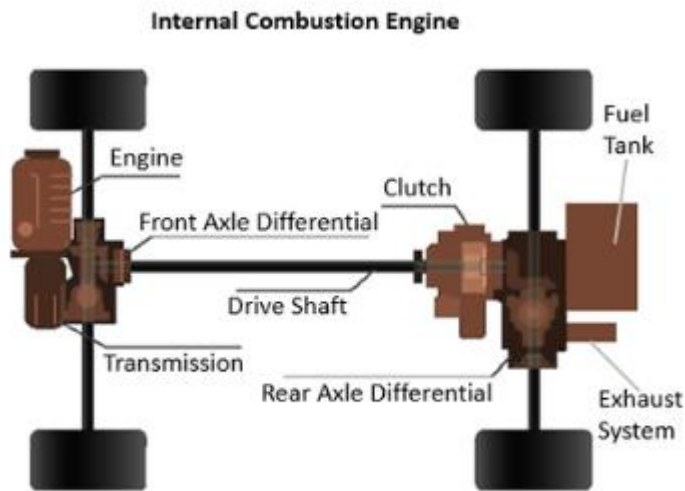


figure 4. gasoline vehicle powertrain architecture.

Ultimately, the choice of powertrain technology for vehicles will depend on a variety of factors, including regional infrastructure, consumer preferences, and the specific operational requirements of the vehicle.

3. Performance Analysis

When evaluating the performance of various powertrain technologies, it is crucial to thoroughly examine key metrics such as energy efficiency, emissions, driving range, and refueling efforts. A comprehensive analysis of these factors can provide valuable insights into the suitability and feasibility of each powertrain option for different applications and use cases.

Vehicle Type	Energy Source	Energy Density (Wh/kg)	Energy Efficiency (Tank To Wheel)	Driving Range (Miles)	Refueling/Charging Time
Battery Electric	Electricity (Li-ion Battery)	150-250	85-90%	150-370+	Fast Charging: 30 mins (80%).. Level 2: 4-8 hrs. Level 1: 12+ hrs
Hybrid Vehicle	Electricity + Gasoline (Regenerative)	150-250 + 12,000	25-40%	400-600+	Gasoline Refueling: 5-10 mins. Battery charges through regenerative braking
Fuel Cell Vehicle	Hydrogen (Fuel Cell)	~33,600*	25-30%	300-400	Hydrogen Refueling: 3-5 mins
Gasoline Vehicle	Gasoline	~12,000	15-20%	300-450	Gasoline Refueling: 5-10 mins

**The energy density of liquid hydrogen is around 33,600 Wh/kg. However, when accounting for efficiency losses from compression, storage, and conversion in the fuel cell, the actual usable energy density for a hydrogen fuel cell vehicle may be lower, typically in the range of 1,000 to 2,000 Wh/kg for the entire system, including the storage and fuel cell components.*

Key Points:

1. Energy Efficiency (TTW):

- BEVs have the highest energy efficiency, followed by HEVs and FCVs.
- Gasoline vehicles are the least efficient in terms of energy use.

2. Carbon Emissions:

- BEVs and FCVs have zero tailpipe emissions, but FCVs' emissions depend on hydrogen production methods.
- HEVs and gasoline vehicles emit CO₂, with HEVs having reduced emissions compared to traditional gasoline vehicles.

3. Driving Range:

- BEVs offer a wide range depending on the battery size, with some models exceeding 370 miles.
- HEVs provide a significantly longer range due to the combination of gasoline and electric power.
- FCVs have a range similar to gasoline vehicles, typically between 300-400 miles.
- Gasoline vehicles also have a broad range, typically between 300-450 miles.

4. Refueling/Charging Time:

- BEVs take the longest to charge, depending on the charger type and the battery size.
- HEVs, FCVs, and gasoline vehicles have similar refueling times, typically between 3-10 minutes, with FCVs requiring 3-5 minutes for hydrogen refueling.

