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Toward Greener Mobility: Comparing Environmental Footprint of Electric and Conventional Vehicles

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***Abstract*—This study applies a Life Cycle Assessment (LCA) framework to compare the environmental footprint of Battery Electric Vehicles (BEVs) and Internal Combustion Engine Vehicles (ICEVs) across production, use, and end-of-life phases. Results indicate that while BEVs generate higher emissions during manufacturing, particularly from battery production, their operational phase offers significant reductions in greenhouse gas (GHG) emissions compared to ICEVs. The environmental advantage of BEVs is strongly influenced by the regional electricity mix; grids with higher shares of renewable energy amplify their benefits, whereas coal-dependent grids diminish them. Sensitivity analysis highlights the importance of vehicle lifetime, charging efficiency, and recycling strategies in shaping life-cycle outcomes. Overall, BEVs demonstrate a net advantage in most scenarios, though achieving true environmental sustainability requires parallel efforts in energy system decarbonization, battery recycling, and circular economy practices.**

Keywords— electric vehicles, internal combustion vehicles, life cycle assessment, emissions, sustainability

I. INTRODUCTION

The transportation sector is a major contributor to global greenhouse gas (GHG) emissions, accounting for nearly one-quarter of the total emissions derived from fossil fuel consumption. Conventional internal combustion engine vehicles (ICEVs) are responsible for significant levels of urban air pollution and carbon dioxide (CO_2) emissions, which accelerate climate change [1]. Therefore, the transition toward low-emission alternatives, particularly electric vehicles (EVs), has become a crucial strategy in achieving the decarbonization goals of the global transportation system.

However, comparing EVs with conventional vehicles is complex due to their distinct emission profiles across different life cycle stages. EVs exhibit clear advantages during the operation phase since they produce no tailpipe emissions. Yet, their manufacturing phase (especially lithium-ion battery production) results in substantial carbon footprints [2]. Conversely, ICEVs are associated with lower production-related emissions but generate higher GHG emissions during use due to their reliance on fossil fuels [3].

Recent studies employing Life Cycle Assessment (LCA) approaches emphasize that the environmental benefits of EVs are highly dependent on a country's electricity mix. In coal-dependent grids, the net emission reduction of EVs is marginal [4]. In contrast, in regions with higher shares of renewable energy, EVs deliver significant reductions in GHG emissions [5]. Moreover, the trend toward larger and more powerful EVs, often referred to as super sized EVs, raises concerns since these vehicles increase energy consumption and production emissions, partially offsetting their environmental benefits [6].

Another critical dimension is the end-of-life management of EV batteries. Without proper recycling strategies, used batteries may contribute to environmental hazards and exacerbate the depletion of critical minerals such as lithium, cobalt, and nickel [7]. Consequently, innovations in recycling technologies and the development of next-generation batteries, including solid-state designs, are considered vital to achieving sustainable e-mobility [8].

Thus, the debate between EVs and conventional vehicles extends beyond operational efficiency and direct emissions. A holistic perspective that integrates the entire life cycle is required to evaluate the net environmental benefits of EVs. Such comprehensive research is also essential in urban logistics, where EV adoption could play a decisive role in reducing emissions [9]. Furthermore, embedding circular economy principles within the EV sector is indispensable to ensuring that the transition to greener mobility supports both climate goals and sustainable resource management [10].

II. METHODS

This study employs a Life Cycle Assessment (LCA) approach using a cradle-to-grave perspective to compare the environmental footprint of Battery Electric Vehicles (BEVs) and Internal Combustion Engine Vehicles (ICEVs). The system boundaries include production (with a particular focus on the battery), usage, and end-of-life stages [11].

In the production phase, material and energy inventories are collected for each major component: the vehicle body, the powertrain, and most importantly, the lithium-ion battery. Battery composition (cobalt, nickel, lithium, etc.), manufacturing processes, and the source of electricity used in factories are incorporated as variables. Previous studies have shown that both the battery and the electricity source significantly influence LCA outcomes [12].

For the usage phase, a driving distance assumption (e.g., 150,000 km to 200,000 km) is adopted as the functional unit. Energy consumption of BEVs is calculated based on motor efficiency, while indirect emissions from electricity generation (if grid-dependent) are assessed according to the carbon intensity of the electricity mix in the study region [13].

Scenario modeling is also applied to compare current electricity mixes with future projections. This approach captures how grid decarbonization may influence the relative environmental performance of BEVs over ICEVs in the long term [11][14].

