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A Multi-Fuel Comparison of Sustainable Vehicle Technologies: Efficiency and Environmental Impact

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Abstract

There is a drastic transition towards sustainable transportation as a critical component for global climate and development strategies. As the automotive sector explores alternatives to fossil fuel-based vehicles, electric vehicles (EVs), hydrogen fuel cell vehicles (FCEVs), hybrid, and biofuel-powered vehicles have emerged as key contenders. While each technology presents potential environmental benefits, they differ significantly in terms of energy efficiency, cost-effectiveness, scalability, and infrastructural requirements—factors that carry important economic implications, particularly in resource-constrained settings.

This study offers a comparative analysis of these sustainable vehicle technologies, focusing on tank-to-wheel energy efficiency and environmental impact, while incorporating relevant economic considerations such as production costs, infrastructure investment needs, and lifecycle externalities. Drawing from existing life cycle assessments (LCA), emissions data, and energy conversion studies, the research evaluates the performance of each fuel type in a range of development contexts.

By examining factors such as electricity generation sources, hydrogen production methods, and biofuel feedstocks affect economic and environmental outcomes, the study aims to identify the most viable transport solutions under varying policy, market, and energy conditions. The findings are intended to inform sustainable mobility planning, while also contributing to broader discussions on efficient resource allocation, clean energy investment, and equitable development in the context of transport decarbonization.

Keywords: Sustainable transportation, electric vehicles (EVs), hydrogen fuel cell vehicles (FCEVs), hybrid vehicles, biofuel-powered vehicles, energy efficiency, environmental impact, lifecycle assessment (LCA), infrastructure investment, production cost, sustainable mobility, clean energy, decarbonization, resource allocation, climate strategy, alternative fuels.

Introduction

The automotive sector is one of the largest contributors to global greenhouse gas emissions leading towards increasing momentum toward decarbonizing transport through the adoption of sustainable fuel technologies. However, the choice of technology such as electric, hydrogen, hybrid, or biofuel-powered vehicles is shaped not only by environmental considerations but also by economic feasibility, infrastructure readiness, and regional energy profiles.

This paper tries to explore and compare the energy efficiency and environmental impact of these following alternative vehicle fuel technologies: electric vehicles (EVs), hydrogen fuel cell vehicles (FCEVs), hybrid and biofuel-powered vehicles. Through a review of existing literature and data, the research aims to highlight the trade-offs, constraints, and potentials of each technology in different development contexts.
Research Question:

1. How much popularity alternate fuel technologies have gained?
2. How much cleaner are they compared to normal internal combustion engine (ICE) cars?
3. Which is the most efficient fuel technology among them?
4. Which fuel technology is the most feasible, sustainable and meets the needs of current scenario?

Hypothesis

While all alternative vehicle fuel technologies provide environmental benefits compared to conventional internal combustion engine (ICE) vehicles, electric vehicles (EVs) are poised to exhibit the highest energy efficiency and lowest lifecycle emissions when powered by renewable electricity, positioning them as the most sustainable choice in regions with robust clean energy infrastructure. Conversely, in settings with restricted access to renewable energy sources or inadequate charging infrastructure, hydrogen fuel cell vehicles (FCEVs), hybrids, or biofuel-powered vehicles may offer more practical and economically viable avenues for the transportation decarbonization of society.

Research Paper Methodology

This study employs a comparative and analytical research design, employing both qualitative and quantitative methodologies to assess the performance of sustainable vehicle technologies, including electric vehicles (EVs), hydrogen fuel cell vehicles (FCEVs), hybrid vehicles, and biofuel-powered vehicles, across key performance indicators (KPIs): energy efficiency, environmental impact, cost-effectiveness, and feasibility.

4.1. Data Collection:

The research primarily relies on secondary data sourced from academic journals, government and industry reports, international agency publications (such as the International Energy Agency (IEA), the IPCC, and the UNEP), and existing Life Cycle Assessment (LCA) studies.

