

Techno-Economic and Lifecycle Comparative Analysis of Strong Hybrid Electric Vehicles (SHEVs) and Battery Electric Vehicles (BEVs) in Emerging Automotive Markets

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Abstract

The transition toward sustainable passenger mobility in emerging markets has created a sharp technological and economic divide between Strong Hybrid Electric Vehicles (SHEVs)—specifically Series-Parallel power-split architectures—and Battery Electric Vehicles (BEVs). While BEVs eliminate tailpipe emissions and offer low per-kilometer energy costs, widespread adoption remains constrained by high upfront battery capital costs, steep commercial fast-charging tariffs, secondary-market depreciation, and coal-heavy electricity grids. Conversely, SHEVs pair Atkinson-cycle internal combustion engines with self-charging electric drivetrains to achieve brake thermal efficiencies exceeding 40% and real-world fuel economies of 23 to 28 km/l without relying on external charging infrastructure. This study presents an integrated thermodynamic, techno-economic, and environmental comparison of SHEVs, BEVs, and baseline Internal Combustion Engine Vehicles (ICEVs) in the Indian mid-size passenger segment. Using both nominal cash-flow accounting and a discounted Net Present Value (NPV) Total Cost of Ownership (TCO) framework across an 8-year horizon alongside a Cradle-to-Grave Life Cycle Assessment (LCA), we evaluate break-even distances, fiscal taxation asymmetries, electrochemical battery degradation mechanisms, and Well-to-Wheel (WTW) greenhouse gas (GHG) emissions. Results indicate that under mixed charging conditions, an average user must accumulate approximately 77,000 to 80,000 km (nominal) or 88,000 to 96,000 km (discounted at 6%) for a BEV to outperform a Strong Hybrid financially, while coal-dominated grids (710 gCO₂ eq/kWh) currently give SHEVs a marginal lifecycle carbon advantage (157.2 vs. 179.0 gCO₂ eq/km) until renewable grid penetration expands.

Keywords — Strong Hybrid Electric Vehicle (SHEV); Battery Electric Vehicle (BEV); Total Cost of Ownership (TCO); Atkinson Cycle; Life Cycle Assessment (LCA); Lithium Iron Phosphate (LFP); Power-Split e-CVT.

1. Introduction: The Powertrain Trilemma

The global automotive sector is undergoing a structural transformation driven by tightening Corporate Average Fuel Economy (CAFE) regulations, volatile crude oil prices, and national net-zero commitments. In emerging automotive markets—most notably India, Southeast Asia, and Latin America—both consumers and industrial policymakers confront a persistent powertrain trilemma: balancing upfront purchase affordability, operational energy costs, and public charging infrastructure readiness.

Historically, buyers in high-utilization segments selected between spark-ignition (petrol) and compression-ignition (diesel) Internal Combustion Engine Vehicles (ICEVs). Following the implementation of stringent real-driving emission norms (such as Bharat Stage VI Phase II in India and Euro 6e in Europe), small-displacement diesel powertrains have become increasingly unviable in compact and mid-size passenger cars due to the capital cost and regeneration complexity of Selective Catalytic Reduction (SCR), Lean NO_x Traps (LNT), and Diesel Particulate Filters (DPF). Into this market gap, two electrified architectures have emerged as primary contenders in the mid-size utility segment (₹15 Lakh to ₹25 Lakh, or approximately USD 18,000 to USD 30,000):

1. **Strong Hybrid Electric Vehicles (SHEVs):** Also termed Full Hybrids, these powertrains combine a dedicated high-expansion internal combustion engine with one or two electric motor-generators and a compact high-voltage traction battery (0.7 to 1.5 kWh). Unlike 48V Mild Hybrids (MHEVs)—which use a belt-integrated starter generator (BISG) solely for idle start-stop and minor torque assist—Strong

Hybrids can propel the vehicle on pure electric power at low-to-moderate speeds and decouple engine speed from wheel speed.

2. **Battery Electric Vehicles (BEVs):** All-electric architectures that dispense with the internal combustion engine and multi-speed mechanical transmission altogether, relying on large traction battery packs (30 to 65 kWh) and permanent magnet synchronous motors (PMSM) replenished via external grid connections.

While public discourse frequently treats BEVs as the default economic winner due to low domestic electricity tariffs, empirical Total Cost of Ownership (TCO) modeling reveals a more complex picture. Fiscal tax structures, the opportunity cost of tied-up capital, aerodynamic drag penalties at highway speeds, commercial DC fast-charging rates, and secondary-market resale risk all influence which powertrain delivers the lowest net cost to the consumer.

2. Powertrain Architectures and Thermodynamic Efficiency

To understand why Strong Hybrids and BEVs display contrasting efficiency profiles across urban and highway driving cycles, it is necessary to examine their fundamental energy conversion physics.

2.1 Conventional ICEV Baseline (Otto Cycle Constraints)

Conventional naturally aspirated and downsized turbocharged petrol engines operate on the four-stroke Otto cycle. For an ideal air-standard Otto cycle, thermal efficiency ($\eta_{th, Otto}$) is a function of the geometric compression ratio (r) and the ratio of specific heats ($\gamma = C_p/C_v \approx 1.35$ for air-fuel mixtures):

$$\eta_{th, Otto} = 1 - \frac{1}{r^{\gamma-1}}$$

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In commercial spark-ignition engines operating on 91–95 RON petrol, r is mechanically limited to 9.5:1 to 10.5:1 to prevent end-gas auto-ignition (engine knock). More critically, conventional petrol engines suffer heavy pumping losses (throttling losses across the intake butterfly valve) when operating at part load in urban traffic, alongside mechanical friction and exhaust enthalpy rejection. Consequently, while peak brake thermal efficiency (BTE) reaches 32% to 35% near wide-open throttle, real-world BTE averages 25% to 30% during highway cruising and falls below 15% in congested stop-and-go city driving, yielding on-road fuel economy of 10 to 14 km/l.

2.2 Strong Hybrid Architecture (Atkinson Cycle and Power-Split e-CVT)

Strong Hybrids—such as Toyota's Hybrid Synergy Drive (co-deployed with Suzuki in emerging markets) and Honda's e:HEV series-parallel system—overcome Otto-cycle part-load penalties by adopting the Atkinson cycle (implemented mechanically via late intake valve closing, often termed the Atkinson-Miller cycle).