The comparison highlights the advantages of hydrogen fuel cell vehicles, despite their higher efficiency losses. This powertrain offers zero tailpipe emissions, long driving ranges, and faster refueling times compared to battery electric vehicles ([Hassan et al., 2023](#)) ([Jiang et al., 2022](#)) ([Thomas, 2009](#)) ([Andriyashin & Илйпов, 2021](#)). However, the key challenge for fuel cell vehicles is that their widespread adoption is still hindered by the limited infrastructure development, higher costs of ownership, and the challenges associated with hydrogen production, storage, and distribution ([Thomas, 2009](#)) ([Jiang et al., 2022](#)) ([Andriyashin & Илйпов, 2021](#)) ([Hassan et al., 2023](#)).

4.Environmental Impact Analysis

While battery electric vehicles have gained traction, hydrogen fuel cell vehicles present a compelling alternative for sustainable transportation by addressing key limitations, such as faster refueling and reduced reliance on critical materials ([Battery Electric and Hydrogen Fuel Cell Electric Vehicles, 2014](#)). Although both powertrain technologies exhibit reduced emissions during operation, the lifecycle environmental impact must be considered, especially regarding battery production and disposal ([Dutta, 2021](#)). FCVs, when powered by green hydrogen, only produce water vapor, eliminating tailpipe emissions and offering versatility in production through renewable energy sources ([Benefits and Challenges, 2023](#)). To help offset the higher upfront costs of fuel cell vehicles, strategic infrastructure development and supportive policies can promote the widespread adoption of FCEVs as a cornerstone of a decarbonized transportation future.

4.1 Quantifying Carbon Emissions Across Diverse Automotive Powertrains.

A key aspect of evaluating the environmental impact of different powertrain technologies is the quantification of their carbon emissions.

The following provides a mathematical example to calculate and compare the carbon emissions across different automotive powertrains, considering a driving range of 100 miles.

1. Gasoline Vehicle

- **Formula:** $\text{CO}_2 \text{ Emissions} = \text{Fuel Consumption (in gallons)} \times \text{Carbon Emission Factor (in kg CO}_2 \text{ per gallon)}$
 - **Example:**
 - Assumption:
 - Fuel consumption = 25 MPG
 - Driving Range = 100 miles
 - Fuel Consumption = $100 \text{ miles} / 25 \text{ MPG} = 4 \text{ gallons}$
 - Carbon Emission Factor = 8.89 kg CO₂/gallon (Tank to Wheel)
 - Calculation: $\text{CO}_2 \text{ Emissions} = 4 \text{ gallons} \times 8.89 \text{ kg CO}_2 \text{ per gallon} = 35.56 \text{ kg CO}_2 \text{ per 100 miles}$

2. Battery Electric Vehicle

- **Formula:** $\text{CO}_2 \text{ Emissions} = \text{Electricity Consumption (in kWh)} \times \text{Grid Emission Factor (in kg CO}_2 \text{ per kWh)}$
 - **Example:**
 - Electricity Consumption: 30 kWh per 100 miles (assuming 0.3kWh/mile range)
 - Grid Emission Factor: For the tank-to-wheel analysis, the grid emission factor would be 0, as this accounts only for the vehicle's direct emissions during operation, resulting in no tailpipe emissions. However, for the purposes of this calculation, an average grid emission factor of 0.4 kg CO₂/kWh is assumed to estimate the carbon emissions associated with generating the electricity used to charge and power the vehicle.
 - Calculation: $\text{CO}_2 \text{ Emissions} = 30 \text{ kWh} \times 0.4 \text{ kg CO}_2 \text{ per kWh} = 12 \text{ kg CO}_2 \text{ per 100 miles}$
 - **Important:** This calculation only considers the operational emissions. A full lifecycle analysis would also include emissions from battery production and disposal.