4.2. Databases and Reports: Emissions and energy data are sourced from reputable databases, including:

1. International Energy Agency (IEA)
2. U.S. Department of Energy (DOE)
3. European Environment Agency (EEA)
4. World Bank and OECD reports
5. Peer-reviewed LCA studies accessible through Scopus/Web of Science

4.3. Comparative Framework:

A multi-criteria analysis (MCA) approach is employed to evaluate each fuel technology based on the following indicators:

- Energy Efficiency: Tank-to-wheel and well-to-wheel efficiency percentages
- Environmental Impact: Greenhouse gas emissions, air pollutants, and lifecycle emissions
- Economic Feasibility: Production cost per vehicle, cost of fuel per kilometre, and infrastructure investment required

- Scalability: Infrastructure readiness, fuel availability, and policy support
- Sustainability: Resource, renewability, impact of transportation on land and water.

4.4. Analytical Tools:

- Comparative Tables: Present comparative data to highlight performance differences between technologies.
- Visual Charts: Utilize visual representations to effectively convey performance comparisons.

4.5. Life Cycle Assessment (LCA):

- Conduct comprehensive LCA to quantify environmental impacts associated with vehicle production, fuel generation, usage, and disposal.
- Utilize LCA results to identify key environmental concerns and potential solutions.

4.6. Efficiency Ratios, Emission Intensities, and Cost Comparisons:

- Calculate and analyse efficiency ratios, emission intensities, and cost comparisons to assess the relative performance of technologies.
- Compare the cost-effectiveness and environmental impact of different technologies.

4.7. Qualitative Assessment:

- Evaluate the policy feasibility of various technologies.
- Assess the energy dependency of different technologies.
- Determine the development suitability of different technologies based on local factors.

Contextual Analysis:

- Given the global relevance of transport decarbonization, the study will analyse technologies in diverse regional contexts.
- Specifically, the study will contrast resource-constrained versus developed settings to evaluate how local factors (e.g., energy mix, economic capacity, geography) influence technological suitability.

5. Literature Review

5.1. Introduction to Sustainable Vehicle Technologies

The transition from internal combustion engine (ICE) vehicles to more sustainable alternatives has become a central theme in climate change mitigation strategies (IEA, 2021). The transportation sector, accounting for approximately 24% of global CO_2 emissions from fuel combustion, is under increasing scrutiny for reform (IPCC, 2022). As a result, technologies such as electric vehicles (EVs), hydrogen fuel cell electric vehicles (FCEVs), hybrids, and biofuel-powered vehicles have emerged as leading alternatives. Each offers different advantages and limitations in terms of energy efficiency, carbon footprint, and economic viability.

5.2. Electric Vehicles (EVs)

EVs have gained significant traction globally due to their high energy efficiency and zero tailpipe emissions. Studies by the International Energy Agency (IEA, 2022) highlight that battery electric vehicles (BEVs) convert more than 77% of electrical energy into motion, compared to 12–30% for gasoline cars. However, the sustainability of EVs is heavily dependent on the source of electricity used for charging. Life cycle assessments (LCA) show that EVs powered by renewable electricity (solar, wind, hydro) produce up to 70% fewer greenhouse gas emissions than conventional vehicles (Transport & Environment, 2021). Nonetheless, challenges persist in battery production, especially regarding lithium, cobalt, and nickel extraction, which raises concerns about supply chains and environmental justice (Wang et al., 2021).

5.3. Hydrogen Fuel Cell Vehicles (FCEVs)

Hydrogen-powered vehicles emit only water vapor at the tailpipe, positioning them as a clean alternative, especially for heavy-duty and long-haul transport. The IEA's Future of Hydrogen (2019) report emphasizes that FCEVs are most beneficial in sectors where batteries are impractical due to weight or refuelling time constraints.

