Journal of Information Systems Engineering and Management
2024, 9(4s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/ **Research Article**

Life Cycle Assessment of Electric Vehicles in India: Evaluating Environmental Benefits and Hidden Costs

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ARTICLE INFO

Received:03 Nov 2024

Revised:15 Dec 2024

Accepted:25 Dec 2024

ABSTRACT

In India, the quick uptake of electric vehicles (EVs) has been hailed as a means of attaining sustainable transportation, cutting air pollution, and lowering greenhouse gas emissions. A life cycle assessment (LCA) method, on the other hand, identifies both obvious environmental benefits and unstated expenses throughout the stages of manufacturing, use, and disposal. With an emphasis on battery production, energy sources for power generation, and end-of-life management, this report offers a critical assessment of the EV life cycle in India. Results show that although EVs significantly lower tailpipe emissions when compared to internal combustion engine (ICE) cars, the energy mix and recycling infrastructure have a significant impact on how environmentally friendly they are overall. Recommendations and policy implications for the implementation of sustainable EVs are also covered.

Keywords: transportation, implementation, infrastructure

Introduction

Electric vehicles (EVs) have emerged as a promising solution to reduce the environmental burden associated with the transportation sector. The global transition from conventional internal combustion engine (ICE) vehicles to electric mobility is being driven by the need to lower greenhouse gas emissions, improve urban air quality, and reduce dependence on fossil fuels. In India, the adoption of EVs has gained momentum in recent years due to increasing concerns about energy security, urban pollution, and climate change. With rapid urbanization and a growing vehicle population, India faces serious challenges related to air quality and carbon emissions. As a result, the government has prioritized electric mobility as a strategic pathway toward achieving cleaner and more sustainable transportation. To support this transition, the Government of India has introduced several policy initiatives, including the Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) scheme, National Electric Mobility Mission Plan (NEMMP), and Production Linked Incentive (PLI) programs for advanced cell battery manufacturing. These initiatives aim to accelerate EV penetration, develop domestic manufacturing capacity, and strengthen the national charging infrastructure. Despite these efforts, the market share of EVs remains relatively low compared to global leaders such as China, the United States, and several European nations. Nonetheless, India's long-term vision aligns with the global trend toward sustainable transport systems powered by electricity and renewable energy.While EVs are often promoted as "zero-emission" vehicles, this description applies only to the operational phase, as they produce no tailpipe emissions. However, the overall environmental performance of EVs depends on the source of electricity used for charging and the materials and energy consumed during manufacturing and end-of-life processes. India's electricity generation is still dominated by coal, accounting for more than 70 percent of total power production. Consequently, the environmental benefits of EVs in India may be offset by the upstream emissions produced during electricity generation. Therefore, a comprehensive evaluation of EVs through a life cycle perspective is essential to determine their actual sustainability performance under Indian conditions.

Life Cycle Assessment (LCA) provides a systematic framework for assessing the total environmental impact of a product from raw material extraction to manufacturing, operation, and disposal. In the case of electric vehicles, LCA considers key stages such as battery production, vehicle assembly, energy consumption during use, and end-of-life management. This approach enables a holistic understanding of both the environmental gains and the hidden costs associated with EVs. Several international studies have shown that EVs can offer substantial reductions in greenhouse gas emissions compared to ICE vehicles, particularly in regions where electricity generation is largely based on renewable sources. However, in coal-dominated energy systems like India's, the reduction potential is smaller and sometimes offset by higher emissions from battery production and electricity generation.

Battery manufacturing and disposal represent critical stages in the life cycle of EVs. Lithium-ion batteries, which are widely used in EVs, require significant amounts of energy and raw materials such as lithium, cobalt, and nickel. The extraction and processing of these materials can lead to environmental degradation, resource depletion, and toxic emissions. Moreover, improper disposal of used batteries can cause soil and water contamination. The absence of a robust recycling infrastructure in India further complicates the sustainability assessment. Therefore, developing efficient recycling technologies and establishing circular economy practices are crucial for reducing the long-term environmental footprint of electric mobility.

