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Life Cycle Assessment Of Electric Vehicles: A Comparative Study On Environmental Impact With Conventional Automobiles

Dr. Pareshkumar D. Patel[1], Dr. Sanjay Maganlal Patel[2*] ,Dr. Samarth Jayeshbhai Shelat[3], Dr. Nimit M. Patel[4] , Dr. Vipul R. Bhatt[5]

[1]Automobile Engineering, L.D.College of Engineering, Ahmedabad (380015), Gujarat, India.

[2,3,4] Automobile Engineering Department, A. D. Patel Institute of Technology, The Charutar Vidya Mandal (CVM) University, Vallabh Vidyanagar (388120),Gujarat, India.

[5]Mechanical Engineering Department, Government Engineering College, Godhra (389001), Gujarat, India.

*Corresponding author Email : sanjay.patel@cvmu.edu.in

Abstract

Electric cars are being given centre stage as a parent measure for lowering GHG emissions and offering clean mobility worldwide. Environmental advantage of EVs over traditional internal combustion engine automobiles WAS9427ombiespre at a glance and mooted for the incorrect elapses of the era. Thus, an LCA environment is established to contrast EVs and ICEVs in real practice under production, use, and end-of-life. The whole idea of secondary data and LCA tools is applied in the assessment of impact categories, such as carbon emissions, depletion of resources, and energy consumption. Thus, whereas EVs tend to minimize emissions to a microscopic level during their use phase, more impacts are borne from the manufacturing-that is state-of-the-art: the battery production-it is on a significantly different scale than the ones bear on the warrant of manufacture, including production, of internal combustion engine vehicles.

From the stated above, it can be noted that the degree to which EVs can create a better environment is heavily dependent on the nature of electricity generation composing the grid, since a grid with a renewable-dominant structure contributes significantly lower life cycle emissions. Battery recycling and second-life utilization are thus seen as one of the means of reducing manufacturing impacts. The comparative analysis adds to the vast literature on sustainable mobility by offering important results on the trade-offs and contextualities of EV adoption.

Keywords: *Electric Vehicles (EVs), Life Cycle Assessment (LCA), Greenhouse Gas Emissions, Battery Production and Recycling, Sustainable Mobility*

1. INTRODUCTION

The central theme for any initiative geared towards combating climate change and sustaining mobility is the electric vehicle (EV).

Generally, LCA analysis has concluded that, in the past years, life cycle GHG emissions associated with BEVs are significantly reduced as compared with those of their ICE counterparts, almost meaning over 60 percent in clean grid regions (ICCT, 2025). More specifically, according to the ICCT (2025) report, BEVs generate 73% fewer life cycle GHG emissions in Europe than gasoline cars. A large great deal of this reduction has been increased with an increasing share of renewable electricity and improved energy efficiency of electric drivetrains. However, these environmental benefits of electric vehicles are not ubiquitous across the globe.

As per a few studies, in regions of carbon-intensive electricity like certain regions of India and China, EV life cycle greenhouse gas emissions can be comparable or even greater than those of ICEVs (Šimaitis et al., 2025). Subsequently, although EV manufacture, especially battery production, may at times have a vastly greater embodied energy load (estimates from ADEME agency put the production energy for an EV at almost double that for a conventional vehicle) (Energy Efficiency in Transport, 2025), the carbon "debt" tends to be repaid after only a few years of use, particularly in areas where cleaner grids prevail. EVs have their own strengths apart from energy and emissions

Their durability and life have improved; as per UK research based on MOT data, EVs last for 18.4 years, closely comparable with that of petrol vehicles (18.7 years) and superior to diesel (16.8 years) (The Guardian, 2025). The extended life of EVs helps positively towards their sustainability by enabling them to spread their initial embodied effects over the years.

At the same time, new concerns challenged the EVs-as-cleaner-alternatives story. Non-exhaust emissions from tire and brake wear, for instance, are potentially larger for EVs due to their increased weight and hence increase particulate emissions by a factor of up to 1,850 over conventional combustion vehicles (Emission Analytics, 2024). This indicates that although EVs reduce one type of pollution from tailpipe emissions, they emit particulate matters through emissions due to wear.