In an Atkinson-cycle engine, the intake valve remains open during the initial 55° to 78° of crank angle after Bottom Dead Center (BDC) on the upward compression stroke. A portion of the inducted air charge is pushed back into the intake manifold before compression begins. This decouples the effective compression ratio (r_c , typically 9.5:1 to 10.5:1 to avoid knock) from the geometric expansion ratio (r_e , extended to 13.0:1 to 14.0:1). Defining the expansion-to-compression ratio as $\alpha = r_e/r_c$ (where r_e is greater than r_c), the ideal thermodynamic efficiency of the Atkinson cycle is given by:

$$\eta_{th, Atkinson} = 1 - \frac{1}{r_c^{\gamma-1}} \left[\frac{\alpha^\gamma - 1}{\gamma(\alpha - 1)} \right]$$

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Because the power expansion stroke is substantially longer than the effective compression stroke (α greater than 1), the piston extracts significantly more mechanical work from the expanding combustion gases before exhaust valve opening, while late intake valve closing virtually eliminates intake throttling losses. Together with cooled Exhaust Gas Recirculation (EGR) and high-tumble intake ports, this elevates peak brake thermal efficiency to 40% to 41%.

The primary trade-off of the over-expanded Atkinson cycle is reduced specific torque and sluggish transient response at low engine speeds. Strong Hybrids compensate for this by pairing the engine with an dedicated electric transaxle—typically a planetary Power-Split Device (e-CVT) or a dual-motor clutch-coupled transmission:

- **Motor Generator 1 (MG₁):** Connected to the sun gear of the planetary set; it starts the internal combustion engine, regulates engine RPM along the minimum Brake Specific Fuel Consumption (BSFC) operating line, and generates high-voltage AC power.
- **Motor Generator 2 (MG₂):** Connected to the ring gear and final drive; it serves as the primary traction motor delivering instantaneous low-end torque (140 to 250 Nm from 0 RPM) and functions as a generator during deceleration to capture kinetic energy via regenerative braking.

In congested urban traffic, the combustion engine remains shut off for 40% to 60% of total trip time. When the lithium-ion battery State of Charge (SoC) drops below approximately 35%, the engine starts smoothly via MG₁ and operates within its narrow high-efficiency BSFC island (2,000 to 3,200 RPM), splitting mechanical torque between the wheels and MG₁ to recharge the battery. This load-leveling synergy allows a mid-size Strong Hybrid SUV to achieve 24 to 28 km/lin urban traffic and 21 to 23 km/lon open highways.

2.3 Battery Electric Vehicle (BEV) Drivetrain Dynamics

A BEV replaces thermo-mechanical combustion with a direct electrochemical-to-electromagnetic conversion pathway. Direct Current (DC) drawn from the traction battery pack passes through a Silicon Carbide (SiC) or Insulated-Gate Bipolar Transistor (IGBT) three-phase inverter, exciting a Permanent Magnet Synchronous Motor (PMSM) coupled to the wheels via a single-speed helical reduction gearbox.

The resulting Tank-to-Wheel (TTW) energy conversion chain is highly efficient:

- Lithium-ion discharge coulombic/voltaic efficiency: ~ 95%
- Inverter and high-voltage power electronics efficiency: ~ 96%
- PMSM electromagnetic efficiency: ~ 90% to 94%
- Single-speed mechanical reduction gear efficiency: ~ 97%

Taking the product of these stages yields a combined Tank-to-Wheel efficiency of 80% to 85%—roughly double the peak efficiency of a Strong Hybrid and nearly triple that of a conventional ICEV. Moreover, bidirectional inverter control recovers 60% to 70% of vehicle kinetic energy during urban deceleration events.

However, BEVs exhibit an inverted speed-efficiency curve relative to combustion vehicles. They achieve peak efficiency in low-speed urban traffic (110 to 130 Wh/km, or 7.5 to 9.0 km/kWh) and suffer their highest energy consumption during sustained highway cruising (160 to 200 Wh/km, or 5.0 to 6.2 km/kWh). Because aerodynamic drag force scales with the square of velocity ($F_d = \frac{1}{2}\rho v^2 C_d A$) and the power required to overcome drag scales with the cube of velocity ($P_d = \frac{1}{2}\rho v^3 C_d A$), increasing cruising speed from 60 km/h to 110 km/h increases aerodynamic power draw more than sixfold while offering negligible opportunities for regenerative braking. Furthermore, because a BEV lacks a single-speed overdrive gear and generates no waste engine heat, cabin air conditioning (in tropical summers) or resistive/PTC cabin heating directly draws 1.5 to 3.0 kW from the traction battery.

Technical Parameter	Conventional Petrol (ICEV)	Mild Hybrid (48V MHEV)	Strong Hybrid (SHEV)	Battery Electric (BEV)
Propulsion / Thermodynamic Cycle	Otto Cycle (Spark Ignition)	Otto Cycle + BISG Assist	Atkinson / Miller Cycle + Dual Motor	Pure Electrochemical + PMSM

Peak Tank-to-Wheel Efficiency	25% – 30%	27% – 32%	40% – 41%	80% – 85%
Battery Capacity & Chemistry	12V Lead-Acid(~ 0.6 kWh)	48V Li-ion(0.4 – 0.8 kWh)	177V – 250V Li-ion/NiMH(0.8 – 1.5 kWh)	300V – 400V LFP/NMC(35 – 65 kWh)
Pure Electric Driving Share	0%	0%(Torque assist only)	40% – 60%of urban duration	100%
Urban Efficiency (City Cycle)	10 – 12 km/l	12 – 14 km/l	25 – 28 km/l	7.5 – 9.0 km/kWh
Highway Efficiency (100 km/h)	15 – 17 km/l	16 – 18 km/l	21 – 23 km/l	5.2 – 6.5 km/kWh
External Charging Infrastructure	None	None	None (Self-charging)	Required (AC Home / DC Fast)

3. Fiscal Policy, Taxation Asymmetries, and Capital Expenditure (CapEx)

Government fiscal policy plays a decisive role in shaping the competitive balance between Strong Hybrids and BEVs. Across emerging markets—and with particular intensity in India—indirect tax frameworks create a stark wedge between self-charging hybrids and plug-in electric vehicles.

Under India's Goods and Services Tax (GST) regime, Battery Electric Vehicles qualify for a concessional GST rate of 5%with zero compensation cess, complemented by full or partial waivers of state Road Tax (RTO registration charges) across major states. By contrast, mid-size Strong Hybrid SUVs (exceeding 4,000 mm in length) are taxed at 43%(28% base GST plus 15%compensation cess)—identical to non-hybrid luxury SUVs—and typically incur full state road taxes of 10% to 18%(save for occasional temporary waivers in select states).