However, well-to-wheel efficiency for hydrogen is relatively low—only 25–35% of input energy is converted to power at the wheels (Roth et al., 2020). The environmental impact of FCEVs also depends on the hydrogen production method:

Grey hydrogen, produced from fossil fuels, undermines sustainability goals.

Green hydrogen, produced via electrolysis using renewables, is cleaner but currently expensive and energy-intensive.

5.4. Hybrid Vehicles

Hybrid electric vehicles (HEVs), including plug-in hybrids (PHEVs), represent a transitional technology combining ICE and battery power. They offer moderate fuel savings and lower emissions, especially in urban driving cycles (ICCT, 2020). However, their long-term environmental benefit is limited by continued dependence on fossil fuels.

Some studies argue that hybrids can act as a bridge for regions with insufficient EV infrastructure but may delay full electrification if overly relied upon (Huang et al., 2020).

5.5. Biofuel-Powered Vehicles

Biofuels, including biodiesel and ethanol, are often promoted as renewable solutions derived from agricultural sources. When produced sustainably, biofuels can offer net reductions in CO_2 emissions, particularly in regions with large agricultural outputs (FAO, 2021).

However, LCAs reveal significant variation in environmental performance based on feedstock type (e.g., corn, sugarcane, algae) and land-use change impacts. Some biofuels contribute to deforestation, food insecurity, and water stress, undermining their sustainability credentials (Searchinger et al., 2008). Second-generation biofuels, derived from waste and non-food crops, show better promise but remain technologically and economically limited at present.

5.6. Comparative Analyses from Literature

Several meta-analyses and comparative studies have attempted to assess the performance of these technologies.

A study by Breetz et al. (2018) finds EVs to be superior in energy efficiency, while FCEVs hold an edge in range and refuelling time.

Another analysis by Faria et al. (2021) concludes that regional energy profiles and policy environments play a crucial role in determining which technology is most viable.

Research from the ICCT (2022) supports EVs as the most scalable and climate-effective solution under current technological trends, especially in urban passenger transport.

5.7. Economic and Infrastructure Considerations

Cost remains a key barrier. EVs are seeing declining battery costs, but require extensive charging infrastructure. Hydrogen requires entirely new fuelling systems, with high upfront investment. Biofuels benefit from compatibility with existing infrastructure, but face constraints in sustainable scaling. Moreover, the total cost of ownership (TCO) varies widely by region and policy support. Incentives, fuel taxes, and carbon pricing can significantly influence adoption rates and consumer choices (IEA, 2022).

5.8. Research Gaps Identified

Limited region-specific comparative LCAs for all fuel types

Lack of integration between environmental and economic evaluations

Insufficient long-term data on second-generation biofuels and hydrogen viability in developing contexts.

6. Analysis and Findings

This section compares electric vehicles (EVs), hydrogen fuel cell vehicles (FCEVs), hybrid vehicles, and biofuel-powered vehicles based on four key metrics: tank-to-wheel energy efficiency, lifecycle greenhouse gas emissions, infrastructure requirements, and scalability. Secondary data from life cycle assessment studies, government reports, and peer-reviewed literature is used.

Energy Efficiency: EVs have the highest tank-to-wheel efficiency, converting about 70-77% of grid electricity. FCEVs have lower efficiency, typically 25-35%, due to energy losses during hydrogen production and conversion. Hybrid vehicles offer moderate efficiency improvements over conventional ICEs, especially in urban driving. Biofuel efficiency varies depending on type and blend, generally lower than EVs and comparable to hybrids.

Lifecycle Greenhouse Gas Emissions: EVs powered by renewable energy have the lowest emissions, while those on coal-heavy grids have higher footprints. FCEVs' emissions depend on the hydrogen source: green hydrogen is nearly emissions-free, while grey hydrogen can produce emissions comparable to or higher than conventional fuels. Hybrids have lower emissions than ICEs but

higher than EVs and green hydrogen vehicles. Biofuel emissions depend on feedstock type, production practices, and land-use changes; second-generation biofuels are environmentally superior to first-generation ones derived from food crops.