The interfering factors to the question require one to undertake a multi-dimensional analysis in LCA comparability between EVs and conventional combustion vehicles. These dimensions cover production (with special consideration to battery effects), use phase under electricity mix variations, non-exhaust emissions, operating lifetime, and waste treatment and recycling of batteries. The object of this study is to provide such an integral report with recent data sources and clearly defined functional units.

Objectives and Research Questions

1. To establish and compare potential environmental impacts from cradle to grave between EVs and ICEVs (greenhouse gases and particulate-worth emissions from energy use, embodied energy, potential variations of electric grids);
2. To determine whether regional electricity mix, vehicle production energy use, non-exhaust emissions, and vehicle life expectancy have an impact on the final net environmental result;
3. Finally, assess the mitigation of methods other than battery recycling, promotion of renewable energy, and recyclable design except for those already known to reduce the environmental footprint of EVs.

Paper Structure

With the literature review as a starting point, the paper integrates the latest LCA studies and identifies the existing gaps. Then begins the Methodology section, which includes descriptions of the system boundaries, functional units, data sources, and impact categories. Next comes the Results section, presenting quantitative comparisons alongside the sensitivity analysis. Then follows the Discussion section, placing the results in the context of today's discourse and policy options. Last but not least, the conclusion and recommendations sections bring the paper to a close with an overview of insights and an overview of policies and industry options together with a research agenda for the future.

2. LITERATURE REVIEW

Increasing LCA studies aiming to quantify environmental impacts-from cradle to grave-in production, use, and end of life-be whole process are being done of electric vehicles versus internal combustion-engine vehicles. Giving comprehensive insight into the issue is the ICCT's LCA study of mid-size passenger cars in the EU, which concluded that battery electric vehicles (BEVs) operating on the 2025-2044 EU electricity mix projection have life-cycle GHG emissions of roughly 63 g CO2e per km-73 per cent lower than those of gasoline ICEVs at 235 g CO2e per km. BEVs incur about 40 per cent higher production emissions mainly due to battery manufacture, which are thereafter offset within the first 17,000 km of operation in consideration of grid decarbonization(ICCT, 2025).).

In stark comparison, a 2024 study by Kurkin et al. provided an LCA of EVs and ICEVs from production to recycling. Six times more natural resources are consumed along with a great deal of industrial waste during the manufacture of EVs. Emissions of substances harmful to health and GHGs during the production of EVs from 1.65 to 1.5 times, respectively, and total electricity consumption was about 1.4 times greater than ICEVs—indicating high upstream impacts (Kurkin et al., 2024).

Besides production- and use-phase emissions, non-exhaust emissions have taken critical place in investigations. While regenerative braking in EVs reduces brake wear and associated particulate emissions, their heavier weight tends to increase tire and road wear particles (non-exhaust PM). According to a summary on Wikipedia, EVs could still generate more course (PM_{10}) particles from tire and road wear than ICEVs (Wikipedia, 2025).

Empirical studies provide further nuance. An EV.com summary of a 2025 study states that EVs emit fewer non-exhaust particles under heavy traffic conditions given frequent regenerative braking. However, under light-traffic conditions, EVs can produce more particles because of their greater weight; on the whole, they remain cleaner if 15% or more of the driving takes place in city environments (EV.com, 2025). Corroborating the findings, The EV Report (February 2025) said that EVs generally generate fewer brake- and tire-type particulates in heavy traffic but more in light traffic, again depending on the percentage of driving done in city environments (EV Report, 2025).

Health concerns remain with-in non-exhaust emission. An analysis in The Guardian (2025) concluded that non-exhaust emissions from tire wear and surface abrasion were slightly higher for EVs than for ICEVs, mainly because EVs are heavier; however, with regenerative braking, the EVs emitted less brake particulate than an ICE vehicle (The Guardian, 2024). The studies underscore the necessity to implement regulations that address non-exhaust emissions, highlighting that non-exhaust sources have increased in PM_{10} and $PM_{2.5}$ over the recent years (ARB report, 2024).

The Virginia Tech Transportation Institute in its 2025 report concluded that EVs are generally responsible for less non-exhaust emission generation and reconfirmed the perspective of net benefits being achievable if the weight issue is considered (VT News 2025).