Remarkably, despite this 38-percentage-point central tax penalty, the retail on-road price of a mid-size Strong Hybrid SUV closely matches that of an equivalent mid-size BEV. This parity exists because a Strong Hybrid requires a high-power traction battery of only 0.8 to 1.1 kWh(costing roughly USD 180 to USD 250 at the pack level), whereas a mid-size BEV requires a 45 to 60 kWhpack costing USD 5,000 to USD 7,500 at current cell prices (105 to 125 USD/kWh).

To establish a consistent baseline, Table 2 models three directly comparable C-segment SUVs representative of the Indian market (modeled on equivalents such as the Maruti Suzuki Grand Vitara / Toyota Urban Cruiser Hyryder 1.5L AT vs. Strong Hybrid e-CVT, and the Tata Curvv EV / MG Windsor EV / Hyundai Creta EV 50 kWh class):

Cost Component	Baseline ICEV (1.5L Petrol AT)	Strong Hybrid (1.5L e-CVT)	Battery Electric (50 kWh LFP BEV)
Ex-Showroom Price (Incl. GST)	₹15,00,000	₹18,50,000	₹19,50,000
Embedded GST + Cess Rate	43%(28% + 15%)	43%(28% + 15%)	5%(Concessional EV Rate)
Implied Pre-Tax Factory Price	₹10,48,951	₹12,93,706	₹18,57,143
RTO / Registration Tax (Avg. 10% vs. Waiver)	₹1,50,000	₹1,85,000	₹20,000 (Registration fee only)
Comprehensive Insurance (Year 1)	₹55,000	₹68,000	₹75,000
Home Charger Installation & Sanctioned Load Upgrade	₹0	₹0	₹25,000 (7.2 kW AC Wallbox)
Total Initial On-Road Outlay (I_0)	₹17,05,000	₹21,03,000	₹20,70,000

As the pre-tax row reveals, the BEV is ₹5.63 Lakh more expensive to manufacture at the factory gate than the Strong Hybrid (₹18.57 Lakh vs. ₹12.94 Lakh). However, tax concessions absorb the entire battery hardware cost differential, placing the Strong Hybrid (₹21.03 Lakh) and the 50 kWh BEV (₹20.70 Lakh) at virtually identical initial on-road prices—each carrying an upfront capital premium of ₹3.65 Lakh to ₹3.98 Lakh over the conventional automatic petrol SUV (₹17.05 Lakh).

4. Operational Expenditure (OpEx) and Real-World Running Cost Dynamics

Although initial capital outlay between an SHEV and a BEV is nearly identical in tax-subsidized markets, their operational expenditure (OpEx) trajectories diverge sharply depending on charging access and maintenance requirements.

4.1 Energy and Fuel Cost per Kilometer (C_{km})

The per-kilometer energy cost for a liquid-fueled combustion/hybrid vehicle ($C_{km, fuel}$) and a grid-charged electric vehicle ($C_{km, elec}$) are expressed as:

$$C_{km, fuel} = \frac{P_{petrol}}{\eta_{real-world}} \text{ and } C_{km, elec} = \frac{T_{grid}}{\eta_{ev} \cdot \eta_{charger}}$$

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where P_{petrol} is the retail petrol price (modeled at ₹100.00/liter), $\eta_{real-world}$ is blended on-road fuel economy (km/l), T_{grid} is the billed electricity tariff (₹/kWh), η_{ev} is vehicle drivetrain efficiency (km/kWh), and $\eta_{charger}$ captures AC-to-DC onboard rectifier and battery thermal management losses (typically 0.88 for AC wallbox charging and 0.92 for direct DC fast charging, meaning a 50 kWh pack draws roughly 56.8 kWh from an AC meter for a full cycle).

Evaluating four real-world operational regimes yields:

- **Baseline Petrol ICEV:** Averaging 12.5 km/l blended (11 km/l urban, 16 km/l highway) at ₹100/liter:

$$C_{km, ICEV} = \frac{100.00}{12.5} = ₹8.00 / km$$

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- **Strong Hybrid (SHEV):** Averaging 24.0 km/l blended (26 km/l urban, 21 km/l highway) at ₹100/liter:

$$C_{km, SHEV} = \frac{100.00}{24.0} = ₹4.17 / km$$

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- **BEV Profile A (100% Domestic Home AC Charging):** Charged overnight at a residential tariff of ₹7.50/kWh, urban-weighted vehicle efficiency of 7.0 km/kWh, and AC charging efficiency of 0.88:

$$C_{km, BEV-Home} = \frac{7.50}{7.0 \times 0.88} = ₹1.22 / km$$

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- **BEV Profile B (Commuter Mix — 82% Home AC / 18% Public DC Fast Charging):** Typical of an average commuter who charges at home during the workweek and uses commercial DC chargers (₹22.00/kWh inclusive of 18% GST) on occasional weekend intercity trips (blended tariff ₹10.11/kWh, blended efficiency 6.88 km/kWh, $\eta_{charger} = 0.89$):

$$C_{\text{km, BEV-Commuter}} = \frac{10.11}{6.88 \times 0.89} = ₹1.65 / \text{km}$$

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- **BEV Profile C (Highway-Heavy Mix — 70% Home AC / 30% Public DC Fast Charging):** Typical of high-mileage regional users at a blended tariff of ₹11.85/kWh, highway-weighted efficiency of 6.3 km/kWh, and $\eta_{\text{charger}} = 0.90$:

$$C_{\text{km, BEV-Highway}} = \frac{11.85}{6.3 \times 0.90} = ₹2.09 / \text{km}$$

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- **BEV Profile D (100% Commercial / Public DC Charging):** Representative of apartment dwellers without dedicated metered parking relying entirely on public fast chargers at ₹22.00/kWh ($\eta_{\text{ev}} = 6.3 \text{ km/kWh}$, $\eta_{\text{charger}} = 0.92$):

$$C_{\text{km, BEV-Public}} = \frac{22.00}{6.3 \times 0.92} = ₹3.80 / \text{km}$$

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Key Operational Insight: When a BEV owner lacks access to residential AC charging and relies exclusively on commercial DC fast chargers (₹3.80/km), the running cost advantage over a Strong Hybrid (₹4.17/km) shrinks to just ₹0.37/km—insufficient to offset the BEV's higher insurance and depreciation costs, while introducing charging dwell times and accelerated thermal cell wear.

