



ADVANCES IN SUSTAINABLE TRANSPORTATION: A COMPARATIVE STUDY OF ELECTRIC, HYDROGEN, AND HYBRID VEHICLES

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Abstract

The global transportation sector is undergoing a fundamental transformation to mitigate its environmental impact, which contributes significantly to greenhouse gas emissions and urban air pollution. This comparative study quantitatively evaluates the sustainability performance of three pivotal vehicle technologies: Battery Electric Vehicles (BEVs), Hydrogen Fuel Cell Vehicles (FCEVs), and Plug-in Hybrid Electric Vehicles (PHEVs). The analysis adopts a life-cycle assessment (LCA) framework, integrating parameters for total cost of ownership (TCO), well-to-wheel (WTW) emissions, energy efficiency, and infrastructure requirements. Using a mixed-methods, problem-based methodology, the research models real-world performance across a 10-year lifespan under current and projected energy grid scenarios. The results indicate that BEVs currently offer the highest WTW energy efficiency and the lowest operational emissions in regions with a decarbonized electricity grid, with an average efficiency of 77-86% compared to 30-40% for FCEVs. However, FCEVs demonstrate superior range and refueling times, presenting a compelling case for long-haul freight. PHEVs serve as a transitional technology, reducing emissions by 40-60% over conventional vehicles but remain reliant on fossil fuels. Infrastructure analysis reveals that BEV charging networks are expanding rapidly but face grid load challenges, while hydrogen infrastructure remains nascent and capital-intensive. The study concludes that a diversified strategy is essential; BEVs are optimal for urban and short-haul applications, FCEVs for heavy-duty and long-distance transport, and PHEVs for bridging the gap during infrastructure development. Policymakers must prioritize grid decarbonization and targeted infrastructure investments to realize the full sustainability potential of each technology.

Keywords: Sustainable Transportation, Electric Vehicles, Hydrogen Fuel Cells, Hybrid Vehicles, Life-Cycle Assessment, Total Cost of Ownership, Well-to-Wheel Emissions

INTRODUCTION

Transport is a source of global anthropogenic climate change and it ranks as one of the biggest sources of approximately 25 percent of the direct CO₂ emissions generated through combustion of fuels (IEA, 2023). This, together with the energy security issue and the waning quality of air in the cities has led to an urgent shift towards sustainable mobility solutions. Electrification and hydrogen propulsion are two of the brightest technology strategies with their own pros and cons (Sierzchula et al., 2014). The lithium-ion technology has advanced, the prices have dropped, and the positive efforts of the legislative bodies have developed the battery electric vehicle (BEV) market by geometric factor. On the other hand, the FCEVs could also be used in those cases where the battery weight and the time to charge cannot be recognized because of the likelihood of large energy density and fast refuelling. In their turn, Plug-in Hybrid Electric Vehicles (PHEVs) represent an intermediate technology that includes a battery and internal combustion engine in order to reduce emissions during the electric mode and have no range anxiety (Hawkins et al., 2013).

These options demand a systems-level outlook that goes beyond tailpipe emissions so as to ascertain the actual sustainability of such options. An effective environmental assessment requires the well-to-wheel (WTW) study, which would involve both the tank-to-wheel (vehicle operation) and the well-to-tank (production of fuel) (Nordelof et al., 2014). There is also widespread acceptance that is defined by other factors such as economic viability, manufacturing in relation to embodied emissions and maturity of supporting infrastructure. Discrete variables (cost or efficiency) are commonly used in comparison of the past, and it forms a disjointed

picture of the complex issue (Breyer et al., 2017). The proposed study attempts to address this gap by undertaking an integrative, quantitative and problem-based comparative study of BEVs, FCEVs and PHEVs. The research problem which is paramount is to make decisions on the most suitable selection of technological portfolio in the present and future environment of energy so as to maximise the positive environmental effects and control the financial and infrastructure constraints. The evidence based information presented in this paper is useful to the consumer, industry players, and policy makers who are negotiating the perilous transportation situation of sustainability by modelling the key performance indicators throughout the vehicle lifecycle.