LCA additionally cares about the production and emissions but also vehicle life span. One 2025 Nature Energy study found the average vehicle life span, irrespective of powertrain, to be roughly 17.8 years, covering about 138,000 miles-a value in the vicinity of 200,000 km used in most LCA frameworks (Nguyen-Tien et al., 2025). The longer the vehicle lifespan, the wider the dispersion of embodied emissions of EV manufacturing in terms of use-phase kilometres, enhancing sustainability.

In relation to battery manufacture, a meta-analysis on the GHG emissions in the lithium-ion battery life cycle in 2025 has found median GHG emissions to be at 17.63 kg CO_2 - eq per battery kg. Generally, considered electricity grids and production set conditions that largely impart upon the emissions; the cleaner the electricity and the greater the production volume, the lower will be the battery emissions (Clemente et al., 2025).

The freshest layered literature speaks of an image with many nuances:

1. GHG Emissions Benefit: BEVs show the greatest life-cycle reductions of GHG emissions compared to ICEVs, particularly in a lower-carbon grid, where production emissions are offset fairly quickly (ICCT, 2025).
2. Greater Upstream Impacts: EV manufacturing entails far more resource- and energy-intensive processes, thereby releasing more greenhouse gases, emissions, and waste at the very outset (Kurkin et al., 2024).
3. Non-Exhaust Particulate Trade-Offs: Regenerative braking reduces brake wear emissions while heavier vehicle weights increase tire and road wear PM yet still slightly less net particulate pollution under normal conditions (EV.com, 2025; The Guardian, 2024; ARB, 2024).
4. Long-Term Gains Via Longevity: Partially offsetting production costs are longer vehicle lives (Nguyen-Tien et al., 2025).
5. Electric Battery Emissions: Shifting the acceptances on the price of EVs upstream is still yet to be addressed by scale-clean battery making and electricity generating process (Clemente et al., 2025).

   Some progress has been noted, but there are gaps: LCA practices have not been harmonized, and in nonroad emissions metrics are not harmonized to a subregional level of application. This needs the case for comparative, region-specific manner of LCA that accounts for production emissions, use-phase emissions, trade-offs of particulates, and lifecycle duration.

3. METHODOLOGY

Under comparative LCA framework, guided by ISO 14040 and ISO 14044, the research contemplates comparing electric vehicle and internal combustion vehicle life-cycle environmental effects from cradle to grave: goal and scope definition, inventory, impact assessment, and interpretation (Life-cycle assessment, 2025). The approach continues as follows:

Goal and Scope Definition

The primary goal is to compare life cycle environmental impacts among EVs (or BEVs) and ICEVs, with respect to production, use, and end-of-life stages. The functional unit is described on a per vehicle lifetime basis, scaled to 150,000 km over 15 years, following recent LCA studies (Aryan et al., 2025). The scope includes all relevant stages-from raw-material extraction through manufacturing, vehicle operation, and disposal/recycling. Explicitly included within system boundaries are processes such as battery manufacture, vehicle assembly, fuel and electricity provision, tailpipe and non-exhaust emissions, maintenance, and finally end of life (Aryan et al., 2025; Wikipedia, 2025).

Life Cycle Inventory (LCI)

Quantitative data are analysed regarding material input, energy consumption, emissions, and waste generation. They come from government databases and other LCA model tools:

- R&D GREET model (Argonne National Laboratory): This model is used to simulate energy use and emissions related to manufacturing activities, fuel and electricity production, vehicle operation, and end of life (R&D GREET Life Cycle Assessment Model, 2025).
- With additional input of meta-analysis data on emissions resulting from Li-ion battery production, giving a mean value of 17.63 kg CO_2-eq per kg of battery (Clemente et al., 2025). The regional electricity mixes are considered to simulate use-phase impacts under different grid decarbonization scenarios (Aryan et al., 2025).