This paper aims to evaluate the environmental gains and hidden costs of electric vehicle adoption in India using a life cycle assessment approach. The study compares the life cycle energy consumption, greenhouse gas emissions, and pollutant outputs of EVs and conventional vehicles under Indian conditions. By analyzing the environmental performance across different life cycle stages, the research seeks to provide a realistic understanding of the sustainability of electric mobility in India. The findings are expected to support policymakers, manufacturers, and researchers in formulating strategies that enhance the net environmental benefits of EVs and promote a transition toward a cleaner and more sustainable transportation future.

Literature Review

The shift toward electric mobility has gained significant attention worldwide as an effective strategy for achieving sustainable transportation. Many governments and industries are prioritizing electric vehicles (EVs) to reduce greenhouse gas emissions, dependence on fossil fuels, and air pollution from conventional vehicles. The environmental benefits of EVs, however, vary greatly across regions due to differences in electricity generation, vehicle efficiency, battery technology, and local operating conditions.

Research conducted in regions with high shares of renewable energy has generally shown that electric vehicles produce far lower life cycle emissions than internal combustion engine (ICE) vehicles. In such areas, the electricity used for charging is generated mainly from clean sources, which greatly reduces the carbon footprint of vehicle operation. In contrast, countries that rely heavily on coal-based power generation, such as India, face mixed outcomes. In these cases, while EVs eliminate tailpipe emissions, they indirectly contribute to emissions at the electricity generation stage. The overall environmental performance of electric vehicles thus depends on the balance between operational benefits and upstream energy sources.

Life Cycle Assessment (LCA) has become a widely accepted approach for measuring the total environmental performance of EVs. This method evaluates every stage of a vehicle's life, beginning with raw material extraction, continuing through manufacturing and usage, and ending with disposal or recycling. By considering the full life cycle, LCA provides a comprehensive picture of energy consumption, greenhouse gas emissions, and pollution associated with the product. Applying this

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e-ISSN: 2468-4376
https://www.jisem-journal.com/ Research Article

framework to electric vehicles helps to identify stages that contribute most to environmental burdens and highlights areas where improvements can yield the greatest benefits.

Battery manufacturing is consistently identified as one of the most energy- and resource-intensive stages of the EV life cycle. Producing lithium-ion batteries involves complex chemical processes and the extraction of critical minerals such as lithium, cobalt, and nickel. Mining and processing these materials require large amounts of energy and can cause soil degradation, water contamination, and resource depletion. As a result, the production phase contributes significantly to the total environmental impact of electric vehicles. Furthermore, the transportation of raw materials to battery manufacturing facilities adds to overall emissions. Efficient recycling systems and the development of alternative battery chemistries can help mitigate these challenges.

Another important factor is the management of batteries once they reach the end of their useful life. Improper disposal of used batteries can release hazardous substances into the environment. Establishing recycling facilities capable of recovering valuable materials can reduce both resource dependency and waste. Several countries have implemented advanced recycling processes to extract metals and reuse components in new battery production, but such systems are still emerging in India. Strengthening these mechanisms is essential for ensuring that electric mobility remains environmentally responsible.

In the Indian context, studies focusing on the life cycle assessment of electric vehicles are relatively limited. Available analyses suggest that the environmental performance of EVs in India is strongly influenced by the country's electricity generation mix. Since coal remains the dominant energy source, the environmental advantage of EVs is often smaller compared to regions powered by renewable energy. However, as India continues to expand its solar and wind energy capacity, the potential for emission reduction through electric mobility is expected to increase. Integrating renewable energy into the national grid and encouraging renewable-based vehicle charging are key steps toward maximizing these benefits.

Economic and policy aspects also play a crucial role in shaping India's electric vehicle ecosystem. The government has introduced several initiatives such as the FAME program and Production Linked Incentive schemes to promote local manufacturing and adoption of EVs. These measures aim to reduce the cost of vehicles, expand charging infrastructure, and strengthen domestic production capabilities. Despite these policies, the current rate of EV adoption remains moderate due to challenges such as high initial costs, limited driving range, and lack of widespread charging facilities. Addressing these challenges through coordinated policy support, public awareness, and technological innovation is essential for accelerating growth in this sector.