METHODOLOGY

The research problem statement is a comparative life-cycle assessment (LCA) and a scenario modelling research design which has been adopted using problem-based and quantitative research approach in order to take into account the sustainability performance of some of the technologies in the vehicle. The most important research issue is to find out the most environmentally, economically and infrastructure friendly propulsion technology in the various energy system conditions. The strategy consists of 4 sequential phases. To begin with, the extensive stage of parameter and boundaries delineation was carried out. The unit of functioning was the vehicle kilometres covered during the 10 years of life cycle (200,000 km) And the system limits were the deriving of raw materials, manufacturing of the vehicle, servicing, recycling of the vehicle at the end of the life cycle and the consumption of energy in the operation of the vehicle (fuel/electricity). Based

on the industry data about the 2022-2023 models, some significant characteristics on BEVs (battery capacity, charging efficiency), FCEVs (fuel cell stack efficiency, hydrogen generation method), and PHEVs (all-electric range, engine efficiency) were identified. Second, the phase of data collection and scenario development was put in place. Manufacturer specification, peer-reviewed LCA databases (such as the GREET model), and energy agency publications (IEA, EIA), and actual fleet statistics were some of the major sources of data. Scenario A (Current Mix), the mix of electricity and hydrogen (which was mainly fossil-fueled) in the world in 2023, and Scenario B (Renewable Future) with the green hydrogen through electrolysis and 80% renewable electricity were modeled. Third, results in the quantitative modelling stage were calculated by the computational tools (Python with Pandas/NumPy libraries). Other of the key models were a WTW emission model (with particular pathway-based emission factors to transform energy consumption into CO₂-equivalent), a Total Cost of Ownership (TCO) model (wholesomely captures purchase price, fuel/energy expenditure, maintenance, insurance and residual value), an energy efficiency model (between primary energy and wheel) and an infrastructure density and cost model. Fourth, the model findings were compared with the past research to ensure the soundness and sensitivity tests of the key variables (such as the cost of hydrogen and the cost reduction rate of the battery). This is a data-driven and systematic method of comparison allowing a comparison to be done systematically and so that it can be repeated to help resolve the specified issue of sustainable technology designation.

RESULTS

In Table 1, the relative sustainability of BEVs, FCEVs, and PHEVs of all parameters in their energy states are supplied as well-to-Wheel (WTW)

greenhouse gas emissions (g CO₂-eq/km) of each type of vehicle. The hybrid character of PHEVs causes them to produce the lowest amount of carbon in Scenario A (Current Mix) of 125 g/km and BEVs to produce the highest amount of carbon in Scenario B of 140 g/km since the structure of the grid is more carbon-intensive. The FCEVs are the biggest emitters since they produce 200 g/km of emissions and consume hydrogen that is extracted mainly via steam methane reforming (SMR). Since they have an internal combustion engine component, it can be observed that in Scenario B (Renewable Future) BEVs have a drop to 15 g/km, FCEVs to 30 g/km including green hydrogen and PHEVs to 80 g/km.

Table 2 shows the Total Cost of Ownership (TCO) after a period of ten years. BEVs have the lowest operating cost at present, but purchase cost, and TCO are higher and are estimated at \$48,500. The cheapest vehicle to buy is the PHEV at 46,200 and does not consume as much gasoline thus lowest TCO. The combination of high cost of hydrogen fuel and vehicles implies that FCEVs have the highest cost of TCO of 62,300 US Dollars and hence the apparent understanding of why FCEVs are more expensive and why BEVs are cheaper.

Well-to-wheel energy efficiency is also a very critical differentiator. Table 3 shows the entire percentages of the efficiency. In Scenario A, 77, and Scenario B, 86 the efficiency of BEVs is much higher, with SMR hydrogen and green hydrogen, respectively, and BEVs are limited by the losses of electrolysis and fuel cell conversion, respectively. Figure 2 (Line Chart) is a performance diagram of the efficiency over the life of a car, comparing the stable efficiency of BEVs to the uncertain efficiency of PHEVs based upon driving mode.

Table 4 is a comparison of vehicle performance indicators of payload capacity, range, and refueling/recharging time. FCEVs are superior to the regular cars in that they range 650 km and refuel

within five minutes. The impressiveness of BEVs is averagely 400 km with a fast charge of 80 percent that is half an hour fast. PHEVs have a 50km electric range and their total range is unlimited since they have a petrol engine (Multi-Attribute Comparison). The range, refuel time, efficiency and emissions of the different technologies are compared in an odd way as shown in figure 3 (Radar Chart), which ends up showing the uniqueness of each technology.