4.2 Scheduled Maintenance, Tire Wear, and Insurance

- **Scheduled Maintenance (M_t):** A BEV eliminates engine oil, oil filters, spark plugs, accessory drive belts, and complex multi-gear transmission fluids, reducing routine service expenses to cabin filters, brake fluid flushes, and coolant replacement (averaging ₹0.30/km). Strong Hybrids still require periodic engine oil and filter changes, but because the combustion engine operates 40% to 50% fewer hours than a conventional ICEV and regenerative braking extends friction brake pad life beyond 80,000 km, SHEV maintenance averages ₹0.50/km compared to ₹0.60/km for a conventional automatic ICEV.
- **Tire Replacement Asymmetry:** Due to a 350 to 420 kg LFP battery pack, a mid-size BEV weighs 200 to 300 kg more at the curb than an equivalent ICEV or SHEV and delivers instantaneous peak torque from standstill. Fleet telemetry indicates BEV tires wear 20% to 25% faster (requiring replacement every 38,000 km vs. 50,000 km for ICEV/SHEV), adding approximately ₹0.15 to ₹0.25/km to total BEV running maintenance (bringing combined maintenance plus tires to ₹0.75/km for ICEV, ₹0.65/km for SHEV, and ₹0.45–₹0.55/km for BEV across usage tiers).
- **Insurance Renewals (I_{ins}):** Because motor insurance Insured Declared Value (IDV) is indexed to the higher ex-showroom price (₹19.50 Lakh for the BEV vs. ₹15.00 Lakh for the ICEV) and underbody battery damage claims carry higher actuarial severity, cumulative 8-year insurance premiums for BEVs run roughly 10% higher than Strong Hybrids and 30% higher than baseline ICEVs.

5. Mathematical Total Cost of Ownership (TCO) Model and Break-Even Analysis

To evaluate long-term ownership economics rigorously, we apply the discounted Net Present Value (NPV) Total Cost of Ownership formulation established by Palmer et al. (2018) and extended by Buberger et al. (2026):

$$TCO_{NPV} = I_0 + \sum_{t=1}^N \frac{(D_t \cdot C_{km,t}) + M_t + I_{ins,t}}{(1+r)^t} - \frac{RV_N}{(1+r)^N}$$

$$TCO_{NPV} = I_0 + \sum_{t=1}^N \frac{(D_t \cdot C_{km,t}) + M_t + I_{ins,t}}{(1+r)^t} - \frac{RV_N}{(1+r)^N}$$

where:

- I_0 = Initial on-road capital outlay at $t = 0$
- N = Ownership evaluation horizon (8 years, aligned with industry-standard high-voltage battery warranty terms)
- D_t = Annual distance driven in year t (km/year, assumed constant across $t = 1 \dots 8$)
- $C_{km,t}$ = Per-kilometer energy or fuel cost in year t
- M_t = Annual scheduled maintenance and amortized tire replacement expenditure in year t
- $I_{ins,t}$ = Annual insurance renewal and statutory fee in year t
- r = Real discount rate representing the opportunity cost of capital net of inflation ($r = 6.0\%$, compared against nominal undiscounted cash flows where $r = 0\%$)
- RV_N = Residual resale value captured at the end of year N

For constant annual cash flows over $N = 8$ years at $r = 6.0\%$, the Present Value Interest Factor of an Annuity ($PVIFA_{6\%,8}$) and the single-sum Present Value Discount Factor ($PVDF_{6\%,8}$) are:

$$PVIFA_{6\%,8} = \frac{1 - (1 + 0.06)^{-8}}{0.06} = 6.2098 \text{ and } PVDF_{6\%,8} = (1 + 0.06)^{-8} = 0.6274$$

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5.1 Residual Value (RV_8) and Depreciation Asymmetry

Depreciation represents the single largest fixed cost in passenger vehicle ownership. At the 8-year mark, conventional ICEVs and Strong Hybrids retain approximately 36% to 38% of their original ex-showroom price in emerging-market secondary channels (₹5.50 Lakh for the ICEV and ₹7.00 Lakh for the Strong Hybrid). Strong Hybrids command robust second-hand demand in Tier-2 and Tier-3 towns because they require no charging infrastructure, and replacement 1.1 kWh hybrid battery modules cost a manageable ₹1.20 Lakh to ₹1.60 Lakh.

Conversely, 8-year-old BEVs experience steeper market depreciation, retaining approximately 25% of ex-showroom value (₹4.85 Lakh). Because the standard 8-year / 1,60,000 km manufacturer battery warranty expires at Year 8, secondary buyers apply a substantial risk discount to account for potential out-of-warranty traction pack replacement (₹5.0 Lakh to ₹7.0 Lakh) and rapid technological obsolescence as newer cell chemistries enter the market.

5.2 Multi-Scenario 8-Year TCO Simulation (Nominal vs. Discounted NPV)

Table 3 evaluates three distinct driver utilization profiles over an 8-year ownership cycle, reporting both **Nominal Cash Outlay** ($r = 0\%$)—which reflects total out-of-pocket rupees spent—and **Discounted Net Present Value** ($r = 6.0\%$)—which accounts for the time value of money:

1. **Scenario 1 — Low-Utilization Urban Driver:** 8,000 km/year(64,000 km over 8 years; ~ 22 km/day; 100% Home Charging at ₹1.22/km).
2. **Scenario 2 — Average Commuter:** 15,000 km/year(1,20,000 km over 8 years; ~ 41 km/day; Commuter Mix Charging at ₹1.65/km).
3. **Scenario 3 — High-Utilization Daily/Highway User:** 25,000 km/year(2,00,000 km over 8 years; ~ 68 km/day; Highway Mix Charging at ₹2.09/km).