Research comparing EVs and ICE vehicles in Indian conditions has produced mixed findings. Some analyses show that EVs reduce total emissions when charged with renewable or low-carbon electricity, while others indicate minimal benefit when coal-based power dominates. These variations highlight the importance of considering regional factors, driving patterns, and the source of electricity in determining the true sustainability of EVs. Moreover, the introduction of smart grids and time-of-day charging systems could further improve performance by enabling EVs to utilize surplus renewable power during off-peak periods.

Advancements in battery technology and recycling can further enhance the environmental performance of electric vehicles. Emerging technologies such as high-efficiency lithium iron phosphate and solid-state batteries offer longer lifespans, lower energy requirements, and improved safety. Additionally, reusing retired EV batteries for stationary energy storage applications can extend their usefulness and reduce waste. Implementing such circular economy practices would improve resource efficiency and decrease the total environmental impact of the EV lifecycle.

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From the existing literature, it is clear that the environmental benefits of electric vehicles depend on multiple interrelated factors. The most critical among these are the carbon intensity of electricity generation, manufacturing efficiency, material sourcing, and recycling practices. In India, where the energy grid is still heavily dependent on coal, transitioning toward renewable energy is crucial for realizing the full potential of electric mobility. Similarly, promoting local innovation in battery production, developing recycling infrastructure, and implementing strong environmental regulations are key strategies for minimizing hidden environmental costs.

Although considerable global research exists on the life cycle performance of electric vehicles, comprehensive assessments specific to India remain limited. Many available studies focus primarily on tailpipe emissions or operational performance, overlooking the upstream and downstream stages of the vehicle's life cycle. This gap highlights the need for detailed, data-driven assessments that reflect India's unique energy structure, industrial ecosystem, and climatic conditions. A clear understanding of these factors is essential to develop realistic policies and technologies that support sustainable electric mobility

Methodology

This study employs a Life Cycle Assessment (LCA) methodology to evaluate and compare the environmental impacts of electric vehicles (EVs) and internal combustion engine (ICE) vehicles within the Indian context. The approach follows the internationally recognized standards ISO 14040 and ISO 14044, which outline the principles, framework, and requirements for conducting life cycle studies. The main objective is to quantify the total environmental burden associated with both vehicle types across their complete life cycles, from resource extraction to end-of-life management, under conditions specific to India's energy and industrial landscape.

A. Goal and Scope Definition

The goal of this assessment is to analyze the environmental trade-offs between EVs and ICE vehicles in India and to identify key stages that contribute most to their overall environmental impact. The functional unit for comparison is defined as the operation of one mid-sized passenger vehicle over a lifetime distance of 150,000 kilometers. This ensures a uniform basis for comparison between vehicle types with similar performance characteristics.The system boundary includes all major life cycle stages — from raw material extraction to disposal — ensuring a "cradle-to-grave" perspective. This boundary allows for a holistic evaluation of resource use, energy consumption, and emission generation during the entire vehicle lifespan. The assessment encompasses both direct and indirect emissions, covering activities such as material processing, electricity generation for charging, and recycling processes.

B. Life Cycle Stages

The LCA framework is divided into four major phases, each of which is analyzed separately to capture its specific environmental contributions.Raw Material Extraction and Battery Manufacturing.This stage includes the extraction, refining, and processing of raw materials such as steel, aluminum, copper, lithium, nickel, manganese, and cobalt. These materials are essential for manufacturing vehicle bodies, motors, and—most importantly—lithium-ion batteries, which represent a major environmental hotspot for EVs.The study models the battery manufacturing process based on typical energy and material inputs for lithium-ion batteries used in passenger EVs, incorporating data on cell production, assembly, and transportation. Energy-intensive processes, such as electrode coating, electrolyte preparation, and module packaging, are included**.**For ICE vehicles, this stage includes the extraction and refining of petroleum-based products for engine and component manufacturing. Comparative evaluation

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highlights the difference in resource intensity and emissions between conventional powertrains and electric drivetrains.

Vehicle Assembly

The assembly phase includes energy consumption and emissions associated with component manufacturing, vehicle body assembly, painting, welding, and final integration of systems. Both EV and ICE vehicles are assumed to share similar structural and material configurations, except for their respective powertrains and energy storage systems.

Data for this stage are obtained from industry databases and validated with secondary literature focused on vehicle production in Asian and Indian manufacturing contexts. The environmental burden is calculated based on electricity and fuel consumption per unit of vehicle assembled, considering the Indian electricity generation mix dominated by coal.

