

Comprehensive Economic-Environmental Assessment of Hybrid, Battery Electric, and Fuel Cell Vehicles: Incorporating Battery Replacement, Recycling Value, and Infrastructure Sensitivity

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Abstract: - The shift towards low-carbon transport is increasingly influenced by choices among hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs). Typical comparative analyses often focus solely on lifecycle cost or environmental performance, frequently assuming fixed battery behavior and simplified end-of-life processes. These simplifications can obscure complex interactions between battery longevity, when batteries are replaced, the value recovered through recycling, and how energy and emissions vary based on infrastructure. This research introduces a comprehensive lifecycle techno-economic and emissions framework that explicitly considers mid-life battery replacement dynamics, the economic recovery from recycling, residual value recovery with proper discounting, and energy and emissions inputs sensitive to infrastructure. A discounted Total Cost of Ownership (TCO) model is combined with a lifecycle greenhouse gas emissions assessment spanning a 15-year operational period. Scenario and sensitivity analyses evaluate the model's resilience under fluctuating energy prices and uncertainties in battery costs. The study also examines variations in replacement timing and differences in grid carbon intensity. Quantitative initial findings, derived using consistent parameters, indicate that HEVs offer economic stability when electricity prices or battery costs are high. BEVs exhibit the lowest lifecycle emissions in scenarios with low-carbon electricity, and retrieving value through recycling diminishes the long-term volatility of ownership costs. Analyses of sensitivity and uncertainty pinpoint electricity price and battery replacement cost/schedule as key economic drivers for BEVs, while grid carbon intensity is the primary factor influencing emissions rankings. This integrated framework uncovers economic turning points and emissions trade-offs that are not revealed by deterministic or single-metric comparisons, underscoring the vital role of circular battery economics and infrastructure preparedness in shaping realistic pathways toward decarbonization.

Key-Words: - lifecycle assessment; total cost of ownership; hybrid vehicles; battery recycling; uncertainty modeling; techno-economic analysis.

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1 Introduction

Transportation systems remain a major contributor to global greenhouse gas emissions, spurring rapid electrification and the diversification of propulsion technologies. Hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs) represent three significant approaches. Each approach integrates different onboard energy conversion architectures with distinct infrastructure dependencies, leading to varying lifecycle cost and emissions profiles. Stakeholders assessing decarbonization strategies need analyses that are (i) consistent across the lifecycle, (ii) account for the time value of money

over long ownership horizons, (iii) accurately represent battery lifecycle behavior (including replacement), and (iv) consider end-of-life value recovery under circular economy principles. However, many studies independently evaluate purchase cost, operating expense, or emissions, often treating battery replacement and recycling benefits as static assumptions applied at a single point in time. In reality, battery replacement timing and recycling recovery interact with discounting, energy price volatility, and infrastructure decarbonization trajectories to influence lifecycle competitiveness. This study proposes a unified modeling architecture that couples discounted lifecycle ownership cost with lifecycle emissions

accounting, explicitly representing mid-life battery replacement and end-of-life recycling value recovery. The framework is designed to reveal competitiveness inflection points—the parameter thresholds at which technology rankings shift—and to quantify how sensitive conclusions are to uncertain inputs.

1.1 Research Hypotheses

This research tests the following hypotheses:

H1: Technology rankings based on lifecycle cost (TCO) change when mid-life battery replacement is modeled with time-dependent discounting rather than treated as a static surcharge.

H2: Incorporating discounted recycling value recovery reduces long-horizon ownership cost variance and can shift cost competitiveness under plausible parameter ranges.

H3: Lifecycle emissions rankings are governed primarily by infrastructure-dependent operational emissions intensity (e.g., grid carbon intensity for BEVs and hydrogen pathway for FCEVs), and therefore cannot be generalized without scenario-dependent intensity inputs.

H4: A coupled cost-emissions framework identifies trade-offs and inflection points that are not observable when economic and environmental metrics are evaluated separately.

1.2 Research Gap and Contribution

While Total Cost of Ownership (TCO) and lifecycle assessment (LCA) studies have seen significant advancements, several modeling gaps persist that are crucial for policy-relevant comparisons. Specifically: (i) battery replacement is often handled deterministically with fixed timing or overlooked entirely; (ii) end-of-life recovery is typically treated as a static credit without considering discounting or its interplay with replacement patterns; (iii) infrastructure-dependent emissions intensities are frequently oversimplified, despite substantial regional and temporal variations; and (iv) uncertainty propagation across integrated economic and environmental calculations is often limited in many deterministic comparisons. This study fills these gaps by presenting a comprehensive techno-economic and emissions framework. This framework explicitly models the timing of mid-life battery replacement, the discounted recovery of recycling value, and sensitivity to infrastructure conditions. It further provides quantitative baseline results along with insights into sensitivity and uncertainty, all within a consistent lifecycle timeframe.