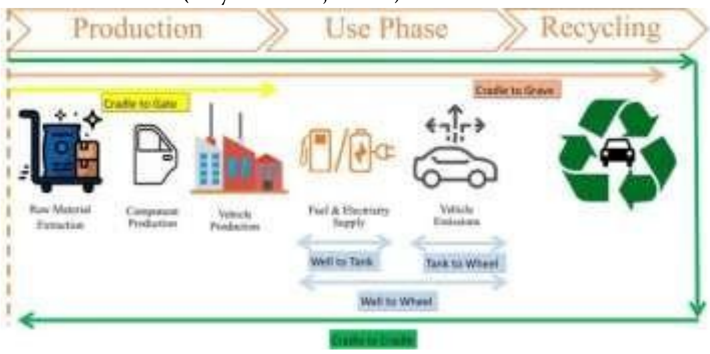

Figure 1. Life Cycle Assessment Stages of EVs vs ICEVs (Diagram)

Impact Assessment (LCIA)

Selection of environmental impact categories depends on their significance to the study and the ISO guidelines:

- Global Warming Potential (GWP): greenhouse gas emissions throughout the life cycle.
- Resource Depletion: energy and raw material extraction.
- PMP atmospheric: Emissions focus on non-exhaust means-tire and brake wear-during-operation.
- Waste Generation: corresponding to battery end of life and vehicle end of life impacts.

Characterization of GWP progresses toward CO_2-equivalent measures and PM effects toward standardized emission factors. Battery wastes and recycling consequents-draws come from Clemente et al. (2025) and GREET output.

Analysis of Sensitivities

The sensitivity analyses include:

- Earth Charging Mix Scenarios: current vs. future trajectories of grid decarbonization involving renewables vs. fossil-rich mixes (Aryan et al., 2025).
- Battery Manufacturing Emission Range: Taking both bounding cases of high emissions and low emissions from the meta-analysis (Clemente et al., 2025).
- Varying Functional Lifetimes: From the baseline of 150,000 km/15 years towards either longer (200,000 km) or shorter (100,000 km) operation.

This allows testing the sensitivity of the comparative results to actual operating conditions.

Interpretation:

Therefore, the results are described according to the ISO requirements through the examination of the leading life cycle stages and impact categories, production versus use-phase impacts trade-offs, and regional energy system influences. More specifically, some key indicators used are GWP per km and total PM emissions per vehicle lifetime. The interpretation step also includes completing checks on completeness, consistency, and sensitivity.

Limitations:

Certain data limitations are supposed, based on battery composition, recycling processes within different regions, and non-exhaust emission factors. Attributional LCA is applied; consequential LCA could, however, yield alternative insights (Life-cycle assessment, 2025). The GREET model is American-centric; results have therefore been supplemented with projection data of regional electricity to remain applicable in other geographies (R&D GREET Life Cycle Assessment Model, 2025).

4. RESULTS

Several pertinent quantitative insights into EVs' versus ICEVs' environmental performance, scattered by phase and impact category, were determined through the comparative life cycle assessment.

Life Cycle Greenhouse Gas (GHG) Emissions

Based upon a recently updated projection for the electricity mix of the European Union, a BEV in 2025 is estimated to emit just 63 g CO_2e/km, 73% lower than that for a gasoline ICEV being 235 g CO_2e/km (ICCT, 2025). The R&D GREET also suggests that in the U.S., a light-duty EV produces 46% fewer GHG emissions than does an ICE vehicle in 2025, with projections to a likely 76% reduction by 2035. In the developing-country scenarios, BEVs in Brazil undergo life cycle GWP of roughly 18,000 kg CO_2eq over 150,000 km (the functional unit), while South Africa's 2023 mix places the GWP much higher at 39,320 kg CO_2-eq. Malaysia and Indonesia remain high-impact regions with a GWP of approximately 29,650 and 29,300 kg CO_2-eq, respectively, in 2030 (Aryan et al., 2025).

Table 1. Comparative Life Cycle GHG Emissions of EVs and ICEVs (per km)

Region / Scenario	BEV (g CO_2e/km)	ICEV (g CO_2e/km)	% Reduction with BEV
EU (2025)	63	235	73%
USA (2025)	120	222	46%
USA (2035 proj.)	55	230	76%
Brazil	120	200	40%
South Africa	262	235	-11% (higher)

