



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

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Abstract

The rapid growth of electric vehicles (EVs) is widely regarded as a key strategy for reducing greenhouse gas emissions and mitigating climate change. However, a comprehensive evaluation of their true environmental performance requires a full life cycle assessment (LCA) that considers emissions and resource use from raw material extraction to end-of-life disposal. The environmental impacts of electric vehicles across four primary stages: battery material extraction and processing, vehicle manufacturing, operational use, and recycling or disposal. EVs typically generate significantly lower tailpipe emissions compared to internal combustion engine vehicles, their overall environmental advantages depend heavily on electricity generation sources, battery chemistry, and production practices. Battery manufacturing, particularly lithium-ion battery production, contributes substantially to energy consumption, water use, and carbon emissions. Additionally, the extraction of critical minerals such as lithium, cobalt, and nickel raises concerns related to ecological degradation, resource depletion, and supply chain ethics.

Keywords: Electric Vehicles (EVs); Life Cycle Assessment (LCA); Carbon Footprint; Greenhouse Gas Emissions

Introduction

The global transportation sector is undergoing a significant transition as governments, industries, and consumers respond to growing concerns over climate change, air pollution, and energy security. Road transport remains one of the largest contributors to greenhouse gas emissions worldwide, primarily due to the widespread use of internal combustion engine vehicles powered by fossil fuels. In this context, electric vehicles (EVs) have emerged as a promising alternative, often promoted as a cleaner and more sustainable solution for future mobility. Electric vehicles produce zero tailpipe emissions, which positions them as an effective strategy for improving urban air quality and reducing dependence on petroleum-based fuels. Many countries have introduced ambitious targets for phasing out conventional vehicles, alongside financial incentives and regulatory frameworks aimed at accelerating EV adoption. However, the environmental superiority of EVs cannot be assessed solely on the basis of their operational performance. A comprehensive evaluation requires examination of the entire life cycle of the vehicle, from raw material extraction and manufacturing to use-phase energy consumption and end-of-life management. Life Cycle Assessment (LCA) provides a structured

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methodology for analyzing the cumulative environmental impacts associated with a product or system throughout its lifespan. When applied to electric vehicles, LCA reveals a more complex environmental profile than is often assumed. While EVs generally outperform conventional vehicles in terms of operational emissions, their production phase, particularly battery manufacturing, involves energy-intensive processes and the extraction of critical minerals such as lithium, cobalt, and nickel. These activities can result in substantial carbon emissions, water consumption, land degradation, and social concerns linked to mining practices. Furthermore, the overall environmental benefits of electric vehicles vary significantly depending on regional electricity generation mixes. In countries where electricity is primarily derived from renewable sources, EVs tend to deliver substantial lifecycle emission reductions. In contrast, in regions heavily reliant on coal-based power generation, the climate advantages may be less pronounced. This variability highlights the importance of integrating transportation electrification with broader energy system decarbonization. Another critical dimension involves end-of-life management and battery recycling. As EV adoption expands, the volume of spent lithium-ion batteries will increase, raising questions about waste management, resource recovery, and circular economy strategies. Effective recycling systems and second-life battery applications can significantly improve the overall sustainability of electric mobility by reducing resource extraction and minimizing environmental impacts. Given these complexities, a balanced and evidence-based assessment of electric vehicles is essential. This study adopts a life cycle perspective to examine both the environmental benefits and hidden costs associated with EV production, operation, and disposal. By identifying key impact stages and contextual variables, the research aims to contribute to a more nuanced understanding of the environmental implications of the transition toward electric mobility.

Conceptual Framework of Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a systematic analytical method used to evaluate the environmental impacts of a product, process, or system throughout its entire lifespan. Rather than focusing on a single stage such as manufacturing or usage, LCA adopts a cradle-to-grave perspective, examining impacts from raw material extraction to production, distribution, operation, and final disposal or recycling. In the context of electric vehicles (EVs), this framework is essential for understanding the full environmental implications of transitioning from conventional internal combustion engine vehicles to electric mobility.

The conceptual foundation of LCA is built on four key phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation. The first phase establishes the purpose of the study, defines system boundaries, and identifies functional units, such as emissions per kilometer driven. Clear system boundaries are particularly important in EV studies because environmental outcomes can vary depending on whether the analysis includes battery production, infrastructure development, or electricity generation.