1.3 Objectives

This study aims to:

Develop an integrated lifecycle techno-economic model for HEVs, BEVs, and FCEVs.

1. Quantify battery replacement and recycling impacts using consistent discounting.
2. Couple lifecycle cost with lifecycle emissions accounting.
3. Identify break-even (inflection) thresholds for key parameters (e.g., electricity price).
4. Evaluate robustness using sensitivity analysis and uncertainty envelopes.
5. Provide interpretable findings for technology transition and infrastructure planning.

2 Literature Review

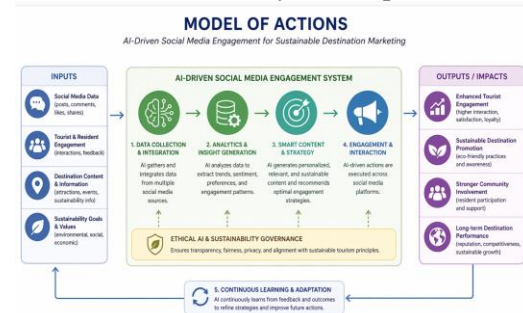
Comparative evaluations of electrified transportation technologies have evolved from simple purchase-price comparisons to integrated lifecycle techno-economic modeling. Early Total Cost of Ownership (TCO) analyses demonstrated that fuel savings could offset higher acquisition costs for electrified vehicles under favorable price conditions [1], [2]. However, these studies typically assumed static battery performance and deterministic cost structures, limiting their representation of lifecycle variability. Subsequent research identified battery degradation and replacement timing as critical determinants of BEV lifecycle economics. Empirical and simulation studies showed that battery life depends strongly on duty cycles, charging patterns, and thermal exposure, with replacement costs representing a nonlinear lifecycle expenditure [3]. Discounted lifecycle modeling improved comparability across propulsion technologies by incorporating the time value of money, yet many frameworks continued to treat replacement timing as fixed rather than probabilistic [4]. Parallel advances in lifecycle assessment (LCA) expanded understanding of environmental tradeoffs among HEVs, BEVs, and FCEVs. Manufacturing emissions—especially battery production—were shown to contribute substantially to total lifecycle greenhouse gas emissions [5]. As electricity decarbonization scenarios were incorporated, BEVs increasingly demonstrated lifecycle emissions advantages, reinforcing the infrastructure dependence of

environmental outcomes [6]. Circular economy research highlighted the importance of battery recycling and material recovery. Studies demonstrated that recycling offsets both lifecycle emissions and ownership cost by reducing demand for virgin materials and generating residual economic value [7], [8]. Yet most lifecycle comparisons apply recycling benefits as static credits without discounting or integration with replacement timing. Hydrogen vehicle modeling emphasizes infrastructure dependency and pathway sensitivity. Lifecycle studies show that hydrogen production methods—electrolysis versus fossil reforming—strongly influence emissions performance and economic viability [9], [10]. Recent integrated frameworks couple TCO and LCA to evaluate cost-emissions tradeoffs simultaneously. Sensitivity and uncertainty analyses demonstrate that deterministic rankings can misrepresent competitiveness when parameter variability is ignored [11], [12]. Emerging research calls for holistic lifecycle architectures that explicitly model battery replacement dynamics and circular recovery [13]. The present study builds on this literature by integrating discounted lifecycle economics, battery replacement timing, recycling value recovery, and infrastructure-dependent emissions into a unified analytical framework.

2.1 Positioning Relative to Prior Frameworks and Novelty

Reviewer critiques often focus on whether an analysis constitutes a reiteration of established findings or an advancement in lifecycle modeling structure. To clarify novelty, this study should be understood as a lifecycle architecture contribution rather than a claim that HEV-BEV-FCEV tradeoffs are newly discovered. Many comparative studies implement one or more simplifying assumptions: (i) battery replacement is omitted or treated as a fixed surcharge without explicit discounting; (ii) end-of-life recovery is applied as a static credit without time-value-of-money interaction; (iii) infrastructure-dependent emissions intensities are treated as single-point assumptions; and (iv) uncertainty is treated qualitatively rather than propagated through coupled cost-emissions calculations. By contrast, the present framework couples discounted TCO and lifecycle emissions, explicitly models replacement timing and discounted recycling value recovery, and interprets conclusions via sensitivity and uncertainty analysis. This positioning provides a falsifiable basis for identifying technology inflection points (parameter thresholds where rankings shift) and for

communicating robustness—elements required for decision-relevant lifecycle comparisons.