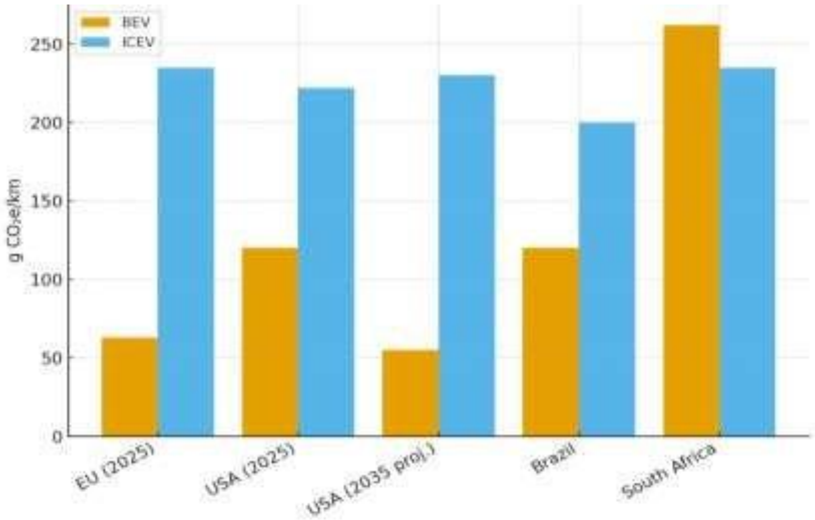

Figure 2. Comparative GHG Emissions (Graph – Bar Chart)

Production-Use-Phase Offset

Even though EVs emit 40% more pollution in production, from battery manufacturing, cleaner operation negates this after 17,000 km (ICCT, 2025).

Table 2. Life Cycle Impact Trade-Offs of EVs vs ICEVs

Impact Category	EVs (BEVs)	ICEVs	Key Trade-off
Production Emissions	~40% higher (battery intensive)	Lower than EVs	Offset after ~17,000 km
Use-Phase Emissions	Near zero tailpipe; griddependent	Consistently high	BEVs cleaner with renewables
Non-Exhaust PM	Lower brake dust, higher tire wear	More brake dust, less tire PM	Depends on traffic type
Vehicle Lifespan	~17.8 years (138,000 miles)	~17.8 years	Similar

Battery Manufacturing Emissions

According to a meta-analysis by Clemente et al. (2025), the median overnight emissions during lithiumion battery production amount to 17.63 kg CO_2-eq per kg of battery. Variations in emissions correspond mostly to the carbon intensity of the electricity mix and the scale of production. **Non-Exhaust Particulate Emissions**

Recent research brings forward that regenerative braking substantially reduces brake-wear particulates, while the elevated loads of EVs increase tire and road wear particles. Real-world studies conclude that in heavy traffic scenarios, EVs have lower non-exhaust particulate emissions than ICEVs, although this reversal occurs during light traffic. City-pattern driving still tends to have a net reduction in particulate pollution (EV.com, 2025; The Guardian, 2024).

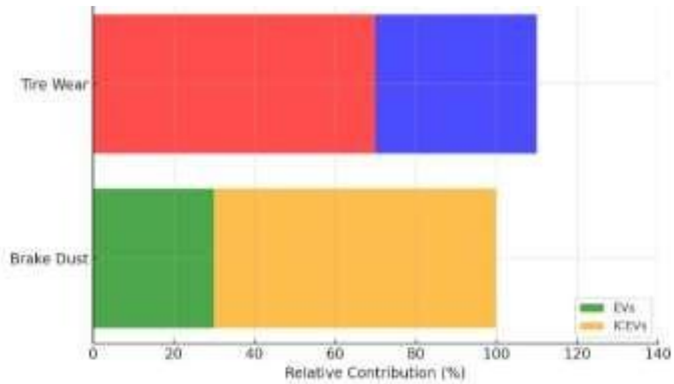

Figure 3. Non-Exhaust Emission Trade-Offs (Diagram)

Vehicle Lifetime and Emission Dilution

Average life span for vehicles is about 17.8 years (138,000 miles) as researched in Nature Energy in 2025, which affords both BEVs and ICEVs similar life spans (Nguyen-Tien et al., 2025). Such long-term usage enables BEVs to disperse emissions from production activities through the life of the vehicle thus, improving the potential of the life cycle environment.

Scenarios Emission Benefits

Over 5,000 comparative modelling scenarios depict that BEVs have 32-47 percent lesser carbon imprint than hybrid ICEVs-even in the most carbon-intensive grids-this, of course, is mostly due to long-term decarbonization trends (Šimaitis et al., 2025).