Infrastructure and Economic Viability

EVs benefit from an expanding global charging network, although significant investment is still required, particularly in developing regions. Battery manufacturing and recycling infrastructure also pose challenges. Hydrogen technology lags behind in terms of refuelling infrastructure due to the high costs and technical complexities involved in hydrogen storage and transportation. Hybrid vehicles require no additional infrastructure beyond existing fuelling stations, which enhances their economic appeal in the short term. Biofuel use is supported by existing infrastructure but is constrained by feedstock availability and supply chain variability.

Scalability and Market Readiness

EVs are the most scalable solution at present, supported by strong policy incentives, falling battery costs, and technological advances. Hydrogen FCEVs have high potential in specific sectors such as freight and public transport but require substantial policy and industrial support. Hybrids also serve as a practical transitional technology but may inhibit long-term decarbonization efforts if over-relied upon. Biofuels face scalability issues due to land, water, and food resource constraints, although they remain relevant in certain rural and agricultural contexts.

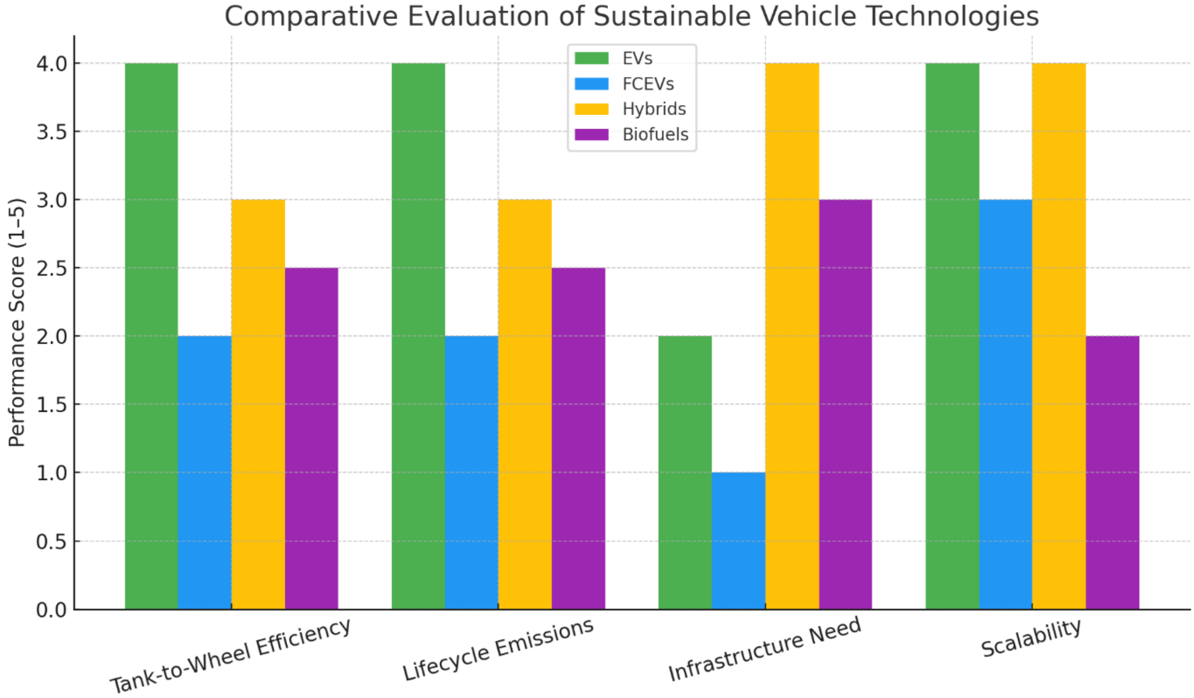
Criteria	**EVs**	**FCEVs**	**Hybrids**	**Biofuels**
Tank-to-Wheel Efficiency	High (~77%)	Low (~30%)	Medium	Variable