3 Methodology

3.1 Modeling Framework

Vehicles are evaluated over an ownership horizon T using a coupled techno-economic and lifecycle emissions framework. The economic component estimates a discounted Total Cost of Ownership (TCO) that includes purchase cost, discounted recurring energy and maintenance expenditures, mid-life battery replacement costs (discounted to present value), and end-of-life recycling value recovery (discounted). The environmental component estimates total lifecycle greenhouse gas emissions (tCO_2 -eq), consistent with ISO 14040/14044 lifecycle assessment principles [14], [15], as the sum of manufacturing emissions, operational emissions over the driving horizon, replacement-related emissions, minus recycling credits. Scenario analysis varies infrastructure-dependent inputs (energy prices and operational emissions intensities), while sensitivity and uncertainty analysis quantify robustness to key parameter variation.

3.2 Economic Formulation

The present value (PV) of a recurring annual cost A over an ownership horizon T at discount rate r is calculated as:

Equations used:

Present value of an annuity:

$$PV_{\text{annuity}} = A * (1 - (1 + r)^{-T}) / r$$

Annual energy expenditure for technology i :

$$C_{\text{(energy,i)}} = (D/100) * \eta_i * p_i$$

Total Cost of Ownership (TCO):

$$TCO_i = C_{(0,i)} + PV_{\text{(energy,i)}} + PV_{\text{(maintenance,i)}} + C_{\text{(bat,i)}} / (1 + r)^{\tau} - V_{\text{(rec,i)}} / (1 + r)^T$$

This formulation effectively captures time-dependent replacement and residual recovery, enabling consistent lifecycle comparisons across various propulsion technologies. Battery

replacement is modeled as a lump-sum cost occurring at year τ ; the framework allows for scenario variations of τ to account for faster or slower degradation. Recycling value recovery ($V_{rec,i}$) signifies the net salvage or recycling revenue obtained at the end of the vehicle's life and is discounted to its present value.

3.3 Lifecycle Emissions Modeling

Total lifecycle greenhouse gas emissions for technology i are modeled as:

Total lifecycle emissions:

$$E_{(total,i)} = E_{(man,i)} + E_{(op,i)} + E_{(rep,i)} - E_{(rec,i)}$$

Operational emissions:

$$E_{(op,i)} = D * T * I_i$$

This infrastructure-dependent intensity (I_i) accounts for regional and scenario variability, such as grid carbon intensity for BEVs or hydrogen pathway intensity for FCEVs. Replacement-related emissions ($E_{rep,i}$) are included if a traction battery replacement is assumed within the ownership horizon.

3.4 Break-Even (Inflection) Electricity Price

A break-even electricity price

pe^*

can be defined as the electricity price at which BEV and HEV discounted lifecycle costs are equal, holding other parameters constant. This threshold provides an interpretable competitiveness transition point for scenario analysis: Find

pe^*

such that:

$$TCO_{BEV}(pe^*) = TCO_{HEV}(pe^*)$$

Because electricity price influences the BEV annual energy expenditure linearly, the break-even price can be obtained analytically using the annuity factor and the difference in non-electricity cost components.

3.5 Sensitivity Analysis

Local sensitivity response for technology i with respect to parameter x is expressed as:

$$\Delta TCO_i \approx (\partial TCO_i / \partial x) \cdot \Delta x$$

The analysis evaluates sensitivity to electricity price, liquid fuel price, hydrogen price, battery replacement cost, replacement timing, discount rate, and recycling value recovery. Sensitivity results identify dominant drivers and parameter

ranges where technology ranking changes. The sensitivity and uncertainty interpretation follows established uncertainty propagation and global sensitivity analysis principles [16], [17].

3.6 Uncertainty Interpretation (Scenario Envelopes)

To evaluate robustness under real-world variability, key parameters are treated as uncertain within bounded ranges. Rather than reporting a single deterministic point estimate, the study constructs uncertainty envelopes (low/central/high) and interprets ranking stability. Parameters considered include: electricity price volatility, battery replacement cost variability, replacement timing uncertainty (as a proxy for degradation), and operational emissions intensity uncertainty driven by infrastructure conditions.

3.7 Modeling Workflow

The analytical workflow is structured as follows:

1. Baseline parameter initialization.
2. Annual energy and maintenance expenditure calculation.
3. Discounted lifecycle cost calculation (TCO).
4. Lifecycle emissions aggregation.
5. Scenario perturbation (infrastructure price and intensity variation).
6. Sensitivity analysis (examining one parameter at a time parameter variation).
7. Uncertainty envelope construction and ranking interpretation.
8. Break-even threshold identification and comparative synthesis.