Cost Component (8-Year Horizon)	Baseline Petrol ICEV	Strong Hybrid (SHEV)	BEV (Home / Mixed Charging)
Initial On-Road Capital Outlay (I_0)	₹17,05,000	₹21,03,000	₹20,70,000
8-Yr Insurance + Fixed Fees (Nominal / PV at 6%)	₹2,60,000 / ₹2,01,818	₹3,10,000 / ₹2,40,630	₹3,40,000 / ₹2,63,917
Resale Value at Year 8 (RV_8 Nominal / PV at 6%)	₹5,50,000 / ₹3,45,077	₹7,00,000 / ₹4,39,189	₹4,85,000 / ₹3,04,295
Net Capital + Fixed Cost (Nominal, $r = 0\%$)	₹14,15,000	₹17,13,000	₹19,25,000
Net Capital + Fixed Cost (Discounted NPV, $r = 6\%$)	₹15,61,741	₹19,04,441	₹20,29,622
SCENARIO 1: Low Usage (64,000 km / 8,000 km/yr)			
Fuel / Energy Cost (Nominal / PV at 6%)	₹5,12,000 / ₹3,97,427	₹2,66,880 / ₹2,07,159	₹78,080 / ₹60,608 (₹1.22/km)
Maintenance & Tires (Nominal / PV at 6%)	₹48,000 / ₹37,259	₹41,600 / ₹32,291	₹28,800 / ₹22,355 (₹0.45/km)
Total 8-Yr Nominal TCO ($r = 0\%$)	₹19,75,000 (Winner)	₹20,21,480	₹20,31,880
Total 8-Yr Discounted NPV TCO ($r = 6\%$)	₹19,96,427 (Winner)	₹21,43,891	₹21,12,585
SCENARIO 2: Average Usage (1,20,000 km / 15,000 km/yr)			
Fuel / Energy Cost (Nominal / PV at 6%)	₹9,60,000 / ₹7,45,175	₹5,00,400 / ₹3,88,423	₹1,98,000 / ₹1,53,692 (₹1.65/km)
Maintenance & Tires (Nominal / PV at 6%)	₹90,000 / ₹69,860	₹78,000 / ₹60,545	₹60,000 / ₹46,573 (₹0.50/km)
Total 8-Yr Nominal TCO ($r = 0\%$)	₹24,65,000	₹22,91,400	₹21,83,000 (Winner)
Total 8-Yr Discounted NPV TCO ($r = 6\%$)	₹23,76,776	₹23,53,409	₹22,29,887 (Winner)
SCENARIO 3: High Usage (2,00,000 km / 25,000 km/yr)			
Fuel / Energy Cost (Nominal / PV at 6%)	₹16,00,000 / ₹12,41,959	₹8,34,000 / ₹6,47,371	₹4,18,000 / ₹3,24,462 (₹2.09/km)
Maintenance & Tires (Nominal / PV at 6%)	₹1,50,000 / ₹1,16,434	₹1,30,000 / ₹1,00,909	₹1,10,000 / ₹85,385 (₹0.55/km)
Total 8-Yr Nominal TCO ($r = 0\%$)	₹31,65,000	₹26,77,000	₹24,53,000 (Winner)
Total 8-Yr Discounted NPV TCO ($r = 6\%$)	₹29,20,134	₹26,52,721	₹24,39,469 (Winner)

5.3 Exact Break-Even Distance Derivations

Setting the cumulative TCO functions of any two powertrains A and B equal ($TCO_A(D) = TCO_B(D)$) yields the exact cumulative break-even distance (D_{BE}) required to recover upfront capital and depreciation differentials. Under nominal accounting ($r = 0\%$) and discounted NPV accounting ($r = 6\%$, where annual savings are scaled by $\frac{PVIFA_{6\%,8}}{8} = 0.7762$):

$$D_{BE, \text{Nominal}} = \frac{\Delta \text{Net Capital}_{\text{Nom}}}{\Delta c_{\text{op}}} \quad \text{and} \quad D_{BE, \text{NPV}} = \frac{\Delta \text{Net Capital}_{\text{NPV}}}{\Delta c_{\text{op}} \times 0.7762}$$

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where Δc_{op} is the combined fuel and maintenance cost saving per kilometer.

1. **Strong Hybrid vs. Baseline Petrol ICEV:**

- **Net Capital Differential:** ₹2,98,000(Nominal) and ₹3,42,700(Discouted NPV at 6%).
- **Operational Savings (Δc_{op}):** (₹8.00 + ₹0.75) – (₹4.17 + ₹0.65) = ₹8.75 – ₹4.82 = ₹3.93 / km.
- **Break-Even Distance:**

$$D_{BE, \text{Nom (SHEV vs ICEV)}} = \frac{2,98,000}{3.93} = 75,827 \text{ km (9,478 km/year)}$$

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$$D_{BE, \text{NPV (SHEV vs ICEV)}} = \frac{3,42,700}{3.93 \times 0.7762} = 1,12,343 \text{ km (14,043 km/year)}$$

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2. **BEV vs. Baseline Petrol ICEV (Commuter Mix at ₹1.65/km energy + ₹0.50/km maintenance):**

- **Net Capital Differential:** ₹5,10,000(Nominal) and ₹4,67,881(Discouted NPV at 6%).
- **Operational Savings (Δc_{op}):** ₹8.75 – (₹1.65 + ₹0.50) = ₹8.75 – ₹2.15 = ₹6.60 / km.
- **Break-Even Distance:**

$$D_{BE, \text{Nom (BEV vs ICEV)}} = \frac{5,10,000}{6.60} = 77,273 \text{ km (9,659 km/year)}$$

$$D_{BE, \text{Nom (BEV vs ICEV)}} = \frac{5,10,000}{6.60} = 77,273 \text{ km (9,659 km/year)}$$

$$D_{BE, \text{NPV (BEV vs ICEV)}} = \frac{4,67,881}{6.60 \times 0.7762} = 91,331 \text{ km (11,416 km/year)}$$

$$D_{BE, \text{NPV (BEV vs ICEV)}} = \frac{4,67,881}{6.60 \times 0.7762} = 91,331 \text{ km (11,416 km/year)}$$

3. **BEV vs. Strong Hybrid (Head-to-Head Crossover under Commuter Mix):**

- **Net Capital Differential:** In nominal terms, the BEV faces a ₹2,12,000 fixed-cost disadvantage against the Strong Hybrid (₹19,25,000 – ₹17,13,000) due to steeper Year-8 depreciation. In discounted NPV terms, because the Year-8 resale penalty is discounted by 0.6274, the fixed-cost gap narrows to ₹1,25,181 (₹20,29,622 – ₹19,04,441).
- **Operational Savings (Δc_{op}):** ₹4.82/km(SHEV) – ₹2.15/km(BEV) = ₹2.67 / km.
- **Break-Even Distance:**

$$D_{BE, \text{Nom (BEV vs SHEV)}} = \frac{2,12,000}{2.67} = 79,401 \text{ km (9,925 km/year)}$$

$$D_{BE, \text{Nom (BEV vs SHEV)}} = \frac{2,12,000}{2.67} = 79,401 \text{ km (9,925 km/year)}$$

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Synthesis of the Break-Even Findings:

- **Below 75,000 km (< 9,500 km/year):** The conventional Petrol ICEV is the most economical choice under both nominal and discounted frameworks. Neither the Strong Hybrid nor the BEV accumulates sufficient fuel savings to offset the ₹3.65–₹3.98 Lakh upfront purchase premium.
- **Impact of Discounting on Strong Hybrids vs. BEVs:** In nominal out-of-pocket terms, the Strong Hybrid beats the BEV between 75,827 km and 79,401 km because of its ₹2.15 Lakh higher resale value at Year 8. However, when future cash flows are discounted at $r = 6\%$, the present value of a resale cash flow 8 years in the future diminishes significantly, allowing the BEV (which starts ₹33,000 cheaper at Year 0 due to GST subsidies) to overtake the ICEV at 91,331 km whereas the heavily taxed Strong Hybrid requires 1,12,343 km to break even against the ICEV in strict NPV terms.
- **The Public-Charging Exception:** If an apartment-dwelling BEV buyer relies 100% on commercial DC fast chargers (₹3.80/km + ₹0.50/km maintenance = ₹4.30/km), the BEV's operational advantage over the Strong Hybrid (₹4.82/km) falls to ₹0.52/km, pushing the nominal break-even distance against the Strong Hybrid to an unattainable 4,07,692 km. Thus, home AC charging is a strict prerequisite for BEV economic viability.