Criteria	EVs	FCEVs	Hybrids	Biofuels
Lifecycle Emissions	Low-high (renewable or non-renewable powered)	Low–High (depends on H_2 source)	Medium	Variable (depends on feedstock)
Infrastructure Need	High (charging + grid)	High (production + refuelling)	Low	Low–Medium
Scalability	High	Medium	High	Low–Medium

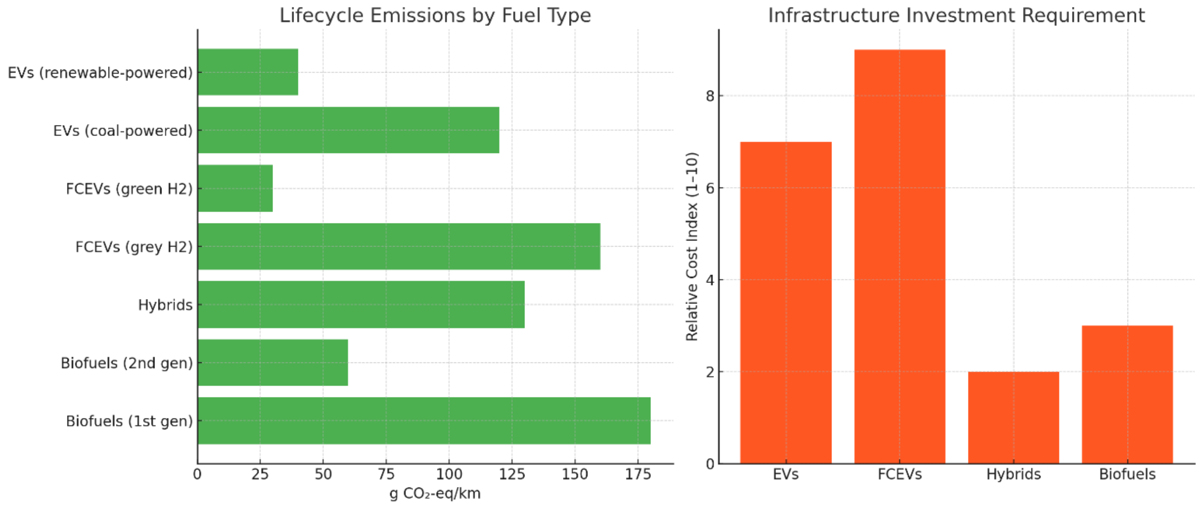
6.1. Comparative Summary

(Table 1)

(Figure 1: Comparative Evaluation of Sustainable Vehicle Technologies)



(Figure 2: Lifecycle Emissions by Fuel Type and Infrastructure Investment Required for Each Fuel Type)



This analysis suggests that while no single technology universally outperforms others, in the present scenario, EVs offer the better combination of environmental performance and scalability, particularly when supported by clean electricity. Hydrogen and biofuels may serve as complementary solutions in niche or regional applications, while hybrids provide a bridge in the near term.

7. Discussions

The findings presented in this study reveal a complex and dynamic landscape of sustainable fuel technologies, each shaped by trade-offs between energy efficiency, environmental impact, and economic feasibility. While electric vehicles (EVs) emerge as the leading option in terms of tank-to-wheel efficiency and emissions reduction, their overall effectiveness depends heavily on the cleanliness of the electricity grid, availability and efficient mining of rare earth metals and the availability of charging infrastructure. Hydrogen fuel cell vehicles (FCEVs), though technologically promising, face challenges related to production costs, energy conversion losses, and the underdevelopment of refuelling infrastructure. However, Hybrids seems to be a more viable option for the short term.