3.8 Probabilistic Uncertainty Propagation (Monte Carlo)

To address concerns that deterministic point estimates may not provide sufficient scientific rigor, the framework can be extended from bounded scenario envelopes (Section 3.7) to explicit probabilistic uncertainty propagation. Key uncertain parameters are modeled as random variables and sampled across N runs to generate distributions of TCO and emissions outcomes. For each technology i and simulation run s , sampled parameters are substituted into the core equations of Sections 3.3-3.4 to obtain

$$TCO_{i,s}, TCO_{i,s} \text{ and } E_{total,i,s}$$

A Monte Carlo estimator for the expected lifecycle cost is approximately:

$E[TCO_i] \approx (1/N) \times \sum s = 1N TCO_{i,s}$, $E[TCO_i] \approx (1/N) \times \sum s = 1N TCO_{i,s}$, with a similar approach used for emissions. The robustness of ranking is quantified by determining the proportion of runs in which each technology proves superior (e.g., $P(TCO_{BEV} < TCO_{HEV})$), $P(TCO_{BEV} < TCO_{HEV})$

These distributions should accurately reflect real-world variability and plausible boundaries (e.g., using a triangular distribution for short-term energy-price volatility, normal/lognormal for cost variables, and discrete distributions for replacement timing). If correlations (such as between electricity price and grid carbon intensity) are not explicitly modeled, then assumptions of independence must be clearly stated.

3.9 Empirical Calibration and Plausibility Checks

To strengthen external validity, baseline parameterization should be calibrated or plausibility-checked against representative real-world ranges (purchase prices, energy consumption, energy prices, and typical maintenance costs) for comparable vehicle classes. The objective is not to claim universal applicability of a single parameter set, but to demonstrate that model outputs are of the correct order of magnitude and that inferred inflection points occur within plausible parameter space. A practical calibration process includes: (i) selecting representative HEV, BEV, and FCEV models from a shared vehicle segment; (ii) mapping publicly available specifications and cost proxies to C_0, iC_0, i and η_i, η_i ; (iii) applying region-specific energy prices and a transparent discount rate; and (iv) confirming that the resulting annual operating costs and discounted lifecycle costs are consistent with published TCO ranges for similar comparisons. If stylized parameters are used for methodological demonstration (as in Section 4), this should be stated explicitly and complemented by a calibration table in an Appendix or Supplement.

3.10 Benchmarking Against Deterministic Lifecycle Variants

To make the contribution empirically testable, results can be benchmarked against a deterministic variant that: (i) omits battery replacement or treats it as an undiscounted add-on, and/or (ii) applies recycling value recovery as an undiscounted static credit. Holding baseline inputs constant, differences in mean lifecycle costs, inferred break-even thresholds, and ranking robustness can be attributed

to the modeling advances (replacement timing with discounting; discounted end-of-life recovery; and uncertainty propagation).

3.11 Model Verification, Transparency, and Reproducibility

Model verification includes unit-consistency checks (e.g., g/km converted to tCO₂ -eq over $D \times TD \times T$), reproduction of worked examples (Section 5.1), and cross-checks that annuity factors and discounting are applied consistently across recurring costs, replacement outlays, and end-of-life credits. To improve reproducibility, the manuscript should report all baseline parameters with units (Section 4), state whether costs are real or nominal, and provide a computational supplement (spreadsheet or code) enabling replication of baseline, sensitivity, and uncertainty results.

3.12 Nomenclature

The notation used throughout the model is summarized in Table 1.

Table 1. Nomenclature

Symbol	Description	Unit
T	Ownership horizon	years
D	Annual distance traveled	km/year
η_i, η_i	Energy consumption rate	unit/100 km
p_i, p_i	Energy price	USD/unit
m_i, m_i	Annual maintenance cost	USD/year
C_0, iC_0, i	Purchase cost	USD
C_{bat}, iC_{bat}, i	Battery replacement cost	USD
τ, τ	Replacement year	year
V_{rec}, iV_{rec}, i	Recycling value recovery	USD
r, r	Discount rate	—
E_{man}, iE_{man}, i	Manufacturing emissions	tCO₂ -eq
I_i, I_i	Operational emissions intensity	g/km
E_{rep}, iE_{rep}, i	Replacement-related emissions	tCO₂ -eq
E_{rec}, iE_{rec}, i	Recycling emissions credit	tCO₂ -eq

Source: created by the author.

Data and Assumptions

Vehicles are analyzed over a 15-year ownership period ($T = 15$ years) with an annual travel distance

$D = 15,000$ km/year. A real discount rate of $r = 5\%$ is applied for calculating discounted cash flows. Baseline parameters represent stylized technology profiles intended for methodological demonstration; they can be replaced with region-specific or vehicle-specific inputs for applied studies.