6. Electrochemical Battery Chemistry, Degradation, and Thermal Management

In tropical and subtropical markets where ambient summer temperatures routinely reach 42°C to 48°C and road-surface radiation exceeds 55°C, electro-thermal stress accelerates both calendar aging and cyclic capacity fade in lithium-ion traction batteries.

Total capacity fade ($\Delta Q_{\text{tot}} = \Delta Q_{\text{cal}} + \Delta Q_{\text{cyc}}$) is governed primarily by parasitic Solid Electrolyte Interphase (SEI) film growth on the graphite anode—which irreversibly consumes cyclable lithium ions—and cathode lattice micro-cracking or lithium plating under high C-rate charging. Both mechanisms follow an Arrhenius relationship with absolute temperature (T , in Kelvin):

$$\Delta Q_{\text{cal}} = A_{\text{cal}} \cdot \exp\left(-\frac{E_{a,\text{cal}}}{R \cdot T}\right) \cdot t^{0.5} \quad \text{and} \quad \Delta Q_{\text{cyc}} = B_{\text{cyc}}(C_{\text{rate}}, \text{DoD}) \cdot \exp\left(-\frac{E_{a,\text{cyc}}}{R \cdot T}\right) \cdot (Ah)^z$$

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where E_a is the activation energy, $R = 8.314 \text{ J/(mol} \cdot \text{K)}$ is the universal gas constant, t is storage time (scaling with $t^{0.5}$ due to diffusion-limited solvent migration through the SEI layer), C_{rate} is charge/discharge current normalized to cell capacity, DoD is Depth of Discharge, and Ah is cumulative ampere-hour throughput.

6.1 LFP vs. NMC in Battery Electric Vehicles

Contemporary BEVs in emerging markets rely on two primary cathode chemistries:

1. **Lithium Iron Phosphate (LiFePO₄ / LFP):** Constructed around an olivine crystal lattice featuring strong covalent phosphorus-oxygen (P – O) bonds that stabilize the oxygen framework during delithiation. Although LFP offers lower gravimetric energy density (140 to 165 Wh/kg at the cell level), it exhibits exceptional thermal runaway resistance (exothermic onset temperature exceeding 270°C vs. 180°C to 210°C for layered oxides), contains zero cobalt or nickel, and achieves 2,500 to 3,500 Equivalent Full Cycles (EFC) before declining to the 80% State of Health (SoH) End-of-Life (EoL) threshold. In a 50 kWh BEV delivering 340 km of real-world range per full cycle, 2,500 EFC corresponds to 8,50,000 km—indicating that calendar aging (1.5% to 2.2% capacity loss per year at 35°C) rather than cyclic wear dictates usable pack lifespan in warm climates.
2. **Nickel Manganese Cobalt (LiNi_xMn_yCo_zO₂ / NMC 622 and 811):** Provides superior gravimetric energy density (220 to 265 Wh/kg), enabling larger capacities in compact wheelbases. However, high-nickel layered cathodes experience accelerated transition-metal dissolution and oxygen release when

held above 80%SoC at ambient temperatures above 35°C, yielding a shorter cyclic life of 1,200 to 1,800 EFCand requiring aggressive liquid chiller thermal management.

6.2 How Strong Hybrids Survive High Daily Micro-Cycle Counts

A recurring engineering question is how a Strong Hybrid's compact 0.8 to 1.1 kWhbattery pack survives for 10 to 15 years despite undergoing dozens of charge-discharge cycles every day at high C-rates (up to 15C to 25Cduring regenerative braking pulses). The durability stems from strict Depth of Discharge (DoD) window constraints enforced by the Hybrid Control Unit (HCU):

- Whereas a BEV owner routinely cycles the traction battery between 10%and 100%SoC (90% DoD), the HCU in a Strong Hybrid restricts normal operation to a narrow central buffer between 40%and 80%SoC (40% DoD), and often 45%to 65%SoC (20% DoD) during steady cruising.
- Mechanical volume expansion and contraction of the graphite anode and cathode lattice behave non-linearly, spiking sharply above 85%SoC (where anode potential approaches 0 V vs. Li/Li⁺, risking lithium plating) and below 20%SoC. By confining operation to the middle 20% to 40%SoC window according to Wöhler-type fatigue curves ($\text{Cycles} \propto \text{DoD}^{-k}$, with $k \approx 2.0$ to 2.4), high-power hybrid lithium-ion and Nickel-Metal Hydride (NiMH) cells withstand 30,000 to 50,000 shallow micro-cycles, reliably exceeding 2,50,000 kmof service life with forced cabin-air cooling.

7. Cradle-to-Grave Life Cycle Assessment (LCA) and Environmental Impact

A comprehensive policy evaluation must extend beyond private financial TCO to quantify external environmental costs via Cradle-to-Grave greenhouse gas (GHG) emissions (gCO₂eq/km). Following the ISO 14040 and ISO 14044 standards over a functional lifetime of 2,00,000 km, total lifecycle emissions are partitioned into three stages:

1. **Cradle-to-Gate (Vehicle and Battery Manufacturing):** Bauxite, iron ore, copper, lithium, nickel, and graphite mining, precursor refining, electrode coating/drying, and vehicle assembly.
2. **Well-to-Wheel (WTW Use Phase):** Comprising **Well-to-Tank (WTT)** upstream fuel production (crude extraction, refining, ethanol blending, or power plant combustion plus grid transmission and distribution losses) and **Tank-to-Wheel (TTW)** direct tailpipe exhaust emissions.
3. **End-of-Life (Grave and Recycling):** Vehicle dismantling, structural metal scrap recovery, and hydrometallurgical/pyrometallurgical battery recycling credits.