The second phase, life cycle inventory (LCI), involves the collection and quantification of inputs and outputs across all stages of the vehicle's life. For electric vehicles, this includes data on raw material extraction for battery components, energy consumption during manufacturing,

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electricity use during operation, and materials involved in recycling or disposal. The accuracy and reliability of this data significantly influence the credibility of the assessment.

Life cycle impact assessment (LCIA), the third phase, translates inventory data into measurable environmental impact categories such as global warming potential, resource depletion, water use, acidification, and human toxicity. In EV assessments, global warming potential is often a primary focus, but broader environmental indicators are increasingly considered to capture hidden costs associated with battery production and mineral extraction.

The final phase, interpretation, synthesizes results to identify critical impact stages and evaluate trade-offs. For electric vehicles, interpretation often reveals that while operational emissions are substantially lower than those of conventional vehicles, production-related emissions, especially from lithium-ion batteries, represent a significant upfront environmental burden. However, this initial impact may be offset over time depending on vehicle lifespan and electricity sources.

A central conceptual distinction in LCA is between cradle-to-gate, cradle-to-grave, and cradle-to-cradle approaches. Cradle-to-gate analysis covers impacts up to the factory exit stage, whereas cradle-to-grave extends to end-of-life disposal. Cradle-to-cradle emphasizes circularity, incorporating recycling and material recovery processes. For electric vehicles, adopting a cradle-to-cradle perspective is increasingly important as battery recycling technologies evolve and circular economy principles gain prominence.

the LCA framework provides a comprehensive and balanced method for assessing the environmental performance of electric vehicles. It moves beyond simplified comparisons based solely on tailpipe emissions and enables policymakers, manufacturers, and researchers to identify areas for improvement across the entire value chain. By grounding EV sustainability claims in systematic life cycle analysis, more informed decisions can be made regarding technology development, energy policy, and resource management.

Raw Material Extraction and Battery Production Impacts

The environmental profile of electric vehicles begins long before the vehicle reaches the road. A substantial share of total life cycle emissions is generated during the extraction of raw materials and the production of lithium-ion batteries. These early stages are energy intensive and resource dependent, making them critical components in any comprehensive assessment of electric vehicle sustainability.

Lithium-ion batteries require significant quantities of lithium, cobalt, nickel, manganese, graphite, and copper. The extraction of these minerals often involves open-pit mining, chemical processing, and high water consumption. Lithium extraction from brine deposits, commonly found in arid regions, can strain local water resources and disrupt fragile ecosystems. Hard-rock mining of lithium and nickel also requires substantial energy inputs, often sourced from fossil fuels, contributing to carbon emissions before battery assembly even begins.

Cobalt mining presents additional concerns. A significant portion of global cobalt supply originates from regions where mining practices have raised environmental degradation and labor rights issues. Beyond social considerations, cobalt processing generates hazardous waste and toxic byproducts that can affect soil and water quality if not properly managed. These



factors highlight that the environmental footprint of battery materials extends beyond greenhouse gas emissions alone.

Battery manufacturing itself is another major contributor to environmental impact. The production of cathodes, anodes, electrolytes, and battery cells requires high temperatures and controlled environments, which consume large amounts of electricity. In regions where electricity grids rely heavily on coal or other fossil fuels, the carbon intensity of battery production increases substantially. Studies consistently show that battery manufacturing accounts for a significant proportion of total electric vehicle production emissions.

Material refining and global supply chains further add to the environmental burden. Raw materials are often extracted in one country, processed in another, and assembled elsewhere. This geographically dispersed production network increases transportation emissions and energy consumption across multiple stages of the supply chain. The complexity of these supply chains also raises concerns about resource security and geopolitical dependency.

Despite these impacts, technological advancements are gradually reducing the environmental intensity of battery production. Improvements in energy efficiency, shifts toward renewable-powered manufacturing facilities, and the development of alternative battery chemistries with lower critical mineral content are contributing to more sustainable production processes. Additionally, efforts to increase recycled material content in batteries can reduce the need for virgin resource extraction.

raw material extraction and battery production represent the most environmentally intensive phases of the electric vehicle life cycle. While EVs offer clear operational advantages in terms of reduced tailpipe emissions, their overall sustainability depends significantly on improving mining practices, decarbonizing manufacturing processes, and strengthening circular economy strategies. Addressing these upstream impacts is essential for ensuring that electric mobility delivers meaningful long-term environmental benefits.