7.1. Economic Considerations and Resource Allocation

From an economic standpoint, the adoption of any sustainable vehicle technology entails both upfront and long-term costs. For EVs, the declining cost of lithium-ion batteries has improved their affordability, but the demand for rare earth materials like lithium, cobalt, and nickel introduces concerns related to supply chain stability, pollution near the mining areas and environmental externalities. Moreover, building a widespread charging infrastructure requires substantial public and private investment, especially in developing regions where electricity access remains uneven.

In the case of hydrogen, the high capital expenditure associated with electrolysers, hydrogen transport, and refuelling stations poses a significant barrier to market entry. The viability of hydrogen as a mainstream fuel hinges on achieving economies of scale and reducing the cost of green hydrogen production through renewable energy deployment and innovation in electrolysis technologies.

Biofuels offer the advantage of compatibility with existing infrastructure and vehicle fleets, but they are constrained by sustainability issues related to land use, biodiversity loss, and competition with food crops. Second-generation biofuels mitigate some of these issues but are not yet widely adopted due to limited production capacity and higher costs.

7.2. Policy and Institutional Dynamics

Government policy plays a pivotal role in shaping the economics of sustainable transportation. Subsidies, tax incentives, and regulatory mandates—such as fuel economy standards and carbon pricing—can accelerate the adoption of cleaner technologies. In regions with strong institutional support and renewable energy investments, EVs are gaining rapid momentum. Conversely, in regions with limited fiscal space or fossil-fuel-dominated energy systems, hybrids or biofuels may offer more realistic short-term pathways.

Importantly, policy decisions must also consider distributional equity. Electrification strategies that depend heavily on urban infrastructure risk excluding rural and low-income populations. A balanced portfolio approach—one that combines EVs, hydrogen, hybrids, and biofuels—may therefore be more suitable for achieving inclusive and context-sensitive decarbonization.

7.3. Strategic Implications for Developing Economies

For economies that are energy-import dependent or have limited industrial capacity, selecting the right technology mix is crucial for long-term economic resilience. Investing in EV infrastructure can reduce oil imports and promote renewable energy deployment, but it may also require reliance on foreign battery supply chains. Hydrogen technologies offer energy storage benefits and potential for industrial decarbonization, but require significant upfront investment and innovation. Biofuels, particularly from waste or agricultural byproducts, can support rural development and create employment, though scalability remains limited.

An economic analysis therefore supports a diversified strategy, aligned with national energy resources, technological capabilities, and development goals. The optimal approach will vary by region, but coordinated planning is essential to ensure efficient resource allocation and minimize stranded investments.

8. Research Contribution

This study contributes to the existing literature on sustainable vehicle technologies by offering a multi-dimensional comparison of electric vehicles, hydrogen fuel cell vehicles, hybrids, and biofuel-powered vehicles—not only from an environmental standpoint but also incorporating economic feasibility and regional adaptability.

Key contributions include:

8.1. Comparative Framework: The development of a unified framework that evaluates energy efficiency, environmental impact, and economic viability across multiple alternative fuel technologies.

8.2. Integrated Analysis: By bringing together findings from life cycle assessments, infrastructure studies, and policy documents, the research offers an integrated view that highlights the trade-offs and synergies between fuel types.

8.3. Contextual Evaluation: The study emphasizes the influence of regional and developmental contexts in determining the most viable sustainable transport solution—an area that is often generalized in global assessments.

8.4. Policy-Oriented Insights: The findings aim to inform policymakers and stakeholders by outlining technology-specific recommendations that align with broader goals of decarbonization and sustainable mobility.

9. Conclusion

This study presents a comparative analysis of key sustainable fuel technologies: electric vehicles (EVs), hydrogen fuel cell vehicles (FCEVs), hybrids, and biofuel-powered vehicles. The analysis evaluates these technologies based on their energy efficiency, lifecycle emissions, infrastructure requirements, and economic feasibility.