7.1 Manufacturing Carbon Debt

Producing a BEV is substantially more carbon-intensive at the factory gate than producing an ICEV or SHEV due to high-temperature cathode calcination, dry-room dehumidification, and solvent recovery during cell manufacturing (emitting 65 to 95 kg CO₂eq per kWhof battery capacity in Asian supply chains):

- **Baseline ICEV Production Footprint:** ~ 6.5 tonnes CO₂eq(32.5 gCO₂eq/km amortized over 2,00,000 km).
- **Strong Hybrid Production Footprint:** ~ 7.0 tonnes CO₂eq(35.0 gCO₂eq/km over 2,00,000 km, reflecting the small 1.1 kWhbattery and dual electric motors).
- **50 kWh BEV Production Footprint:** ~ 11.0 tonnes CO₂eq(55.0 gCO₂eq/km over 2,00,000 km).

Consequently, a 50 kWh BEV leaves the assembly plant carrying an upfront "carbon debt" of 4.0 tonnes CO₂eqrelative to a Strong Hybrid and 4.5 tonnes CO₂eqrelative to a conventional ICEV.

7.2 Grid Carbon Intensity and the Coal Paradox

The distance required for a BEV to pay back its manufacturing carbon debt depends directly on the Grid Emission Factor (GEF) of the electricity network:

- **Coal-Dominated Grid Scenario (GEF = 710 gCO₂eq/kWh at power plant busbar, representative of India's weighted grid average):** A mid-size BEV with a blended drivetrain efficiency of 7.09 km/kWh (0.141 kWh/km at the battery) and an AC/DC charging efficiency of $\eta_{\text{charger}} = 0.89$ draws 0.1584 kWh/km at the wall socket. Accounting for 4.7% regional distribution losses between the generation busbar and consumer meter ($\eta_{\text{grid}} = 0.953$, equivalent to 0.1662 kWh/km generated at the power plant), upstream Well-to-Tank emissions are:

$$\text{WTT}_{\text{BEV, Coal}} = 0.1662 \text{ kWh/km} \times 710 \text{ gCO}_2\text{eq/kWh} = \mathbf{118.0 \text{ gCO}_2\text{eq/km}}$$

$$\text{WTT}_{\text{BEV, Coal}} = 0.1662 \text{ kWh/km} \times 710 \text{ gCO}_2\text{eq/kWh} = \mathbf{118.0 \text{ gCO}_2\text{eq/km}}$$

- **Renewable / Rooftop Solar Grid Scenario (GEF = 50 gCO₂eq/kWh amortized lifecycle PV footprint):** Charging from a domestic rooftop solar installation or decarbonized renewable grid reduces upstream emissions to:

$$\text{WTT}_{\text{BEV, Solar}} = 0.1662 \text{ kWh/km} \times 50 \text{ gCO}_2\text{eq/kWh} = \mathbf{8.3 \text{ gCO}_2\text{eq/km}}$$

$$\text{WTT}_{\text{BEV, Solar}} = 0.1662 \text{ kWh/km} \times 50 \text{ gCO}_2\text{eq/kWh} = \mathbf{8.3 \text{ gCO}_2\text{eq/km}}$$

- **Strong Hybrid and ICEV Well-to-Wheel Emissions (E20 Petrol):** Combusting 1 liter of E20 petrol (20% bio-ethanol blend) releases approximately 2,280 gCO₂eq in net tailpipe fossil carbon (TTW) and incurs ~ 450 gCO₂eq/liter in upstream extraction, refining, and agricultural processing (WTT), totaling 2,730 gCO₂eq/liter. At 24.0 km/l, the Strong Hybrid generates 95.0 g/km TTW and 18.7 g/km WTT (113.7 gCO₂eq/km WTW). At 12.5 km/l, the baseline ICEV generates 182.4 g/km TTW and 36.0 g/km WTT (218.4 gCO₂eq/km WTW).

Lifecycle Stage (gCO ₂ eq/km over 2,00,000 km)	Petrol ICEV (12.5 km/l)	Strong Hybrid (24.0 km/l)	BEV (Coal Grid: 710 g/kWh)	BEV (Solar/Green Grid: 50 g/kWh)
Vehicle + Battery Production (Cradle-to-Gate)	32.5	35.0	55.0	55.0
Well-to-Tank (Fuel Refining / Grid Power Generation)	36.0	18.7	118.0	8.3
Tank-to-Wheel (Direct Tailpipe Exhaust)	182.4	95.0	0.0	0.0
Maintenance & End-of-Life Recycling Net Impact	8.0	8.5	6.0	6.0
Total Cradle-to-Grave (gCO ₂ eq/km)	258.9 g/km	157.2 g/km	179.0 g/km	69.3 g/km
Lifecycle GHG Reduction vs. Baseline ICEV	Baseline (0%)	−39.3%	−30.9%	−73.2%

Consistent with the empirical findings of Agarwal et al. (2025) for the Indian passenger fleet, when a 50 kWh BEV is charged exclusively from a coal-dominated grid (710 gCO₂eq/kWh), its total Cradle-to-Grave GHG footprint (179.0 gCO₂eq/km) exceeds that of an E20-fueled Strong Hybrid (157.2 gCO₂eq/km) by 13.9%, primarily due to the BEV's upfront battery manufacturing carbon debt combined with coal power plant heat rates. For the BEV to achieve lifecycle carbon parity with the Strong Hybrid (157.2 g/km), the grid emission factor must fall below a critical crossover threshold of ~ 578 gCO₂eq/kWh.

Nevertheless, two critical environmental distinctions favor BEVs even during the grid transition phase:

1. **Elimination of Urban Street-Level Criteria Pollutants:** Even when powered by coal plants, BEVs produce zero tailpipe NO_x, CO, unburned hydrocarbons, and exhaust PM_{2.5} inside densely populated metropolitan corridors, shifting emissions to remote point-source power stations equipped with electrostatic precipitators and flue-gas desulfurization.

2. **Dynamic Decarbonization Over Vehicle Lifetime:** While a Strong Hybrid's carbon intensity is permanently locked to liquid hydrocarbon combustion over its 15-year lifespan, a BEV automatically becomes cleaner each year as national grids add utility-scale solar and wind capacity—or immediately drops to 69.3 gCO₂/eq/km (55.9% lower than the Strong Hybrid) when paired with a 3 kW residential rooftop solar PV array.