Sensitivity analysis is conducted on key parameters such as vehicle lifetime, battery capacity, charging efficiency, and the share of renewable energy in the electricity mix. This aims to evaluate how sensitive the results are to variations in these assumptions [15].

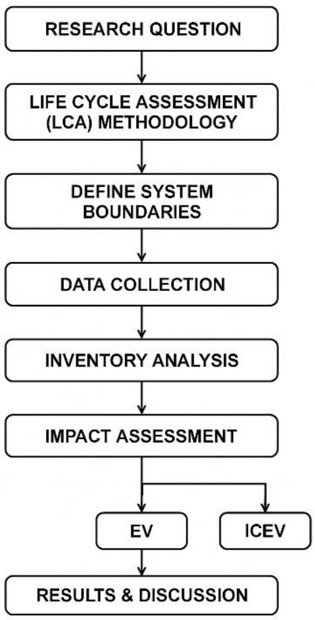

Fig. 1. Research Methodology

The environmental impact indicators assessed include Global Warming Potential (GWP), Greenhouse Gas (GHG) emissions expressed as CO_2-equivalent, cumulative energy demand, consumption of critical materials, and additional categories such as human toxicity and ecosystem degradation where data are available [16].

The Life Cycle Inventory (LCI) methodology draws on publicly available and verified databases such as Ecoinvent, as well as national or institutional datasets on energy and environmental statistics. Impact calculations follow the ISO 14040/44 standards to ensure comparability and consistency across studies [12][17].

For the end-of-life phase, recycling and disposal scenarios are incorporated. Battery recycling rates, recycling technologies (e.g., hydrometallurgical processes), and potential second-life applications are considered, as these factors can significantly alter the overall environmental footprint of the life cycle [15][18].

Analytical tools such as *OpenLCA* or equivalent software are employed to model the material and energy inventories as well as environmental impacts. GHG emissions are converted into CO_2-equivalents to allow direct comparison between BEVs and ICEVs [13][14].

Finally, validation is carried out by benchmarking the results against recent studies and by analyzing regional variations in electricity carbon intensity, fuel composition, and vehicle usage conditions (e.g., in developing versus developed countries). This step is essential to reduce biases linked to specific contextual assumptions [14][16].

III. Result

This chapter presents the results of the LCA conducted to compare the environmental footprint of EVs and ICEVs. The discussion is structured to reflect the major stages of the vehicle life cycle, beginning with the production phase, where battery manufacturing and critical material use contribute significantly to initial emissions, followed by the usage phase, which emphasizes operational energy consumption and the influence of electricity mix on overall performance.

A. Emissions in the Production Phase

The production of electric vehicles (EVs) generally results in a higher carbon footprint compared to internal combustion engine vehicles (ICEVs) during the initial stage, primarily due to the high energy requirements of lithium-ion battery manufacturing. The extraction of lithium, cobalt, and nickel demands significant energy and generates substantial CO_2 emissions [19]. Recent Life Cycle Assessment (LCA) studies indicate that EV production emissions can be 1.5–2 times higher than those of conventional vehicles with comparable engine capacity [20].

TABLE I. Comparison of Production Emissions EV vs ICEV

Aspect	***EV***	***ICEV***
Vehicle production emissions	8–12 t CO_2-eq	5–7 t CO_2-eq
Battery contribution	3–5 t CO_2-eq	-
Main manufacturing energy	Electricity	Oil, gas, electricity
Critical materials	Li, Ni, Co, Al	Steel, Al, Cu
Potential reduction	Up to 40%	Limited

Another key factor is the electricity mix used in battery manufacturing plants. When production relies on coal-based electricity, battery-related emissions increase substantially. Conversely, when renewable energy sources dominate the grid, production-phase emissions can be reduced by 30–40% [21]. This highlights how regional variations in the energy mix critically affect the environmental performance of EVs from the very beginning of their life cycle.

In addition to batteries, the overall manufacturing of EVs requires large amounts of critical materials. The high content of aluminum and copper in EVs increases production energy intensity since both metals require extraction and refining processes with considerable carbon emissions [22]. This means that while EVs are environmentally beneficial in the usage phase, their production phase still represents a significant burden.

Nevertheless, when evaluated over the full life cycle (*cradle-to-grave*), most studies confirm that EVs remain environmentally advantageous. The higher emissions in the production stage are offset by lower operational emissions, especially in regions with increasingly decarbonized power systems [23]. Therefore, decarbonizing battery production and shifting manufacturing toward renewable energy sources are crucial strategies for reducing EVs' overall carbon footprint.