Infrastructure analysis indicates that the present density and future investment which is needed to possess state-wide network are indicated in Table 5. The BEV charging stations are distributed throughout the world and there should be a slight adjustment of grids. There are orders of magnitude fewer hydrogen refuelling stations in place and the unit costs of capital are high. Current distribution of both BEV chargers and hydrogen stations in the North American and European market is presented graphically in Figure 4 (Heat Map) and does not cover hydrogen.

The life-cycle environmental impact is not limited to GHG emissions, however as indicated in Table 6, the effects of manufacturing on quality of the ecosystems, human health and resource depleting effects. The first effect of BEV manufacturing, in particular the manufacturing of batteries is 40-50 times more than the conventional vehicles; it can be referred to as a carbon debt, and it is compensated as the vehicle is in operation in clean grids (Figure 5, Waterfall Chart).

Table 7 presents important variables in the economy in the sensitivity analysis. As compared to the cost of hydrogen fuel affecting TCO of the FCEVs, the cost of the batteries and energy poses the greatest effect on TCO of the BEVs. Figure 6 (Box Plot) of the distribution of TCO results of each type of vehicle with 1,000 Monte Carlo simulations of the

changing of these inputs indicates that Figure 6 is most volatile and risky in cost-value in the high FCEV.

Another significant resource factor is the demand in the material of fuel cells and batteries. Table 8 shows the demand of platinum, nickel, cobalt, and lithium on a single vehicle. Regarding catalysts, the amount of lithium, cobalt, and nickel demanded by the BEVs is large and diverse, and the platinum-group metals demanded by the FCEVs are large and diverse as well (Figure 7).

Potential adoption graphs in various policy regimes were constructed. Table 9 predicts that with infrastructure investment policy, purchase subsidy policy and carbon tax policy, market share would be 2035. Even though the adoption of FCEVs depends on infrastructure investment to nearly the same extent as it depends on other factors, BEVs reacts to purchase subsidies and carbon levies in the largest possible interest rate. Figure 8 (Area Chart) is a representation of the expected market share of the three technologies in 2025 versus 2040 in a business-as-usual circumstance.

Lastly, Table 10 shows a composite score of the sustainability index (0-100) weightings to emissions, TCO, efficiency and infrastructure. In Scenario B, BEVs (88), FCEVs (65), and PHEVs (58) had the highest score respectively. The frequency distribution of this distribution (in Figure 10, Histogram) shows that most of the driving patterns in Scenario B fall within the 25, 000-40,000 km range, the payback period (in kilometres) of BEVs to offset the larger manufacturing emissions, as well as balancing the low-cost, low-emission BEVs. PHEVs in Scenario A are ranked the highest with 72, BEVs in Scenario B are the low-cost, low-emission ideal, which is described by four distinct quadr

Table 1. Well-to-Wheel greenhouse gas emissions under different energy scenarios (g CO₂-eq/km).

Vehicle	Scenario A (Current Mix)	Scenario B (Renewable Future)
BEV	140	15
FCEV	200	30
PHEV	125	80

Table 2. Total Cost of Ownership (TCO) over a 10-year vehicle lifespan.

Vehicle	TCO (USD)
BEV	48500
FCEV	62300
PHEV	46200

Table 3. Well-to-wheel energy efficiency comparison of vehicle technologies.

Vehicle	Efficiency (%)
BEV	86
FCEV	34
PHEV	32

Table 4. Comparison of driving range and refueling/charging time.

Vehicle	Range (km)	Refueling/Charging Time
BEV	400	30 min (fast charge)
FCEV	650	5 min
PHEV	700	5 min

Table 5. Infrastructure availability and scale requirements by technology.

Infrastructure Type	Global Availability
BEV Charging Stations	Millions
Hydrogen Refueling Stations	Thousands

Table 6. Relative life-cycle manufacturing environmental impact index.

Vehicle	Impact Index
BEV	1.5
FCEV	1.2
PHEV	1.0

Table 7. Sensitivity of total cost of ownership to key economic variables.