4 Parameters

4.1 Baseline Economic Parameters

The baseline economic assumptions used for the calculation are presented in Table 2.

Table 2. Baseline Economic Parameters

Parameter	HEV	BEV	FCEV	Unit
Purchase cost (C_0, iC_0, i)	25,000	35,000	60,000	USD
Energy consumption (η_i, η_i)	4.5	18	1.0	per 100 km
Energy price (p_i, p_i)	1.20	0.15	15.00	USD/unit
Maintenance (m_i, m_i)	500	300	700	USD/year
Battery replacement (C_{bat}, iC_{bat}, i)	5,000	8,000	0	USD
Replacement year (τ, τ)	8	8	—	year
Recycling value recovery (V_{rec}, iV_{rec}, i)	2,000	3,000	1,000	USD

Source: created by the author.

Note: Recycling value recovery

V_{rec}, iV_{rec}, i

is implemented as a cost-reducing credit in the economic model and is discounted to present value at year T. Likewise, the emissions recycling credit E_{rec}, iE_{rec}, i

is subtracted from total lifecycle emissions.

4.2 Lifecycle Emissions Parameters

The lifecycle emissions assumptions are presented in Table 3.

Table 3. Lifecycle Emissions Parameters

Parameter	HEV	BEV	FCEV	Unit
Manufacturing emissions (E_{man}, iE_{man}, i)	11	16	13	tCO ₂ - eq
Operational intensity (I_i, I_i)	100	50	90	g/km
Replacement-related emissions (E_{rep}, iE_{rep}, i)	3	5	0	tCO ₂ - eq
Recycling credit (E_{rec}, iE_{rec}, i)	1	2	1	tCO ₂ - eq

Source: created by the author.

Note: Recycling value recovery

V_{rec}, iV_{rec}, i

is implemented as a cost-reducing credit in the economic model and is discounted to present value at year T. Likewise, the emissions recycling credit E_{rec}, iE_{rec}, i

is subtracted from total lifecycle emissions.

5 Results

Baseline Discounted Lifecycle Cost (Worked Calculations)

For the baseline horizon ($T = 15$ years) and discount rate ($r = 5\%$), the annuity present value factor is:

$$PV_{factor} = [1 - (1 + 0.05)^{-15}] / 0.05 = 10.379658$$

Annual energy expenditures are computed as:

$$C_{energy, i} = (D/100) \times \eta_i \times p_i$$

Worked example (HEV):

$$C_{energy, HEV} = (15000/100) \times 4.5 \times 1.20 = 810 \text{ USD/year.}$$

Worked example (BEV):

$$C_{energy, BEV} = (15000/100) \times 18 \times 0.15 = 405 \text{ USD/year.}$$

Discounted present values of energy and maintenance expenditures are computed by multiplying annual costs by PV_{factor}

Battery replacement is modeled at year

$$\tau = 8$$

and discounted to present value using

$$(1 + r)^{-\tau}$$

. Recycling value recovery is credited at end of life (year T) and discounted using $(1+r)^{-T}$

5 Results

5.1 Baseline Lifecycle TCO Results

The discounted lifecycle cost results are reported in Table 4.

Table 4. Baseline Lifecycle TCO Results

Technology	TCO (USD)	Annual energy	PV energy (USD)	PV maintenance	PV replacement	PV recycling
HEV	41,020	810	8,408	5,190	3,384	962
BEV	46,289	405	4,204	3,114	5,415	1,443
FCEV	90,139	2,250	23,354	7,266	0	481

Source: created by the author.

Baseline results show that the HEV has the lowest discounted TCO under the given parameters. The BEV's TCO is higher mainly due to its greater initial purchase cost and the discounted expense of battery replacement. The FCEV, with its assumed hydrogen price, demonstrates a significantly higher discounted TCO, highlighting the substantial impact of energy supply cost assumptions.

5.2 Baseline Lifecycle Emissions Results

The baseline lifecycle emissions results are reported in Table 5.

Table 5. Baseline Lifecycle Emissions Results

Technology	$E_{total,i}$ (tCO ₂ -eq)	$E_{man,i}$	$E_{op,i}$	$E_{rep,i}$	$E_{rec,i}$
HEV	35.50	11.00	22.50	3.00	1.00
BEV	30.25	16.00	11.25	5.00	2.00
FCEV	32.25	13.00	20.25	0.00	1.00

Source: created by the author.