B. Emissions During the Use Phase

In the use phase, Battery Electric Vehicles (BEVs) do not generate direct tailpipe emissions, meaning that their operational footprint depends entirely on the electricity used for charging and the efficiency of the electric drivetrain. In contrast, Internal Combustion Engine Vehicles (ICEVs) continuously emit pollutants during fuel combustion. A recent study comparing BEV and ICEV energy consumption under different traffic control conditions found that BEVs consistently require less energy across various speed ranges and driving conditions, highlighting their superior energy performance [24].

The carbon intensity of the electricity mix plays a critical role in determining BEV emissions. When electricity is primarily sourced from renewables or low-carbon generation, BEVs achieve substantially lower greenhouse gas (GHG) emissions compared to ICEVs. Conversely, in regions where coal or fossil-based electricity dominates, the emission advantage of BEVs diminishes. For example, an empirical analysis in Portugal reported that with an average grid intensity of 166 gCO_2e/kWh, BEVs still demonstrated significantly lower operational emissions than petrol ICEVs, although the benefits were less pronounced than in fully renewable scenarios [25].

TABLE II. ENERGY CONSUMPTION AND OPERATIONAL EMISSIONS OF BEV VS ICEV

Vehicle Category	***BEV Energy Consumption (kWh/100 km)***	***ICEV Fuel Consumption (L/100 km) & Emission Comparison***
Small passenger car (Portugal)	16.0	6.5 L/100 km (petrol ICEV); BEV = 70% lower emissions
Mixed BEV models (China, 2020–2022)	1,095–1,364 kWh/year per vehicle	Emissions decreased as grid intensity improved

Energy efficiency is another key differentiator. According to the U.S. Department of Energy and National Renewable Energy Laboratory (NREL), ICEVs typically lose around 60–70% of energy during fuel combustion, while BEVs lose only about 15–20% from charging to wheel motion. This makes BEVs approximately 2.5–4 times more energy efficient than ICEVs, resulting in much lower energy consumption per kilometer driven [26].

Overall, operational CO_2 emissions per kilometer are significantly lower for BEVs than for ICEVs, though results vary depending on regional electricity mixes and vehicle lifetimes. In coal-dominated grids, BEVs may only achieve modest reductions compared to ICEVs, while in low-carbon electricity systems, the reduction can be substantial. A bottom-up assessment of BEV operations in China (2020–2022) confirmed that as grid intensity decreases and charging efficiency improves, annual per-vehicle carbon emissions also decline, underscoring the dynamic link between BEV performance and the electricity system [27].

C. End-of-Life Analysis

End-of-life lithium-ion batteries from electric vehicles contain valuable materials such as nickel, cobalt, lithium, copper, and aluminum that can be recovered for reuse in the production cycle. According to the International Energy Agency (IEA), recycled feedstock from end-of-life EV batteries and stationary storage systems is expected to account for more than 90% of total supply by 2050 [28]. The recovery rate depends on battery chemistry and the efficiency of recycling technologies. For instance, typical EV Li-ion batteries consist of approximately 10–20% nickel, 5–15% cobalt, 10–20% manganese, 5–10% lithium, and additional amounts of copper and aluminum, all of which can be efficiently targeted in modern recycling processes [29].

EV batteries that no longer meet the performance requirements for mobility applications (often below 80% of their initial capacity) still retain sufficient residual capacity for stationary energy storage. Salek et al. [29] demonstrated that retired Nissan Leaf batteries with 75–80% remaining capacity can effectively be repurposed in residential storage systems coupled with photovoltaic (PV) generation, thus extending their useful life and reducing the demand for new batteries. Furthermore, second-life batteries have been shown to provide both technical and economic benefits in hybrid PV-storage systems, though challenges such as certification, degradation behavior, and safety concerns must be carefully managed [30].

TABLE III. KEY DATA SOURCES FOR END-OF-LIFE BATTERY ANALYSIS

Source	***Key Data Extracted***
International Energy Agency (IEA)	End-of-life EV batteries and stationary storage projected to supply >90% of recycled materials by 2050; influence of battery chemistries such as LFP on recycling value.
A. Salek et al.	Residual capacity of 75–80% in retired EV batteries; potential integration into PV-battery hybrid residential systems; technical feasibility of second-life use.
S. Hao et al.	Capacity retention at end of first life (80%) and second life (65%); lifetime extension of 5–12 years; cascading benefits of combining second-life and recycling.

