

A Comparative Life-Cycle Assessment of Next-Generation Electric Vehicles: Balancing Grid Decarbonization and Resource Scarcity

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Abstract: *The global transition to electric vehicles (EVs) is a cornerstone of transport decarbonization. However, the environmental benefits are non-uniform and highly dependent on supply chains and regional energy grids. Objective: This study evaluates the life-cycle environmental impacts of current Lithium Iron Phosphate (LFP) and Nickel Manganese Cobalt (NMC) batteries across varying grid infrastructure regimes. Utilizing a Cradle-to-Grave Life Cycle Assessment (LCA) framework, we model greenhouse gas (GHG) emissions, human toxicity, and mineral depletion using GREET and Ecoinvent databases. EVs operating on a highly decarbonized grid (e.g., >80% renewables) achieve an emissions breakeven point within 18,000 km of driving relative to internal combustion engine (ICE) vehicles. Conversely, in coal-dominated grids, the environmental amortization period extends past 110,000 km. Policy frameworks must integrate localized grid projections with circular economy mandates for battery recycling to avoid shifting the environmental burden upstream.*

Keywords: Lithium Iron Phosphate (LFP), NMC, GHG, GREET.

1. Introduction

Decarbonizing light-duty transportation accounts for a significant share of global climate mitigation goals.

The Problem: Public policy often assumes a binary "EV equals zero emissions" stance. This ignores the carbon debt incurred during raw material extraction, localized ecological destruction in mining zones, and the varying carbon intensity of global electricity grids.

Research Gap: Existing literature heavily focuses on traditional NMC chemistry under static grid assumptions. This paper addresses the gap by dynamically modeling shifting grid mixes alongside the rapid commercial rise of LFP and solid-state alternatives.

Contribution: We provide a dynamic mathematical framework that links hourly grid emissions variance with real-world driving degradation data.

2. Methodology

System Boundaries: A Cradle-to-Grave approach is established. The boundaries encompass four major phases: Material Extraction & Refining (Lithium, Cobalt, Nickel, Graphite) Battery and Vehicle Manufacturing Use Phase (Simulated across 150,000 km of driving) End-of-Life (EoL) (Comparing hydrometallurgical recycling vs. landfilling)

Functional Unit: The functional unit is defined as 1 kilometer driven by a standard mid-sized passenger vehicle under

urban/highway mixed driving cycles. Data Inventory Summary: Vehicle weight: 1,600 kg (ICE base) vs. 1,950 kg (EV base). Battery capacity modeled: 60 kWh. Grid mixes evaluated: Coal-dominant (75% coal), Mixed (40% renewables, 30% gas, 30% coal), and Clean (90% hydro/wind/solar).

2.1 Mineral Scarcity vs. Climate Trade-offs

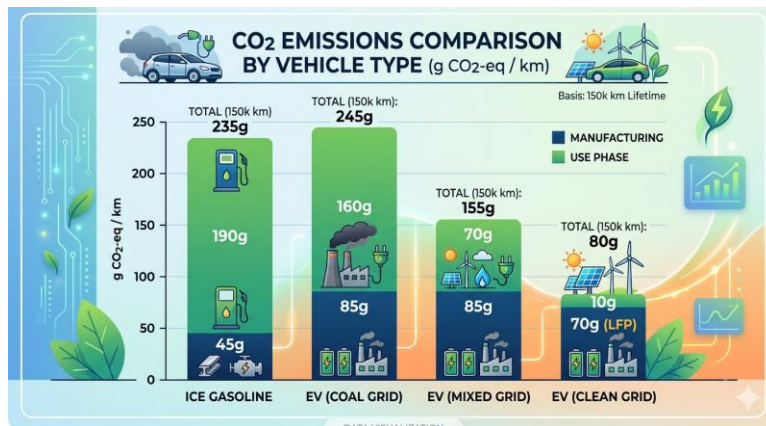
NMC Chemistry: Higher energy density reduces vehicle weight and use-phase energy consumption. However, it scores 4x higher on the Human Toxicity Potential (HTP) metric due to Cobalt refining practices. **LFP Chemistry:** Completely bypasses the Cobalt and Nickel supply chain risks. However, its lower energy density increases overall vehicle mass, increasing non-exhaust particulate matter (PM_{2.5}) from tire wear by 11-15%.

3. Policy and Practical Implications

To fully unlock the environmental potential of EVs, governments cannot look at transportation in isolation. Decarbonizing the power grid must happen in lockstep with EV adoption subsidies. Furthermore, "Battery Passports" tracking raw material provenance must become mandatory to mitigate localized ecological damage during mining.

4. Results & Discussion

Life-Cycle Greenhouse Gas Emissions The manufacturing phase of EVs generates roughly 40% to 70% higher emissions than ICE vehicles, driven entirely by battery cell production.



5. Conclusion

EVs are not inherently clean; they are inherently clean for transporters. Their true environmental footprint is borrowed from the geographical region in which they are built and driven. Future research must deeply explore the environmental economics of second-life vehicle batteries acting as stationary storage units for solar grids.

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