Vehicle Manufacturing Emissions and Energy Consumption

Vehicle manufacturing represents a significant share of the total environmental footprint of electric vehicles, particularly when assessed through a full life cycle perspective. Unlike conventional internal combustion engine vehicles, electric vehicles require additional components such as high-capacity battery packs, power electronics, electric motors, and advanced control systems. These elements increase material demand and energy use during the production phase.

The manufacturing process begins with the fabrication of the vehicle body and chassis, which typically involves steel and aluminum production. Aluminum, widely used in EVs to reduce vehicle weight and improve efficiency, is especially energy intensive to produce. Primary aluminum smelting requires large amounts of electricity, and if this electricity is generated from fossil fuels, it contributes significantly to carbon emissions. Similarly, steel production involves high-temperature processes that release carbon dioxide through both fuel combustion and chemical reactions.

Electric vehicle manufacturing also includes the assembly of electric drivetrains and battery integration systems. While electric motors generally require fewer moving parts than



combustion engines, they rely on materials such as copper and rare earth elements. The extraction and processing of these materials add to the overall environmental burden. Additionally, the installation of complex electronic systems increases the embodied energy within each vehicle.

One of the defining characteristics of EV manufacturing emissions is their concentration at the beginning of the vehicle's life cycle. Electric vehicles typically have higher upfront production emissions compared to conventional vehicles, primarily due to battery production and additional material inputs. However, these higher initial emissions may be offset over time through lower operational emissions, depending on electricity sources and vehicle usage patterns.

Energy consumption during manufacturing varies significantly across regions. Factories powered by renewable energy sources can substantially reduce the carbon intensity of vehicle production. In contrast, facilities operating in coal-dependent regions may produce vehicles with a considerably higher embedded carbon footprint. This regional variation underscores the importance of aligning vehicle electrification with broader industrial decarbonization strategies.

Technological improvements are gradually reducing manufacturing-related emissions. Advancements in lightweight materials, energy-efficient production techniques, and automated assembly processes contribute to lowering overall energy demand. Moreover, some manufacturers are investing in closed-loop material systems that recycle production scrap and reduce raw material waste.

vehicle manufacturing emissions constitute a critical component of the overall environmental performance of electric vehicles. Although EVs may begin their operational life with a higher carbon footprint due to production processes, strategic improvements in manufacturing efficiency, clean energy adoption, and material innovation can significantly enhance their long-term sustainability profile.

Conclusion

The transition to electric vehicles represents a significant step toward reducing emissions from the transportation sector, yet a comprehensive life cycle perspective reveals a more nuanced environmental picture. While electric vehicles eliminate tailpipe emissions and generally offer lower operational greenhouse gas outputs, their overall sustainability depends heavily on upstream and downstream processes. Raw material extraction, battery production, and vehicle manufacturing contribute substantial upfront environmental impacts that cannot be overlooked. Life Cycle Assessment demonstrates that the environmental advantages of electric vehicles are strongly influenced by contextual factors, particularly the carbon intensity of electricity generation. In regions with cleaner energy grids, EVs achieve meaningful reductions in lifetime emissions compared to conventional vehicles. Conversely, where electricity relies heavily on fossil fuels, the climate benefits are less pronounced. This underscores the need to integrate transportation electrification with broader energy system decarbonization. Battery production remains the most environmentally intensive stage, largely due to energy-demanding processes and dependence on critical minerals such as lithium, cobalt, and nickel. Addressing these



impacts requires improvements in responsible mining practices, supply chain transparency, and the development of alternative battery chemistries with lower environmental footprints. Expanding battery recycling and second-life applications can further reduce reliance on virgin resources and strengthen circular economy pathways. Over the long term, technological innovation, renewable-powered manufacturing, and efficient end-of-life management will play decisive roles in enhancing the environmental performance of electric vehicles. Policymakers must therefore adopt a holistic approach that considers not only vehicle adoption targets but also industrial practices, energy transitions, and material sustainability. electric vehicles offer clear potential for reducing transportation-related emissions, but their environmental superiority is not automatic or universal. A full life cycle approach provides the necessary framework for identifying trade-offs, guiding policy decisions, and ensuring that the shift toward electric mobility genuinely contributes to long-term climate and sustainability goals.

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