Despite the promising potential of recycling and second-life use, several challenges remain. First, variability in the State of Health (SoH) and State of Charge (SoC) of retired batteries complicates their safe integration into second-life systems. Second, recycling processes that involve solvents or high-temperature treatments can themselves introduce environmental burdens if not managed responsibly. Finally, the supply chains of critical materials like cobalt and lithium are often associated with environmental and social issues (e.g., mining impacts, labor conditions), making efficient recovery and strict regulatory frameworks essential [28], [29].

A cascading use model (deploying batteries in less demanding second-life applications before final recycling) offers the greatest environmental benefit. Hao et al. [30] showed that EV batteries typically retain about 80% of their initial capacity at the end of first life and around 65% at the end of second life, extending their lifetime by 5–12 years in stationary storage applications. This sequential approach reduces the overall environmental footprint while maximizing material recovery at the final recycling stage. However, economic barriers remain, including costs of collection, logistics, and the need for more efficient and environmentally friendly recycling technologies [30].

D. Emissions in the Production Phase

Significant differences arise when comparing LCA outcomes of electric vehicles (EVs) in developed versus developing countries. In developed regions, where electricity grids are increasingly supplied by renewable sources such as hydropower, wind, and solar, the operational emissions of EVs are substantially lower compared to internal combustion engine vehicles (ICEVs). In contrast, developing countries that remain highly dependent on coal or fossil fuels for power generation show much smaller environmental benefits from EV adoption, and in some cases, EVs may not significantly outperform ICEVs in life-cycle terms. A recent comparative LCA study found that in Brazil, where hydropower dominates, the life-cycle global warming potential (GWP) of a battery electric vehicle (BEV) is about 18,000 kg CO_2-eq under 2023 and 2030 grid scenarios, while in coal-dependent South Africa, the GWP reaches approximately 39,320 kg CO_2-eq in 2023 [32].

Future scenarios involving grid decarbonization considerably increase the environmental advantage of EVs. If developing countries increase the share of renewable energy within their power mix by 2030, the GWP of BEVs can decline substantially, with the largest improvements observed during the use phase of the vehicle. Nevertheless, the battery production stage remains a significant contributor to total life-cycle emissions, especially in contexts where the electricity mix is not yet fully decarbonized [32].

TABLE IV. ENERGY CONSUMPTION AND OPERATIONAL EMISSIONS OF BEV VS ICEV

Country / Region	*Grid Electricity Profile (Major Source)*	*Life-cycle GWP of BEVs*
Brazil (developing)	Hydropower-dominated	18,000 kg CO_2-eq (2023, 2030 scenarios)
South Africa (developing)	Coal-dependent grid	39,320 kg CO_2-eq (2023)
Developed regions (e.g., EU, USA)	Increasing renewable share, decarbonizing policies	BEVs = 50% of ICEV life-cycle emissions (2023)

In developed countries, EVs already outperform ICEVs in life-cycle emissions under current grid conditions, and this advantage is expected to expand with further decarbonization. The Global EV Outlook 2024 from the International Energy Agency (IEA) highlights that mid-sized BEVs sold in 2023 emit roughly half the life-cycle emissions of comparable ICEVs under the Stated Policies Scenario (STEPS), with even lower values projected in the Accelerated Policy Scenario (APS), largely due to cleaner electricity generation [31].

However, implementing grid decarbonization scenarios in developing countries presents several challenges, including investments in renewable energy infrastructure, transmission networks, energy storage capacity, and supportive regulations. Even if cleaner energy sources are introduced, the timing of adoption strongly influences outcomes: the longer fossil-fuel-based grids dominate, the greater the "carbon debt" from battery production before operational savings offset the initial emissions. Thus, future regional scenarios must consider vehicle lifetime, annual mileage, and charging efficiency to realistically capture the life-cycle environmental benefits of EVs [31], [32].

IV. CONCLUSION

The comparative life cycle analysis confirms that EVs offer substantial environmental advantages over ICEVs, particularly during the operational phase where the absence of tailpipe emissions directly reduces GHG emissions and urban pollution. However, the higher production-phase burden of EVs, largely attributed to battery manufacturing, remains a critical challenge. This burden can be mitigated by decarbonizing electricity used in production facilities and by adopting innovative battery technologies with lower material and energy requirements.

Regional and future scenario analysis further reveals that the benefits of EVs are not uniform. In developed regions with rapidly decarbonizing grids, EVs already achieve significant life-cycle emission reductions, while in developing countries with fossil-fuel-based grids, the advantages are less pronounced. The transition to greener mobility therefore depends not only on expanding EV adoption but also on accelerating renewable energy integration, advancing battery recycling, and embedding circular economy strategies to ensure long-term sustainability.

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