3. Hydrogen Fuel Cell Vehicle

- **Formula:** $\text{CO}_2 \text{ Emissions} = \text{Hydrogen Consumption (in kg)} \times \text{Hydrogen Production Emission Factor (in kg CO}_2 \text{ per kg H}_2)$
- **Example:**
 - Hydrogen Consumption: 1.62 kg per 100 miles
 - Hydrogen Production Emission Factor: Hydrogen produced from renewable energy sources, such as electrolysis powered by renewable electricity, boasts a significantly lower carbon footprint, with an emission factor of approximately 0.043 kg CO₂ per kg of hydrogen. Conversely, hydrogen derived from fossil fuel-based processes can result in much higher emission factors, typically ranging from 10 to 14 kg CO₂ per kg of hydrogen. For the purposes of this calculation, the more favorable renewable hydrogen production emission factor will be used to estimate the emissions associated with hydrogen fuel cell vehicles.

Calculation: $\text{CO}_2 \text{ Emissions} = 1.62 \text{ kg H}_2 \times 0.043 \text{ kg CO}_2 \text{ per kg H}_2 = 0.070 \text{ kg CO}_2 \text{ per 100 miles}$

4. Hybrid Electric Vehicle

Formula: This is more complex, as it involves both gasoline and electricity :

$$\text{CO}_2 \text{ Emissions} = (\text{Fuel Consumption in gallons} \times \text{Carbon Emission Factor in kg CO}_2 \text{ per gallon}) + (\text{Electricity Consumption in kWh} \times \text{Grid Emission Factor in kg CO}_2 \text{ per kWh})$$

- **Example:**

- Fuel Consumption: 2 gallons per 100 miles (assuming avg 50 miles/gallon efficiency)
- Carbon Emission Factor: 8.89 kg CO₂/gallon
- Electricity Consumption: 30 kWh per 100 miles (similar as BEV)
- Grid Emission Factor: 0.4 kg CO₂/kWh

- Calculation:

- **CO₂ Emissions from ICE Technology:**
2 gallons × 8.89 kg CO₂ per gallon = **17.78 kg CO₂ per 100 miles**

- **CO₂ Emissions from Battery Technology:**
30 kWh × 0.4 kg CO₂ per kWh = **12 kg CO₂ per 100 miles**

- - Total CO₂ Emissions = 17.78 + 12 = 29.78 kg CO₂ per 100 miles

Table below summarizes these results;

Vehicle Type	CO ₂ Emissions (kg CO ₂ per 100 miles)
Battery Electric Vehicle (BEV)	12
Hybrid Vehicle (HEV)	29.78
Fuel Cell Vehicle (FCV)	0.070 (hydrogen production via electrolysis with renewable resources)
Gasoline Vehicle (ICE)	35.56

Key Considerations and Caveats:

- **Grid Emission Factor:** The grid emission factor varies significantly by region and time of day. Using average values can be misleading.
- **Vehicle Efficiency:** The fuel consumption and electricity consumption values are just examples. Actual values depend on the specific vehicle model, driving conditions, and driver behavior.
- **Manufacturing and Disposal:** The emissions associated with vehicle manufacturing and end-of-life disposal are not included in these calculations. These can be significant, especially for BEVs due to battery production [See EDITOR document].

The data shows that the tank-to-wheel carbon emissions of a gasoline vehicle are higher than those of battery electric vehicles and hydrogen fuel cell vehicles, even when accounting for the carbon-intensive electricity grid and the emissions associated with hydrogen production from renewable sources.

5. Analyzing the Life Cycle Costs of Automotive Powertrains

While emissions and environmental impact are important considerations, the overall life cycle cost of different automotive powertrain technologies is also a critical factor in their widespread adoption.

The total life cycle cost of a vehicle includes the upfront purchase price, fuel/energy costs, maintenance expenses, and end-of-life disposal or resale value. Comparing the life cycle costs of various vehicle technologies provides

valuable insights that inform consumers, policymakers, and the automotive industry about the economic viability of Hydrogen Fuel Cell Vehicles, Battery Electric Vehicles, Hybrid Vehicles, and conventional Gasoline Vehicles.

Total Life Cycle Cost

This analysis considers the following cost components over a 100,000-mile lifespan:

- **Initial Purchase Price:** Reflects the average transaction price of popular models in 2023 in United States.
- **Fuel Cost:** Based on average fuel/electricity prices and fuel efficiency.
- **Operating Cost:** Includes repairs, and other operating expenses.
- **Maintenance Cost :**Covers typical scheduled and unscheduled maintenance.
- **End-of-Life Costs:** Recycling and disposal costs.