It is evident that no single technology can serve as a universal solution. Each option has distinct advantages and trade-offs influenced by regional energy mixes, policy environments, and market readiness.

Electric vehicles excel in tank-to-wheel efficiency and possess significant potential to reduce greenhouse gas emissions, particularly when powered by renewable energy sources. However, their reliance on rare earth materials and the challenges associated with infrastructure development present obstacles. Hydrogen fuel cell vehicles, while offering zero-emission mobility and rapid refuelling, currently face high costs and inefficiencies in hydrogen production and distribution. Biofuels provide a viable transition option with reduced infrastructural hurdles, but their sustainability is contingent upon feedstock choices and land use. Hybrids, although not fully zero-emission, offer a pragmatic bridge technology, particularly in regions with limited charging or refuelling infrastructure.

This comparative analysis emphasizes the significance of balancing environmental objectives with economic pragmatism. The adoption of sustainable transport technologies must align with national and regional development priorities, energy security considerations, and fiscal capacities. Efficient resource allocation and targeted policy support will be crucial for achieving equitable and enduring progress in the transition to low-carbon mobility.

10. Recommendations

1. Adopt a Multi-Technology Strategy Policymakers should avoid a one-size-fits-all approach and instead encourage a diverse energy portfolio that includes EVs, FCEVs, hybrids, and advanced biofuels based on regional capacities and infrastructure.
2. Invest in Clean Energy and Grid Modernization The environmental success of EVs and hydrogen depends on clean electricity. Governments must accelerate investments in renewables, smart grids, and clean hydrogen production to unlock full benefits.
3. Subsidize R&D and Infrastructure Development Focused funding for battery innovation, green hydrogen technology, and second-generation biofuel production can reduce costs and scale deployment.
4. Implement Lifecycle-Based Policy Measures Incentives and regulations should be based on lifecycle emissions and energy efficiency, rather than tailpipe emissions alone, to ensure holistic sustainability.
5. Ensure Equitable Transition Sustainable transport policies should include support for rural and low-income communities through targeted subsidies, infrastructure access, and job creation in clean transport sectors.
6. Encourage International Cooperation Sharing technology, best practices, and supply chain partnerships across borders—especially between developed and developing economies—can accelerate adoption and reduce costs globally.
7. Promote Localized Manufacturing and Supply Chains Establishing domestic supply chains for critical components like EV batteries, fuel cells, and biofuel feedstocks can reduce import dependency, create jobs, and enhance national energy security.
8. Enhance Consumer Awareness and Incentives Governments and industry stakeholders should launch awareness campaigns about the environmental and economic benefits of sustainable fuel technologies, while also offering tax breaks, registration fee waivers, or trade-in incentives.
9. Standardize Regulations and Safety Protocols Developing consistent national and international standards for battery recycling, hydrogen storage, and biofuel blending will ensure safety, interoperability, and market confidence.
10. Support Public and Shared Mobility Electrification Incentivizing electric or hydrogen-based public transport (buses, fleet taxis, etc.) and shared mobility services can accelerate adoption while reducing per capita emissions and congestion.
11. Invest in Recycling and Circular Economy Initiatives Policies must prioritize the development of battery recycling, hydrogen fuel cell recovery, and sustainable waste management systems to minimize resource depletion and environmental harm.
12. Integrate Transport Planning with Urban Development Urban transport systems should be aligned with sustainability goals through transit-oriented development, smart mobility planning, and integration of clean vehicles into city logistics.

13. Monitor and Evaluate Policy Impacts Regularly Establish adaptive frameworks that periodically review the effectiveness of transport policies, incentives, and investments—ensuring evidence-based corrections and continual improvement.