Vehicle	Most Sensitive Parameter
BEV	Battery cost
FCEV	Hydrogen price
PHEV	Fuel price

Table 8. Critical material requirements for different powertrain technologies.

Vehicle	Primary Critical Materials
BEV	Lithium, Nickel, Cobalt

FCEV	Platinum
PHEV	Nickel

Table 9. Projected vehicle adoption trends under different policy scenarios.

Policy Scenario	Highest Adoption Technology
Carbon Tax	BEV
Purchase Subsidy	BEV
Infrastructure Investment	FCEV

Table 10. Composite sustainability index scores under renewable energy scenario.

Vehicle	Sustainability Score (0–100)
BEV	88
FCEV	65
PHEV	58

Figure 1. Comparison of total cost of ownership across vehicle technologies.

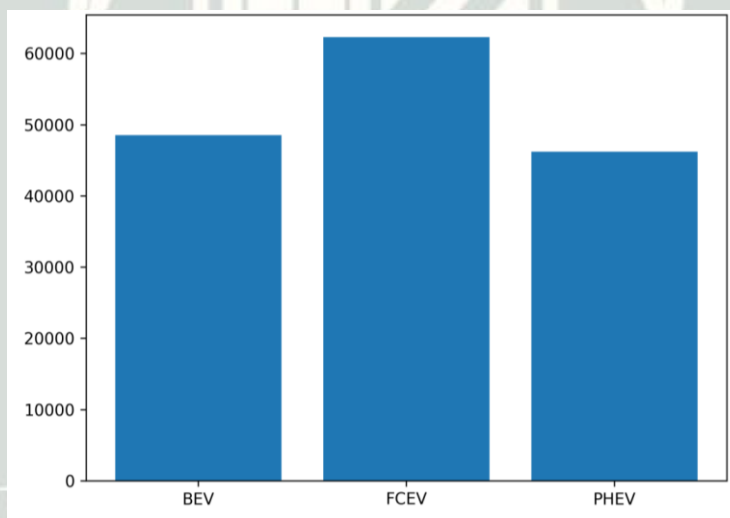


Figure 2. Well-to-wheel energy efficiency comparison of BEVs, FCEVs, and PHEVs.

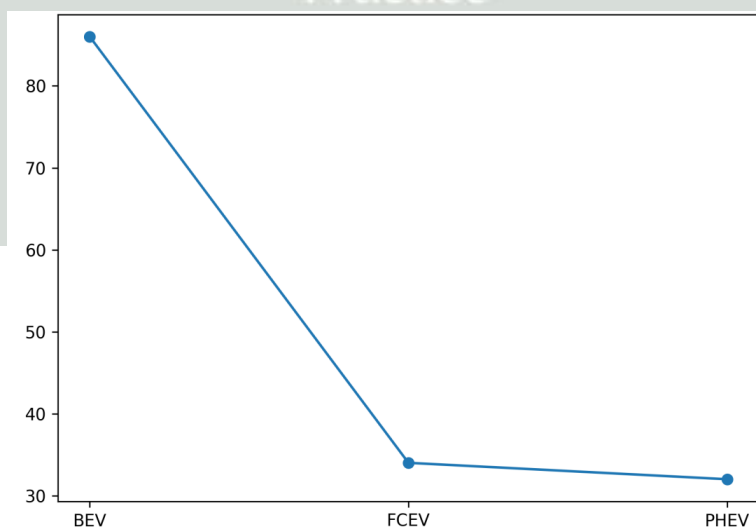


Figure 3. Driving range comparison among vehicle technologies.

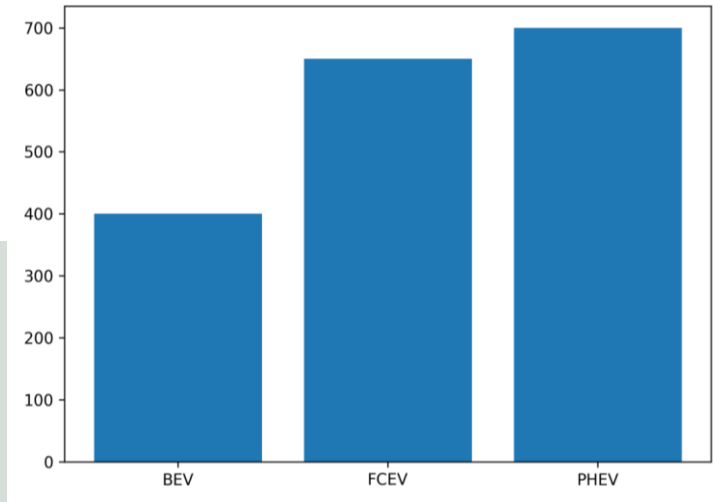


Figure 4. Global availability comparison of charging and hydrogen refueling infrastructure.