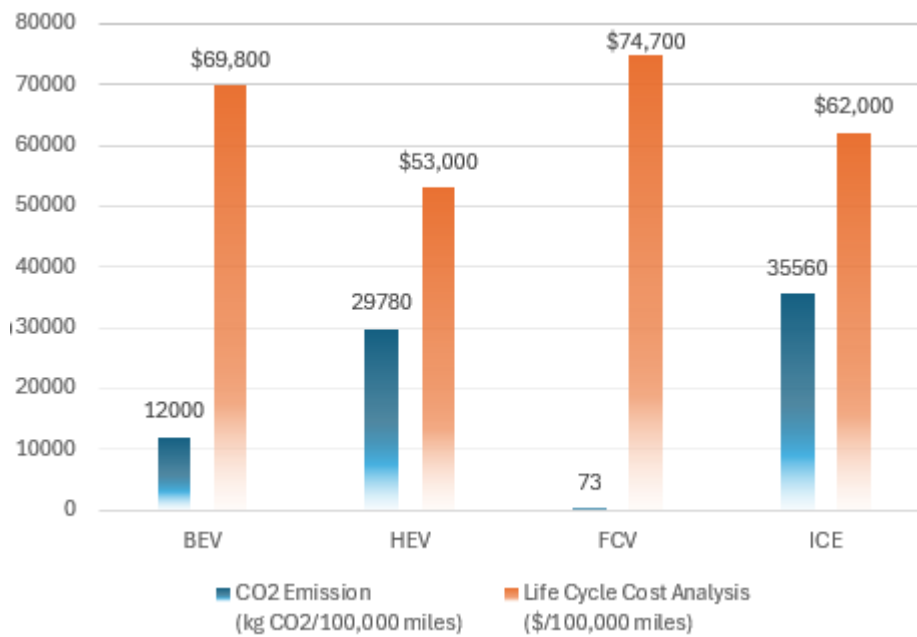
Assumptions:

- 100,000-mile lifespan.
- Fuel and electricity prices based on 2023 averages.
- Average Maintenance and operating costs over the typical 10-year ownership period, based on industry data and market trends.

Cost Breakdown

Cost Component	BEV (e.g., Tesla Model Y)	HEV (e.g., Toyota RAV4 Hybrid)	FCV (e.g., Toyota Mirai)	ICE (e.g., Toyota RAV4)
Initial Purchase Price	\$55,000	\$33,000	\$50,000	\$30,000
Fuel Cost per Mile	\$0.04/mile	\$0.08/mile	\$0.10/mile	\$0.15/mile
Operating Cost	\$800/year	\$1,000/year	\$1,200/year	\$1,500/year
Total Fuel Cost	\$4,000	\$8,000	\$10,000	\$15,000
Total Operating Cost	\$8,000	\$10,000	\$12,000	\$15,000
Total Maintenance Cost	\$800	\$1,000	\$1,200	\$1,500
Total End-of-Life Cost	\$1,200	\$1,000	\$1,500	\$500
Total Life Cycle Cost	\$69,800	\$53,000	\$74,700	\$62,000

A comprehensive view of the cost of ownership for each powertrain technology over a 100,000-mile and 10-year period is summarized in the table below. The data clearly indicates that the hydrogen fuel cell vehicle has the highest total life cycle cost compared to battery electric vehicles, hybrid electric vehicles, and internal combustion engine vehicles. However, when "green hydrogen" produced from renewable energy sources is used to refuel the FCV, it results in significantly lower carbon emissions than the other vehicle technologies. This highlights the tradeoff between the higher upfront costs of FCVs and their potential for nearly zero-emission operation when coupled with sustainable hydrogen production.