8. Decision Matrix and Policy Recommendations

8.1 Consumer Decision Framework

Selecting optimally between a Strong Hybrid and a Battery Electric Vehicle requires aligning the powertrain's economic and physical profile with the buyer's operational constraints:

1. **Select a Battery Electric Vehicle (BEV) when:**
 - **Annual Mileage Exceeds 12,000 km/year** (greater than 35 to 40 km/day): High utilization rapidly amortizes both the initial capital outlay and steeper Year-8 depreciation, delivering net 8-year savings of ₹1.08 Lakh to ₹2.24 Lakh over Strong Hybrids and ₹2.82 Lakh to ₹7.12 Lakh over conventional petrol SUVs.
 - **Dedicated Home or Workplace AC Charging is Guaranteed:** Overnight charging at residential tariffs (₹6.00 to ₹8.00/kWh) or via rooftop solar PV is the essential foundation of BEV economics.
 - **Predictable Urban/Regional Duty Cycle or Multi-Car Household:** When 80% + of trips occur within a 250 km radius or the vehicle serves as the primary daily commuter alongside a secondary liquid-fueled highway vehicle, range and charger-queue anxieties are eliminated.
2. **Select a Strong Hybrid Electric Vehicle (SHEV) when:**
 - **No Dedicated Metered Parking (Apartment / Rented Housing):** Buyers unable to install a private 7.2 kW AC charger who would otherwise depend on ₹20–₹24/kWh commercial DC fast chargers face virtually identical per-kilometer running costs in a BEV (₹3.80/km) and a Strong Hybrid (₹4.17/km), making the SHEV far superior once depreciation and charging time are considered.
 - **Frequent Unplanned Long-Distance Highway Travel:** Delivering 850 to 1,000 + km on a single 45-liter tank and refueling in 3 minutes at any rural fuel station, a Strong Hybrid avoids high-speed EV aerodynamic range penalties and highway charger bottlenecks.
 - **Moderate Mileage (9,500 to 11,500 km/year) with Early Resale Horizon (4 to 6 years):** Strong Hybrids command stronger secondary-market liquidity in semi-urban and rural markets where charging networks remain sparse.

8.2 Policy Recommendations for Emerging Markets

From a regulatory perspective, treating Strong Hybrids and BEVs as zero-sum rivals delays immediate fleet decarbonization:

- **Carbon-Indexed GST / Excise Rationalization:** Taxing a 24 km/l Strong Hybrid (95 gCO₂/km tailpipe) in the same 43% luxury tax bracket as a 10 km/l conventional SUV (190 + gCO₂/km) distorts consumer choice toward cheaper, high-emitting pure ICEVs. Establishing an intermediate emission-linked tax tier (18% to 25% total tax) for Strong Hybrids would accelerate the displacement of pure petrol/diesel vehicles among apartment dwellers and highway users while public charging infrastructure matures.
- **Time-of-Day (ToD) Solar Charging Tariffs:** Electricity regulatory commissions should mandate discounted daytime commercial and workplace slow-charging tariffs between 10:00 AM and 04:00 PM. Aligning BEV charging directly with peak midday solar generation minimizes grid storage requirements and immediately pushes BEV Well-to-Wheel emissions below the Strong Hybrid threshold.
- **Standardized Battery State-of-Health (SoH) Certification:** Mandating open on-board diagnostic (OBD) access to standardized Battery Management System (BMS) SoH certificates at the point of resale would reduce information asymmetry in the used-EV market, mitigating the steep Year-8 depreciation penalty that currently inflates BEV Total Cost of Ownership.

9. Conclusion

This study demonstrates that neither Strong Hybrid Electric Vehicles nor Battery Electric Vehicles hold an unconditional techno-economic or environmental monopoly in emerging automotive markets; rather, their optimality is governed by utilization intensity, charging modality, fiscal taxation, and regional grid carbon intensity. Thermodynamically, Strong Hybrids leverage over-expanded Atkinson-cycle combustion and series-parallel e-CVT load-leveling to achieve 40% +brake thermal efficiency, cutting fuel consumption by nearly half relative to Otto-cycle ICEVs without external infrastructure. Conversely, BEVs achieve an 80% to 85% Tank-to-Wheel efficiency that yields unmatched operational savings when paired with residential AC charging, though aerodynamic drag scaling ($P_d \propto v^3$) and commercial DC fast-charging tariffs (₹20–₹24/kWh) erode this advantage during sustained highway travel.

From a financial standpoint, our dual nominal and discounted NPV ($r = 6\%$) Total Cost of Ownership modeling across an 8-year horizon reveals three distinct operational regimes: below 75,000 km (< 9,500 km/year), conventional petrol ICEVs remain the lowest-cost option because fuel savings cannot amortize the ₹3.65–₹3.98 Lakh upfront electrification premium; for moderate commuters (75,000 to 90,000 km) or buyers without dedicated home charging, Strong Hybrids provide superior risk-adjusted returns due to stronger secondary-market resale retention and immunity from commercial charging tariffs; and above 90,000 km (> 11,500 km/year) with home charging, BEVs emerge as the decisive financial winner, generating net 8-year savings exceeding ₹2.2 Lakh over SHEVs and ₹7.1 Lakh over ICEVs at 2,00,000 km.

Environmentally, our ISO 14040/14044 Cradle-to-Grave Life Cycle Assessment highlights a critical transitional nuance: because a 50 kWh BEV leaves the factory with a 4.0-tonne CO₂eq manufacturing carbon debt over a Strong Hybrid, charging exclusively from a coal-heavy grid (710 gCO₂eq/kWh) results in slightly higher lifecycle GHG emissions for the BEV (179.0 g/km) than for an E20-fueled Strong Hybrid (157.2 g/km), with carbon parity occurring at a grid emission factor of ~ 578 gCO₂eq/kWh. However, when paired with rooftop solar or greening grids, BEV lifecycle emissions drop to 69.3 gCO₂eq/km—a 73.2% reduction over ICEVs—while eliminating urban street-level particulates immediately. Policymakers in developing economies should therefore adopt a complementary dual-pathway strategy: deploying emission-indexed tax reform to use Strong Hybrids as an immediate mass-market bridge away from pure ICEVs, while expanding solar-synchronized charging networks and domestic battery recycling to unlock the full long-term decarbonization potential of Battery Electric Vehicles.

Declarations

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Data availability. All techno-economic parameters, vehicle specifications, retail pricing structures, electricity tariffs, and lifecycle emission inventories analyzed in this study are included within the article tables and mathematical derivations. Additional calculation sheets generated during the current study are available from the corresponding author upon reasonable request.

Author contributions.

Rohan S. Deshmukh: Conceptualization, methodology, thermodynamic and TCO modeling, formal analysis, investigation, data curation, writing—original draft, and writing—review and editing.

The author read and approved the final manuscript.

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