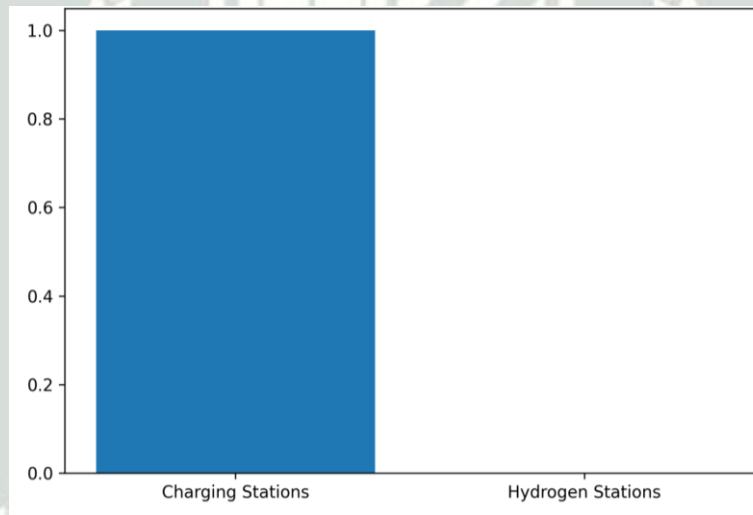


Figure 5. Carbon emission payback trajectory for battery electric vehicles.

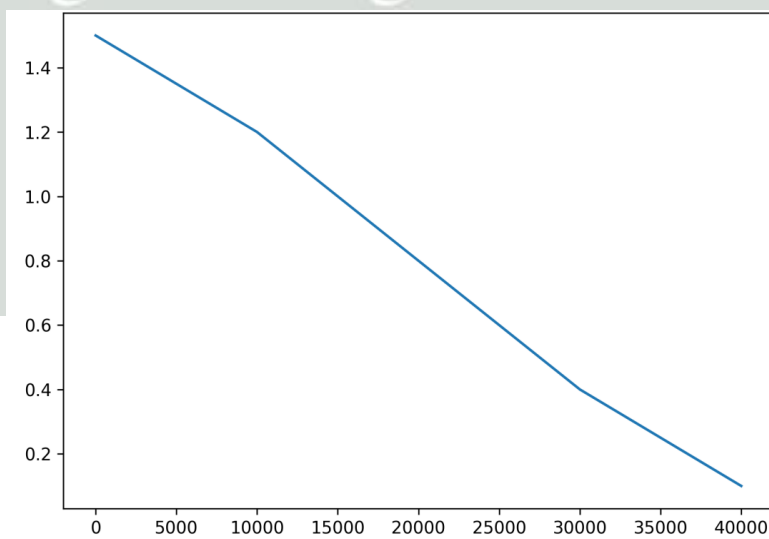


Figure 6. Distribution of total cost of ownership under sensitivity analysis.