Notes:

- **BEV:** The Tesla Model Y has been a top-selling BEV globally ([Car Sales Statistics, 2021](#)). BEVs generally have lower maintenance costs due to fewer moving parts.
- **HEV:** The Toyota RAV4 Hybrid is a very popular HEV. Hybrids offer a balance of fuel efficiency and lower purchase price compared to BEVs.
- **FCV:** The Toyota Mirai is one of the few commercially available FCVs. FCVs have high initial costs and rely on hydrogen availability. Toyota offers free hydrogen fueling for up to 6 years or a value of \$15,000 to help offset the higher upfront costs of fuel cell vehicles.
- **ICE:** The Toyota RAV4 is consistently a top-selling ICE SUV vehicle in the USA. ICE vehicles typically have the lowest initial purchase price but higher fuel and maintenance costs.

Key Takeaways:

- While BEVs have a higher initial purchase price, lower fuel and maintenance costs can make them competitive over the long term.
- HEVs offer a more affordable entry point to electrification and lower fuel costs than traditional ICE vehicles.
- FCVs currently have the highest life cycle costs due to high purchase prices, hydrogen fuel costs, and infrastructure limitations. However, they offer the potential for zero emissions if green hydrogen is used.
- ICE vehicles remain the most affordable option in terms of initial purchase price, but their higher fuel and maintenance costs result in a higher total cost of ownership compared to HEVs and, in some cases, BEVs.

Keep in mind that these are estimates, and individual results may vary based on driving habits, location, and specific vehicle models. As technology evolves and infrastructure improves, these cost dynamics are likely to shift.

5. Conclusion

Hydrogen Fuel Cells – A Path to Drastically Reduced Carbon Emissions in Transportation

Hydrogen fuel cell vehicles offer a compelling pathway towards drastically reducing carbon emissions in the transportation sector and achieving a sustainable transportation future. Their potential to surpass other alternative powertrains lies in the promise of "green" hydrogen production ([Andriyashin & Шыпов, 2021](#); [Jiang et al., 2022](#)). FCEVs address key limitations of battery electric vehicles, offering faster refueling times, longer ranges, and less reliance on critical materials. When powered by hydrogen generated from renewable sources, FCEVs produce only water vapor, eliminating tailpipe emissions entirely ([Andriyashin & Шыпов, 2021](#); [Hassan et al., 2023](#)). The versatility of hydrogen production, with potential sources ranging from renewable energy and nuclear power to biomass, adds to their appeal ([Genovese et al., 2022](#)). Moreover, the possible repurposing of existing natural gas pipelines for hydrogen transport could streamline infrastructure development [See EDITOR document].

However, realizing the full potential of FCEVs requires overcoming significant challenges:

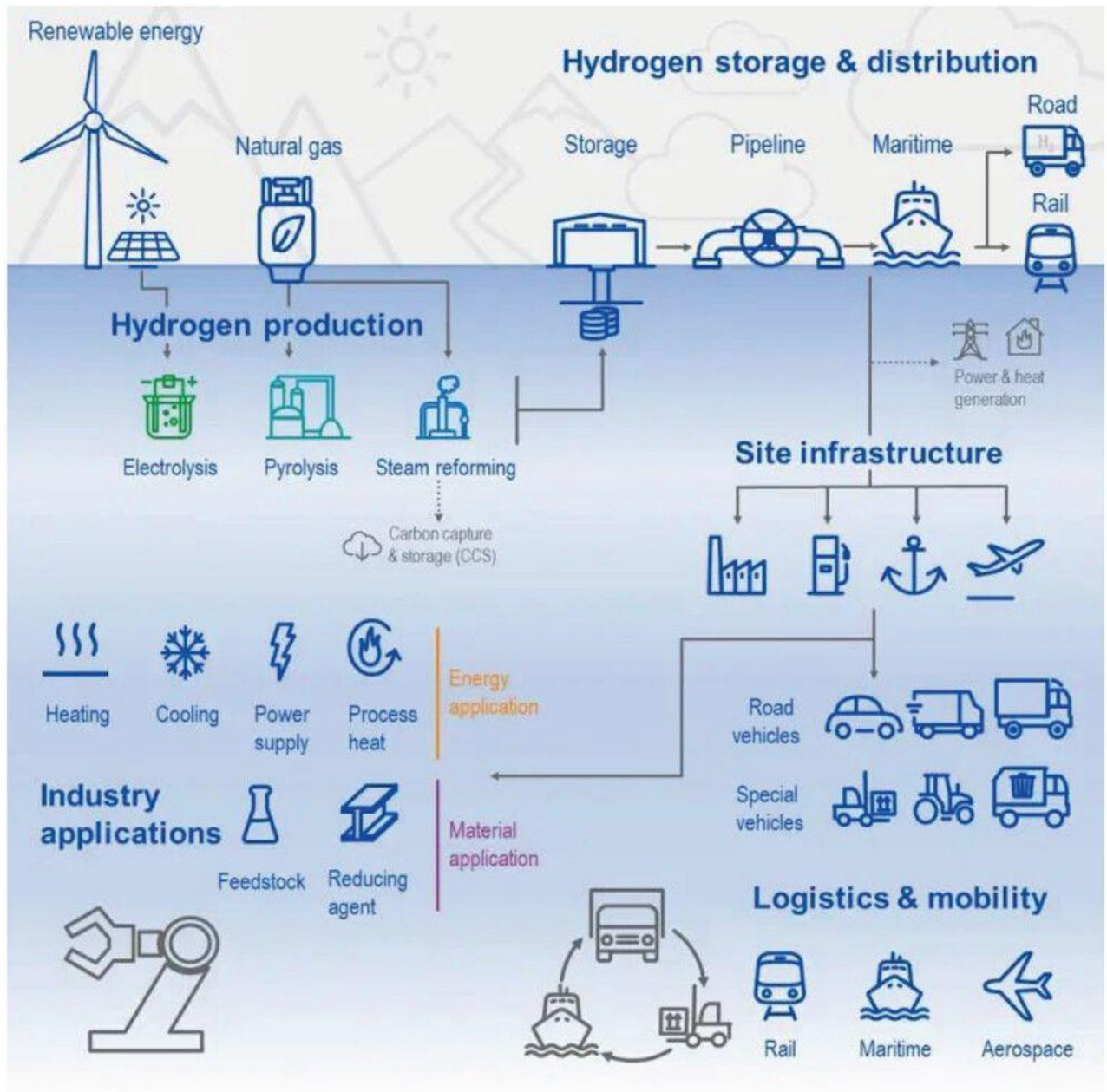
- **Cost:** The cost of fuel cell technology and green hydrogen production remains a barrier to widespread adoption ([Hassan et al., 2023](#); [Wang, 2014](#)). Further research and development are essential to make FCEVs economically competitive.
- **Hydrogen Production:** Scaling up green hydrogen production is crucial. This requires significant investment in renewable energy infrastructure and efficient electrolysis technologies ([Genovese et al., 2022](#); [Jiang et al., 2022](#)).

Currently, the majority of hydrogen produced in the United States is derived from the Steam Methane process, which utilizes natural gas and high-pressure steam to extract hydrogen ([Stropnik et al., 2019](#)). This production method results in the release of carbon emissions. However U.S. Department of Energy has taken initiative to accelerate research and development of applicable hydrogen production technologies to help decarbonize the U.S economy. Hydrogen can be generated using electrolysis process powered by renewable electricity and is known as Green Hydrogen which significantly reduces carbon emissions ([Pasini et al., 2013](#)).

- **Storage:** Efficient and safe onboard hydrogen storage remains a technical challenge. Continued research into advanced storage materials and methods is necessary. As of today there are 3 ways to distribute Hydrogen which includes Liquid Hydrogen Tankers, Compressed Hydrogen Trailers, and Pipelines ([Thompson et al., 2018](#)) ([Pasini et al., 2013](#)). Key challenges for the widespread adoption of hydrogen as a fuel include improving energy efficiency, minimizing hydrogen leakage, maintaining hydrogen purity, and reducing costs.
- **Infrastructure:** Developing a widespread hydrogen refueling infrastructure is critical to support the growth of the FCEV market ([Genovese et al., 2022](#)). Currently in United States the hydrogen refueling infrastructure is still nascent, with only around 74 hydrogen fueling stations in operation, the majority of which are located in the state of California.