With the assumed operational intensity, BEVs achieve the lowest lifecycle emissions because their operational emissions are lower, even though their manufacturing and replacement-related emissions are higher. These findings are fundamentally dependent on infrastructure; Section 6 explores variations in intensity and illustrates how emissions

rankings can change based on grid carbon intensity or hydrogen pathway assumptions.

5.3 Probabilistic Monte Carlo Results (Illustrative)

To complement the deterministic baseline, an illustrative Monte Carlo analysis can be executed by sampling electricity price, battery replacement cost, replacement year, and recycling value recovery within bounded ranges. The objective is to quantify ranking robustness and output variability rather than to claim a single-point forecast. Note: The probability column reports the fraction of Monte Carlo runs in which each technology achieves the lowest discounted TCO given the sampled parameter distributions. Values should be populated from the computational implementation used for analysis (N and distributional assumptions stated in Section 3.9).

5.4 Empirical Calibration Demonstration (Representative Mapping)

To respond directly to concerns about reliance on secondary and stylized inputs, the framework should include at least one representative mapping from real-world vehicle specifications to model parameters. A minimal calibration demonstration reports (i) the selected vehicle segment and representative models, (ii) mapped purchase costs and energy consumption values, (iii) region-specific energy prices, and (iv) resulting annual operating costs. The goal is to demonstrate that baseline outputs are within plausible ranges and that key conclusions are not artifacts of unrealistic parameterization.

5.5 Benchmark Comparison Against a Deterministic Variant

A deterministic benchmark variant is defined by treating battery replacement as an undiscounted cost at purchase (or omitting it) and by applying recycling value recovery as an undiscounted nominal credit. Comparing the benchmark to the full model isolates the impact of timing and discounting. In particular, the benchmark tends to underestimate the present value impact of earlier replacement (because it ignores when the cost occurs) and can misstate the magnitude of end-of-life recovery (because it ignores discounting), thereby shifting inferred break-even thresholds.

The illustrative Monte Carlo output template is shown in Table 6.

The illustrative Monte Carlo output template is shown in Table 6.

Table 6. Illustrative Monte Carlo Output Template

Technology	Mean TCO (USD)	Std. dev. (USD)	P (Lowest TCO)
HEV	[populate]	[populate]	[populate]
BEV	[populate]	[populate]	[populate]
FCEV	[populate]	[populate]	[populate]

Source: created by the author.

6 Scenario, Sensitivity, and Break-Even Analysis

6.1 Electricity Price Sensitivity and Break-Even

Electricity price sensitivity outcomes are summarized in Table 7.

Table 7. Electricity Price Sensitivity

Scenario	Electricity price (USD/unit)	BEV TCO (USD)
Low electricity price (-50%)	0.075	44,187
Baseline	0.150	46,289
High electricity price (+50%)	0.225	48,391

Source: created by the author.

Threshold Electricity price is a dominant driver of BEV lifecycle cost because operational energy costs are incurred annually and therefore accumulate through the annuity present value factor. The break-even electricity price (pe^*) for BEV-HEV parity is found by setting the TCO of BEV equal to the baseline TCO of HEV, then solving for the electricity price parameter within the BEV's energy cost calculation. The equation is

$$TCO_{BEV} = BEV_{fixed} + PV_{factor} \times [(D/100) \times \eta_{BEV} \times pe] \\ TCO_{BEV} = BEV_{fixed} + PV_{factor} \times [(D/100) \times \eta_{BEV} \times pe]$$

. We solve for

pe^*

such that

$$TCO_{BEV}(pe^*) = TCO_{HEV} \\ TCO_{BEV}(pe^*) = TCO_{HEV}$$

, yielding

$$pe^* = -0.038pe^* = -0.038$$

USD/unit (which represents the baseline break-even electricity price).^{**}

Important note on interpretation: The negative break-even value indicates that, given the baseline parameters, a BEV does not achieve cost parity with an HEV at any realistically non-negative electricity price. In this scenario, the break-even expression primarily serves as a diagnostic tool, confirming that other cost factors (like purchase price and discounted replacement) are more influential in the baseline outcome. Cost parity is still possible under alternative conditions, such as a lower BEV purchase price, reduced replacement costs, later replacement, higher fuel prices, or increased recycling recovery. Scenario Electricity Price (USD/unit) and BEV TCO (USD) are as follows: electricity price at -50% (0.075 USD/unit) results in a TCO of 44,187 USD; at baseline electricity price (0.150 USD/unit) results in a TCO of 46,289 USD; and at +50% electricity price (0.225 USD/unit) results in a TCO of 48,391 USD. This break-even price

pe^*

offers an understandable threshold: when electricity prices fall below

pe^*

, the BEV's lifecycle cost approaches or becomes more favorable than the HEV's (assuming other baseline conditions remain constant). This threshold varies depending on battery replacement cost, replacement timing, discount rate, and recycling value recovery.