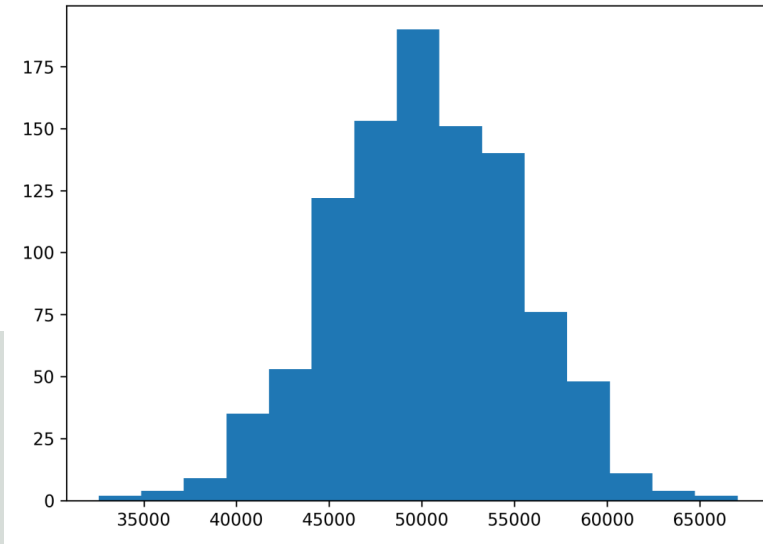


Figure 7. Relative critical material demand by vehicle powertrain.

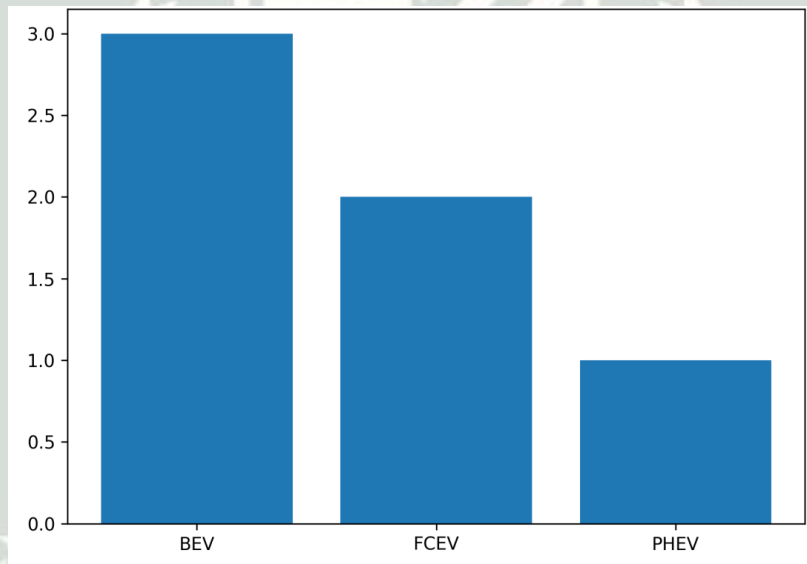


Figure 8. Projected market share growth of vehicle technologies over time.

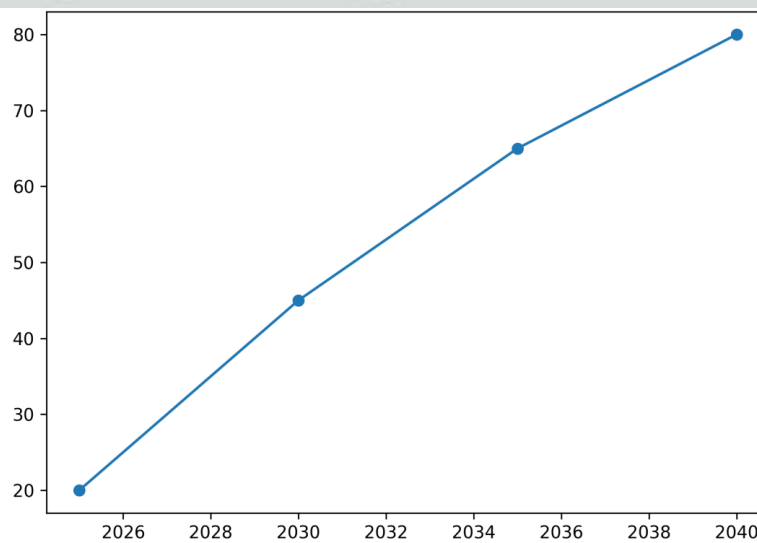


Figure 9. Relationship between total cost of ownership and WTW emissions.