The availability of reasonably priced hydrogen and ease of access to fueling stations are key to accelerating the adoption of FCEVs. Many automakers have set goals to promote the expansion of the hydrogen refueling network in the near future. While significant barriers remain, the potential of hydrogen fuel cell vehicles to

drastically reduce carbon emissions in the transportation sector is undeniable.



Roadmap for the Future:

A comprehensive roadmap for integrating FCEVs into future transportation must address these challenges:

1. **Prioritize Green Hydrogen:** Focus research and investment on green hydrogen production methods powered by renewable energy. Explore diverse production pathways, including electrolysis, photoelectrochemical water splitting, and biological hydrogen production ([Genovese et al., 2022](#)).
2. **Drive Down Costs:** Invest in research and development to reduce the cost of fuel cells, hydrogen storage systems, and electrolysis technologies. Government incentives and private sector partnerships can accelerate cost reductions.
3. **Develop Infrastructure Strategically:** Implement a phased approach to hydrogen refueling infrastructure development, starting with key transportation corridors and expanding outwards ([Genovese et al., 2022](#); [Pivovar, 2019](#)). Leveraging existing infrastructure, such as utilizing existing pipelines, can help streamline the development of the hydrogen transport network.
4. **Public Awareness and Education:** Educate the public about the benefits and safety of hydrogen fuel cell technology to build consumer confidence and encourage adoption.

5. **Policy Support:** Supportive government policies, including emissions regulations, fuel efficiency standards, and incentives for FCEV purchases, can create a favorable market environment ([Cyril & Saravanan, 2020](#); [Jiang et al., 2022](#)).

By addressing these challenges and implementing a well-defined roadmap, FCEVs can become a cornerstone of a sustainable and decarbonized transportation future. Continued research, technological advancements, and collaborative efforts across industry, government, and academia are essential to realizing the full potential of this promising technology ([Béthoux, 2020](#); [Cullen et al., 2021](#)).