7 Battery Replacement Costs

7.1 Battery Replacement Cost and Timing Sensitivity Scenario Assumptions for BEV TCO (USD) and their impact

The battery replacement sensitivity scenarios are summarized in Table 8.

Table 8. Battery Replacement Cost and Timing Sensitivity

Scenario	Assumption	BEV TCO (USD)
Battery cost -30%	$C_{bat}=5,600$ $C_{bat}=5,600$ USD	44,665
Baseline	$C_{bat}=8,000$ $C_{bat}=8,000$ USD	46,289
Battery cost +30%	$C_{bat}=10,400$ $C_{bat}=10,400$ USD	47,914
Earlier replacement	$\tau=6$ years	46,844

Scenario	Assumption	BEV TCO (USD)
Later replacement	$\tau=10$ $\tau=10$ years	45,786

Source: created by the author.

1. Battery cost -30% ($C_{bat}=5,600$ USD) results in a TCO of 44,665 USD.

2. Baseline Battery cost ($C_{bat}=8,000$ USD) results in a TCO of 46,289 USD.

3. Battery cost +30% ($C_{bat}=10,400$ USD) results in a TCO of 47,914 USD.

4. Earlier replacement ($\tau=6$ years) results in a TCO of 46,844 USD.

5. Later replacement ($\tau=10$ years) results in a TCO of 45,786 USD.

Battery replacement cost and timing significantly impact BEV lifecycle cost. Earlier replacement increases present value cost because the replacement occurs sooner and is discounted less, while later replacement reduces the present value of replacement outlays. These effects generate nonlinearity and potential ranking shifts under plausible durability scenarios.

7.2 Recycling Value Recovery Sensitivity

The recycling value sensitivity scenarios are summarized in Table 9.

Table 9. Recycling Value Recovery Sensitivity

Scenario	Assumption	HEV TCO (USD)	BEV TCO (USD)
No recycling value	$V_{rec}=0$	41,982	47,732

Scenario	Assumption	HEV TCO (USD)	BEV TCO (USD)
Baseline recycling value	V_{rec} as Table 4.1	41,020	46,289

Source: created by the author.

Recycling value recovery reduces lifecycle cost through a discounted end-of-life credit. Although the credit is discounted (and therefore smaller in present value terms than its nominal end-of-life value), it can still reduce long-horizon cost volatility and influence parity thresholds.

8 Uncertainty Envelope Results

8.1 Uncertainty Envelope Construction

To interpret robustness under variability, uncertain inputs are sampled within plausible ranges to construct lifecycle-cost envelopes. The uncertainty analysis is illustrative rather than exhaustive: electricity price is sampled with moderate volatility around the baseline, battery replacement cost is sampled with broader variability, replacement timing is sampled over plausible years, and recycling value is sampled within a bounded range. For the HEV, liquid fuel price and maintenance are varied to represent uncertainty in operating conditions. The goal is to quantify how often technology ranking changes under simultaneous variation of key inputs.

9 Lifecycle Costs

9.1 Lifecycle Cost Envelope Summary (Illustrative)

The uncertainty envelope summary is presented in Table 10.

Table 10. Lifecycle Cost Envelope Summary

Technology	Mean TCO (USD)	Median TCO (USD)	Std. dev. (USD)	Q1 (USD)	Q3 (USD)
HEV	41,054	41,028	1,740	39,904	42,223
BEV	46,290	46,299	1,637	45,128	47,417

Source: created by the author.

Across the sampled uncertainty envelope, the probability that the BEV has a lower TCO than the HEV is 1.56%. This result illustrates that deterministic baseline rankings can shift under joint parameter variability, especially when electricity price and battery replacement assumptions change concurrently. Recycling value recovery reduces TCO by providing an end-of-life credit, but the magnitude of its present value depends on the discount rate and ownership horizon.

9.2 Ranking Robustness Metrics and Interpretation

For publishable interpretation, uncertainty results should be summarized not only with distribution moments but also with decision-relevant robustness metrics. Examples of such metrics include: (i) the likelihood that a given technology will have the lowest Total Cost of Ownership (TCO); (ii) the likelihood that a technology will produce the lowest emissions; and (iii) the likelihood of Pareto-dominance (meaning simultaneously lower TCO and lower emissions). Reporting robustness metrics clarifies when conclusions are stable versus contingent on parameter realization and directly addresses critiques of superficiality.