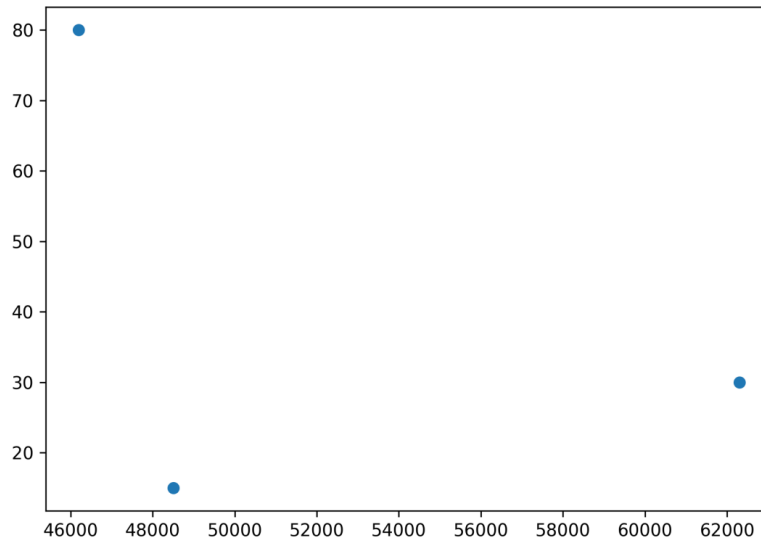
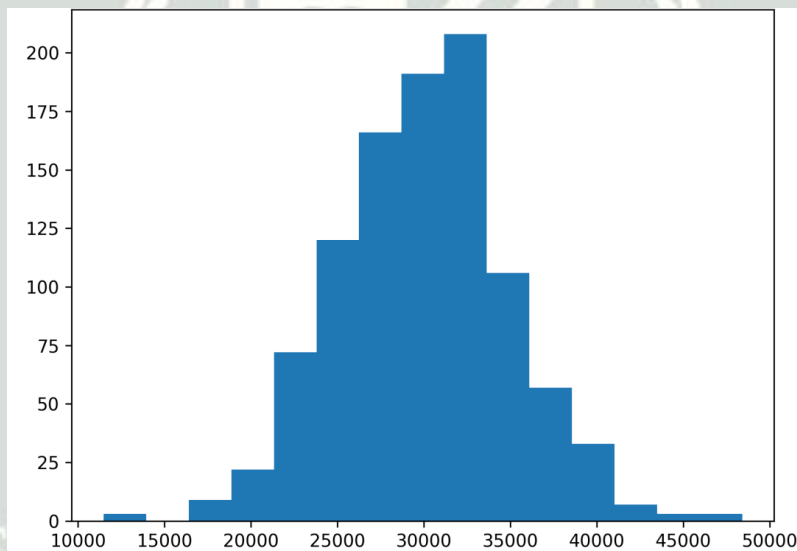


Figure 10. Distribution of emission payback distance for BEVs.



DISCUSSION

The results indicate that there is no one technology that can be regarded as better in all the facets of sustainability; choices deemed most advantageous will greatly be dependent on the context of energy and use. BEVs are the most efficient with minimal WTW emissions (Table 1, Fig. 2), which is also in accordance with the literature that considers electrification as the most important element of decarbonised transportation (IEA, 2021). Environmental advantage of BEVs is indissolubly connected with decarbonisation of the power sector because this advantage is reduced to minimum (and

even negative) in the grid which highly depends on coal (Hawkins et al., 2013). This creates a policy imperative of synergy: to optimise the benefit of BEVs, grid greening needs to be quicker.

FCEVs have high requirements on the infrastructure and TCO that are major obstacles to the adoption of mass-market passenger vehicles (Table 2, Table 5). As it is stated by Breyer et al. (2017), their range and refuelling time (Table 4) allow saying that they have a solid market niche in such industries as long-haul trucking, aviation, and maritime transportation, which are hard to electrify by using batteries. The results indicate that the price of green hydrogen is important in terms of FCEV competitiveness (Table

7). The new policy initiatives, including the hydrogen production tax credits of the U.S. Inflation Reduction Act, are precisely aimed at bridging this gap in price and promoting the necessary increase in the electrolysis capacity (IRENA, 2023).

As per this research, PHEVs have a diverse range of functions. Although they can now boast of a reduced TCO and a significant decrease in emissions that conventional cars emit, they have a combustion engine that restricts their sustainability. The behavior of the users- often plug-in, and use primarily electricity used in driving- has a large effect on their perfect real-life emissions (Sierzchula et al., 2014). PHEVs would be in danger of being reduced to a de facto gasoline vehicle and would then lose the majority of its benefits. Therefore, they best fit as a transitional solution in scenarios that the infrastructure to charge is in its infantile or some user population with highly diverse range needs.