11. Limitations of the Study

1. While this study presents a comparative overview of sustainable vehicle technologies, several limitations must be acknowledged to contextualize the scope and reliability of its findings:
2. Reliance on Secondary Data This research primarily depends on existing literature, databases, and life cycle assessments (LCA), which vary in scope, methodology, and assumptions. As a result, comparative outcomes may be affected by inconsistencies or gaps across different studies.
3. Static Technological Assumptions The analysis reflects the current state of technology and infrastructure for EVs, hydrogen fuel cell vehicles, hybrids, and biofuels. However, rapid innovations—such as improvements in battery energy density, green hydrogen production, or advanced bio-refining techniques—could significantly alter these dynamics in the near future.
4. Lack of Region-Specific Modelling Although the study incorporates general economic and environmental trends, it does not offer a detailed examination of specific national contexts. Regional variations in electricity grids, fuel pricing, energy policy, and consumer behaviour can significantly influence the relative performance and feasibility of each technology.
5. Incomplete Lifecycle Emission Coverage Life cycle emissions data used in the study may exclude critical stages such as vehicle disposal, battery recycling, and indirect emissions from land-use changes in biofuel production. These omissions could underestimate the total environmental impact of some technologies.
6. Infrastructure Cost Estimation The infrastructural investment required for scaling up charging stations, hydrogen refuelling networks, or biofuel distribution systems is generalized. Country-specific variations in labour, land, logistics, and regulatory barriers are not fully captured.
7. Absence of Market Behaviour Analysis The study does not address consumer adoption patterns, behavioural resistance, or socio-cultural barriers to sustainable transport adoption—factors that often determine real-world uptake irrespective of technical performance or cost.
8. Limited Scope of Economic Evaluation While economic indicators such as production cost and investment needs are discussed, broader macroeconomic impacts—such as effects on employment, fiscal revenues, or international trade—are not analysed in detail.
9. Policy and Geopolitical Uncertainty echnological feasibility and environmental outcomes are heavily influenced by government policy, subsidies, and global cooperation. Future shifts in trade regulations, climate commitments, or international conflicts could affect supply chains and technology diffusion, but such variables are beyond the study’s predictive scope.
10. Time Constraints on Research Due to time limitations, the study does not incorporate expert interviews, primary data collection, or dynamic modelling techniques that could enhance the robustness and granularity of findings.

12. Scope for Future Research

1. Given the evolving nature of sustainable vehicle technologies and the limitations highlighted in this study, several areas merit further investigation:

2. Country-Specific Comparative Analysis Future research can undertake a more localized approach by assessing how alternative fuel technologies perform in specific national contexts, taking into account regional energy mixes, infrastructure availability, and economic policies.
3. Dynamic Lifecycle Assessment (LCA) Incorporating real-time, longitudinal LCA studies can improve the accuracy of environmental impact assessments by accounting for future technological advancements, grid decarbonization, and improved recycling methods.
4. Primary Data Collection and Stakeholder Insights Conducting surveys, interviews, and expert consultations can offer deeper insights into consumer preferences, industry readiness, and policy perceptions—factors often missed in quantitative models.
5. Economic Modelling and Cost-Benefit Analysis More advanced economic evaluations, such as input-output modelling` or cost-benefit simulations, can help quantify the broader macroeconomic implications of large-scale adoption of clean vehicle technologies.
6. Policy Simulation Studies Modelling the effects of different policy instruments—subsidies, carbon taxes, vehicle mandates, and infrastructure investments—can provide guidance for governments seeking to design effective decarbonization strategies.
7. Integration with Renewable Energy Systems Further research is needed to explore how transport electrification or hydrogen mobility can be integrated with intermittent renewable energy sources, and how such integration impacts grid stability and storage needs.
8. Comparative Studies on End-of-Life Impact Detailed comparisons of battery recycling, hydrogen fuel cell reuse, and biofuel byproduct management are necessary to ensure long-term sustainability and circular economy alignment.
9. Impact on Employment and Social Equity Investigating how the transition to sustainable transport affects employment, skill development, and access to mobility—especially in rural and marginalized communities—can inform more inclusive policymaking.

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