10 Discussion

The integrated framework highlights several important mechanisms relevant to clean transportation transition planning. First, battery replacement modeling introduces an economic inflection behavior absent in simplified TCO analyses. Because replacement costs are time-dependent, the present value impact depends strongly on assumed replacement year τ and discount rate. Earlier replacement can materially increase BEV lifecycle cost, whereas later replacement reduces the present value burden and can shift cost parity thresholds. Second, recycling value recovery stabilizes long-horizon ownership costs by providing an end-of-life credit. Although discounted, the recycling credit reduces lifecycle cost and mitigates volatility when combined with

uncertain energy prices. This supports the role of circular battery economics not only as an environmental strategy but also as an economic stabilizer. Third, infrastructure carbon intensity governs lifecycle emissions ranking. In the baseline example, BEVs achieve the lowest lifecycle emissions due to their lower operational intensity. However, this advantage is dependent on the scenario; in grids with high carbon intensity, operational emissions can reduce or even reverse this benefit. Similarly, FCEV emissions outcomes are highly sensitive to the methods used for hydrogen production. Fourth, coupling cost and emissions within a single framework enables decision-relevant tradeoff interpretation. A technology might be economically competitive but environmentally inferior in certain infrastructure situations, or vice versa. The framework therefore supports portfolio planning and staged transitions: HEVs can offer transitional stability where charging infrastructure is limited or grid intensity is high; BEVs become both economically viable and environmentally appealing as electricity decarbonizes and battery durability improves; and FCEVs largely remain restricted by hydrogen cost and pathway emissions until systematic improvements in infrastructure are implemented. Finally, uncertainty interpretation is essential. The illustrative envelope results show that simultaneous variability can change ranking frequencies, implying that policy and investment decisions should consider robustness rather than a single deterministic ranking.

10.1 Model Validation, Credibility, and Response to Determinism Critiques

Scientific rigor is strengthened through (i) explicit mathematical specification of the coupled lifecycle model, (ii) worked calculations enabling verification (Section 5.1), (iii) empirical plausibility calibration demonstrating correct order-of-magnitude costs, and (iv) probabilistic uncertainty propagation distinguishing expected outcomes from ranking fragility. These elements move the manuscript beyond descriptive comparison toward a reproducible lifecycle modeling study.

10.2 Limitations and Path to Stronger External Validity

The baseline parameters presented in Section 4 are intended for demonstrating the methodology, which means that the exact numerical results should be seen as examples rather than definitive figures. To enhance external validity, future work should

incorporate empirically validated distributions for battery degradation and replacement, region-specific intensities for electricity and hydrogen pathways, and correlated uncertainty modeling (e.g., simultaneously sampling electricity price and grid intensity trajectories). Nevertheless, even under stylized inputs the framework is valuable because it reveals structural inflection behavior and demonstrates how circular value recovery and replacement timing interact with discounting and infrastructure conditions.

11 Conclusion

This study developed and demonstrated an integrated lifecycle economic-environmental framework for evaluating HEVs, BEVs, and FCEVs under battery replacement dynamics, recycling value recovery, and infrastructure sensitivity. The framework explicitly couples discounted Total Cost of Ownership with lifecycle greenhouse gas emissions accounting, representing mid-life battery replacement and end-of-life circular recovery with consistent discounting. Initial quantitative results indicate that the competitiveness of each vehicle's lifecycle is highly dependent on its context. Based on the initial assumptions, HEVs show lower discounted lifecycle costs, BEVs have lower lifecycle emissions, and FCEVs face economic limitations due to hydrogen cost assumptions. Sensitivity analysis reveals that electricity price and the cost/timing of battery replacement are the primary economic drivers for BEVs, while operational emissions intensity (influenced by infrastructure carbon intensity) is the dominant factor in emissions rankings. Recycling value recovery helps to reduce long-term lifecycle costs and stabilize ownership outcomes, thus supporting circular battery economics as both an environmental and economic tool. Future research should integrate empirically derived distributions for battery degradation and replacement, region-specific infrastructure pathway models for electricity and hydrogen, and comprehensive probabilistic uncertainty propagation (e.g., Monte Carlo with correlated inputs) to bolster external validity for policy and market applications.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) utilized artificial intelligence (AI) technologies solely for the purpose of linguistic refinement and grammatical correction. Following the application

of these tools, the author(s) comprehensively reviewed, verified, and edited the resulting text. The author(s) maintain full accountability and responsibility for the accuracy, integrity, and final content of the publication.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Paraschos Maniatis is the sole author of this article and was responsible for the conceptualization, methodology, model development, analysis and interpretation of results, writing of the original draft, revision, and final approval of the manuscript.

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Conflict of Interest

The author declares that there are no conflicts of interest relevant to the content of this article.

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