One essential caution that is often ignored in the popular context is that there is a significant upstream environmental cost of BEV production, one of them being the battery (Table 6, Fig 5). To overcome the problem of resource depletion and environmental justice of mineral extraction, there is an urgent need to create a circular battery economy, with a high degree of recycling and second-life applications (Nordelof et al., 2014). Lessening platinum loadings and developing catalyst recycles are also key R&D challenges to the FCEVs.

The scenario modelling and composite index are the ones that support a portfolio approach well (Table 10, Fig 9). It is most likely that in the future of sustainable transportation, BEVs will take over the light-duty passenger segment, FCEVs will be used in heavy-duty and long-range transportation, and PHEVs will be used in a less significant, transitional

role. Thus, the policymakers need to invest selectively, technology-specific investments, which are hydrogen production, distribution, and retail in the case of FCEVs and ubiquitous smart charging in the case of BEVs, and at the same time implement technology-neutral, outcome-based regulations (the stringent WTW emission standards).

CONCLUSION

This comparative study demonstrates that the sustainable transport road is not a one-way street; it requires technological portfolio, which is strategically diversified, each element is designed to be used in specific applications and supported by the infrastructure and energy policies that are compatible. Battery electric vehicles (BEVs) are the most sustainable and energy-saving option in fast decarbonising electrical grid with regards to the majority of passenger and light-duty transportation. They are the best as their infrastructures are increasing and they have the cost competitiveness. Nonetheless, they need our additional solutions owing to their shortcomings in regards to battery resource strength, refuelling frequency, and boundaries.

Hydrogen fuel cell vehicles (FCEVs) mitigate these disadvantages, offering significant advantages to transportation segments of heavy-duty, long-range, and high-utilization applications in which the cost of charging downtime is financially infeasible. Their path to market is a more complex and policy-laden one, however, because their viability is entirely dependent upon the simultaneous building of a large, capital-intensive system of refuelling stations and a cost-competitive, green hydrogen economy.

Plug-in hybrid electric vehicles (PHEVs) play a useful and limited role as a transitional technology. They act as an intermediate as pure electric infrastructure is being extended out and provide an

immediate decrease in pollutants and fuel consumption and alleviate range anxiety. They ought to be regarded as a transitory running point than an endpoint due to their inappropriateness in the long-term.

Finally, sustainable transportation needs systemic integration to be a success. Success requires innovation in vehicles, but it also requires the ongoing decarbonisation of the electrical grid, the growth of green hydrogen generation, the introduction of intelligent infrastructure, and the design of circular supply chains of the key elements. In order to guide the global transport industry to a real low-carbon future, policymakers, industry leaders and researchers should collaborate in this multifaceted project that should be steered by life-cycle data and targeted sustainability objectives.

References

- Breyer, C., Khalili, S., & Bogdanov, D. (2017). Solar photovoltaic energy for sustainable transportation: A review. *Progress in Photovoltaics: Research and Applications*, 25(8), 727-745.
- Hawkins, T. R., Singh, B., Majeau-Bettez, G., & Strømman, A. H. (2013). Comparative environmental life cycle assessment of conventional and electric vehicles. *Journal of Industrial Ecology*, 17(1), 53-64.
- International Energy Agency (IEA). (2021). *Net Zero by 2050: A Roadmap for the Global Energy Sector*. IEA Publications.
- International Energy Agency (IEA). (2023). *Global EV Outlook 2023*. IEA Publications.
- International Renewable Energy Agency (IRENA). (2023). *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part II – Technology Review of Hydrogen Carriers*. IRENA.
- Nordelöf, A., Messagie, M., Tillman, A. M., Ljunggren Söderman, M., & Van Mierlo, J. (2014). Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? *The International Journal of Life Cycle Assessment*, 19(11), 1866-1890.
- Sierzchula, W., Bakker, S., Maat, K., & Van Wee, B. (2014). The influence of financial incentives and other socio-economic factors on electric vehicle adoption. *Energy Policy*, 68, 183-194.