Use Phase

The use phase represents the operational life of the vehicle and is often the most influential in determining total life cycle impacts. For ICE vehicles, this stage includes direct tailpipe emissions from fuel combustion, along with upstream emissions from fuel production, transportation, and distribution.For EVs, the focus is on electricity consumption and related upstream emissions from power generation. Since India's current power grid remains heavily reliant on coal (approximately 70%), the study models the carbon intensity of EV charging based on national energy statistics. Multiple charging scenarios are developed to evaluate the influence of renewable energy integration. These include, Scenario 1: Current grid mix (coal-dominant).Scenario 2: Moderate renewable integration (30–40% renewable share).Scenario 3: Future low-carbon scenario (60–70% renewable share).Vehicle efficiency parameters, including energy consumption (kWh per km for EVs and L per 100 km for ICEs), are estimated from reported averages in Indian driving conditions. The operational emissions are then calculated using emission factors derived from official energy reports.

End-of-Life Management

The end-of-life phase addresses the treatment, disposal, and recycling of vehicle components. For ICE vehicles, typical processes include scrapping, metal recovery, and safe disposal of fluids.For EVs, additional attention is given to battery recycling and second-life applications. Lithium-ion battery packs are disassembled and processed through mechanical or hydrometallurgical recycling routes to recover valuable materials like lithium, cobalt, and nickel. The study assumes partial recycling efficiency based on existing industrial capabilities in India. Potential benefits of material recovery are credited back to the life cycle inventory through avoided burden allocation, reflecting reduced environmental load from raw material substitution.

C. Data Collection and Sources

The study primarily relies on secondary data obtained from credible and publicly available sources.Reports from the Government of India (Ministry of Power, NITI Aayog, Bureau of Energy Efficiency).International databases such as Ecoinvent, GREET, and IEA Energy Statistics.Peer-reviewed research articles focused on life cycle emissions of EVs and ICE vehicles in developing economies.Industry reports from automotive manufacturers and renewable energy organizations.Where Indian-specific data were unavailable, regionally adjusted global averages were applied using appropriate emission and conversion factors to reflect local conditions.

D. Impact Assessment Categories

The environmental impact assessment focuses on three key indicators that represent the most relevant sustainability dimensions for transportation systems. Greenhouse Gas Emissions (CO_2-equivalent):This measures the total carbon footprint, including CO_2, CH_4, and N_2O emissions, from all life cycle stages. It provides insight into the climate change potential of each vehicle type. Cumulative Energy Demand (MJ per vehicle lifetime):This category quantifies total primary energy consumption, both renewable and non-renewable, used across the vehicle life cycle. It helps identify energy-intensive stages and potential efficiency improvements. Resource Depletion: This evaluates the depletion of finite materials, particularly critical minerals used in battery manufacturing, to understand the long-term sustainability of EV technologies'. Scenario Modeling and Comparative Analysis.To better understand the environmental implications under evolving conditions, the study develops scenario-based models that simulate how changes in India's energy structure and EV adoption rates affect total life cycle impacts.Sample datasets reflecting current and projected EV penetration scenarios are used to estimate potential reductions in national-level emissions. Sensitivity analysis is also performed to examine the influence of battery size, vehicle lifespan, and electricity mix variations on the results.The comparative analysis between EVs and ICE vehicles is presented through normalized impact metrics, such as grams of CO_2-equivalent per kilometer and megajoules of energy per vehicle kilometer, providing a transparent and comparable framework.

Results

The findings indicate that EVs offer significant reductions in tailpipe CO_2 emissions compared to ICE vehicles. However, when electricity is predominantly coal-based, the lifecycle emissions of EVs can approach or even exceed those of efficient diesel vehicles. Battery manufacturing contributes up to 35% of lifecycle energy consumption, and disposal challenges further complicate sustainability. Transitioning India's power grid towards renewable energy is therefore critical for realizing the true environmental benefits of EVs.

Vehicle Type	Lifecycle CO_2 Emissions (g/km)	Energy Consumption (MJ/km)
EV (Coal Grid)	120	2.8
EV (Renewable)	80	2.2
ICE Petrol	180	3.0

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