References

- Andriyashin, S. N., & Шыпов, H. И. (2021). Fuel cells as a future of automotive industry: A review of current developments [Review of Fuel cells as a future of automotive industry: A review of current developments]. *Journal of Physics Conference Series*, 2061(1), 12002. IOP Publishing. <https://doi.org/10.1088/1742-6596/2061/1/012002>
- Battery Electric and Hydrogen Fuel Cell Electric Vehicles. (2014). <https://www.ucsusa.org/resources/battery-electric-and-hydrogen-fuel-cell-electric-vehicles>
- Benefits and Challenges. (2023). https://www.fueleconomy.gov/feg/fcv_benefits.shtml
- Béthoux, O. (2020). Hydrogen Fuel Cell Road Vehicles: State of the Art and Perspectives. *Energies*, 13(21), 5843. <https://doi.org/10.3390/en13215843>
- Car Sales Statistics. (2021). <https://www.best-selling-cars.com/category/news/>
- Cullen, D. A., Neyerlin, K. C., Ahluwalia, R., Mukundan, R., More, K. L., Borup, R. L., Weber, A. Z., Myers, D. J., & Kusoglu, A. (2021). New roads and challenges for fuel cells in heavy-duty transportation. *Nature Energy*, 6(5), 462. <https://doi.org/10.1038/s41560-021-00775-z>
- Cyril, P. H., & Saravanan, G. (2020). Development of advanced materials for cleaner energy generation through fuel cells. *New Journal of Chemistry*, 44(46), 19977. <https://doi.org/10.1039/d0nj03746j>
- Du, Z., & Zhan, H. (2021). Analysis of Related Technologies Used in Fuel Cell Vehicles. *Journal of Physics Conference Series*, 2125(1), 12011. <https://doi.org/10.1088/1742-6596/2125/1/012011>
- Dutta, P. (2021). ASSESSMENT OF ENVIRONMENTAL IMPLICATIONS OF ELECTRIC VEHICLES: A REVIEW [Review of ASSESSMENT OF ENVIRONMENTAL IMPLICATIONS OF ELECTRIC VEHICLES: A REVIEW]. *Journal of Research in Engineering and Applied Sciences*, 6(4), 188. <https://doi.org/10.46565/jreas.2021.v06i04.008>
- Franceschi, A., Cavina, N., Parenti, R., Reggiani, M., & Corti, E. (2021). Energy Management Optimization of a Dual Motor Lithium Ion Capacitors-Based Hybrid Super Sport Car. *Applied Sciences*, 11(2), 885. <https://doi.org/10.3390/app11020885>
- Genovese, M., Cigolotti, V., Jannelli, E., & Fragiaco, P. (2022). Comparative study of Global, European and Italian Standards on Hydrogen Refueling Stations. *E3S Web of Conferences*, 334, 9003. <https://doi.org/10.1051/e3sconf/202233409003>
- Gogate, M. R. (2018). Gasoline as a motor fuel at the pump: Conventional wisdom and new paradigms. *Petroleum Science and Technology*, 36(16), 1201. <https://doi.org/10.1080/10916466.2018.1465966>
- Hassan, Q., Azzawi, I. D. J., Sameen, A. Z., & Salman, H. M. (2023). Hydrogen Fuel Cell Vehicles: Opportunities and Challenges. *Sustainability*, 15(15), 11501. <https://doi.org/10.3390/su151511501>
- Jiang, J., Xie, K., Liu, Y., Sun, H. R., Yang, W., & Yang, H. (2022). Hydrogen Production Technology Promotes the Analysis and Prospect of the Hydrogen Fuel Cell Vehicles Development under the Background of Carbon Peak and Carbon Neutrality in China [Review of Hydrogen Production Technology Promotes the Analysis and Prospect of the Hydrogen Fuel Cell Vehicles Development under the Background of Carbon Peak and Carbon Neutrality in China]. *ACS Omega*, 7(45). <https://doi.org/10.1021/acsomega.2c04499>

- Pasini, J. M., Corgnale, C., Hassel, B. A. van, Motyka, T., Kumar, S., & Simmons, K. L. (2013). Metal hydride material requirements for automotive hydrogen storage systems. *International Journal of Hydrogen Energy*, 38(23), 9755. <https://doi.org/10.1016/j.ijhydene.2012.08.112>
- Pivovar, B. S. (2019). Catalysts for fuel cell transportation and hydrogen related uses. *Nature Catalysis*, 2(7), 562. <https://doi.org/10.1038/s41929-019-0320-9>
- Stropnik, R., Lotrič, A., Montenegro, A. B., Sekavčnik, M., & Mori, M. (2019). Critical materials in PEMFC systems and a LCA analysis for the potential reduction of environmental impacts with EoL strategies. *Energy Science & Engineering*, 7(6). <https://doi.org/10.1002/ese3.441>
- Thomas, C. (2009). Fuel cell and battery electric vehicles compared. *International Journal of Hydrogen Energy*, 34(15). <https://doi.org/10.1016/j.ijhydene.2009.06.003>
- Thompson, S. T., James, B. D., Huya-Kouadio, J., Houchins, C., DeSantis, D., Ahluwalia, R., Wilson, A. R., Kleen, G., & Papageorgopoulos, D. (2018). Direct hydrogen fuel cell electric vehicle cost analysis: System and high-volume manufacturing description, validation, and outlook. *Journal of Power Sources*, 399, 304. <https://doi.org/10.1016/j.jpowsour.2018.07.100>
- Wang, J. (2014). Commercialization of fuel cells: myth or reality? arXiv (Cornell University). <https://doi.org/10.48550/arXiv.1401>.
- Zheng, W., Xin, W., Xu, E., He, S., Qin, J., & Wang, H. (2021). Sizing of the Propulsion System for a Heavy-Duty Fuel Cell Commercial Vehicle. *Scientific Programming*, 2021, 1. <https://doi.org/10.1155/2021/1497178>