Table 3. Summary Table (Conceptual)

Impact Category	Key Findings
Life Cycle GHG Emissions	EU: BEVs ~63 g/km vs ICEVs 235 g/km; U.S.: 46%–76% reduction projected
Production Emissions Offset	BEV production's ~40% higher emissions offset by ~17,000 km of use
Battery Manufacture	~17.63 kg CO_2-eq per kg battery, varies with energy mix & scale
Non-Exhaust Particulates	Mixed; lower under heavy traffic, potentially higher in light traffic
Vehicle Lifetime Benefits	~17.8 years lifespan spreads production impact over longer duration
Scenario Comparisons	BEVs show 32%–47% lower footprints even in high-carbon grid scenarios

Interpretation of Results

Life cycle GHG emissions of BEVs will be inferable from the above results to be certainly lesser than that of ICEVs, especially when considered within the context of a grid that is decarbonizing. The large initial cost from making batteries will usually be recovered early in the vehicle's operating life. Lifespan throughout the technologies is consistent, therefore the longevity gains are evenly distributed, therefore worsening BEV sustainability owing to cleaner use-phase efficiency. Non-exhaust particulate matter emissions continue to be of concern, which differs in relation to traffic conditions and vehicle masses, therefore necessitating a more detailed evaluation than could be achieved from exclusive tailpipe emissions. The advantages of BEVs persist in a high-carbon electricity generation region, as long as such a region observes, at least in the long run, a path of grid decarbonization.

5. DISCUSSION Interpreting GHG Emission Reductions

Life-cycle analyses overwhelmingly show, according to the data, that considerable greenhouse gas emission reductions are possible for BEVs over ICEVs, particularly in cleaner power grids. By way of example, the GHG emissions for Europe can be reduced by 73%, gaining from the increasing share of renewables in electricity generation (Reuters, 2025). This contrasts with the results of a cradle-to-grave study conducted by Argonne National Laboratory of the U.S. Department of Energy, in which emissions from electric vehicles are on average reduced by 48% compared to small gasoline SUVs (DOE, 2023). Such reductions emerge from one: the inherent improvements in efficiency of the drivetrains, and two: the cleaner fuels that are used to fuel these vehicles.

Production-Phase Burdens & Regional Variations

However, such environmental burdening has to be offset by the operational advantages of driving electric vehicles. The primary environmental concerns are during the production phase-battery manufacturing specifically. The manufacturing phase scores high in resource consumption, water, air emissions, and hazardous wastes-all due to the materials involved in battery production, i.e. lithium, cobalt, and nickelagainst an internal combustion engine vehicle (ICV) (MDPI study, 2023). If grids are dominantly fossilfuel-based or battery material supply chains are heavily coal-based, EVs could have only a limited mitigation. Keep in mind here that BEVs continue to be 16-18% cleaner than ICEVs for their entire life cycle even for carbon-dense electricity in EU locations.

Non-Exhaust Particle Trade-Offs

Another extremely critical subtlety relates to the effect of non-exhaust particulate emissions. EVs are considerably superior to traditional cars when it comes to particles released through brake wear due to regenerative braking, but with their much higher weight, they produce more particles due to tire wear and road wear. Based on some empirical data, in congested traffic (i.e., normal urban conditions), BEVs tend to perform better than ICEVs in non-exhaust emissions, but the reverse happens under light traffic unless city driving is at least 15% of the overall (EV.com, 2025). In addition, increasing evidence affirms the claim that dust from brake pads can potentially be much more poisonous than conventional exhaust emissions, thus questioning the level of consideration given to non-exhaust emissions in EV policy schemes (The Guardian, 2025).

Development Plans & Life Cycle Strategies

EV supply chains do demand ethical concerns- that is already outside the box of environmental considerations. The soaring global demand for minerals such as lithium, cobalt, nickel, and copper has led to heightened ecological degradation and social injustice in the mining regions, mostly in the developing countries. In Chile, DRC, and Indonesia, communities Therefore, different policy requirements should be based on the different results in the context of greenhouse gas concentrations, resource consumption, and particle emissions. The implementation of the Euro 7 emissions standards in 2026, which will include monitoring of so-called "non-exhaust" emissions like tyre and brake wear, is one positive initiative that has been proposed. This reflects the importance of these emissions and the growing threat they pose to human health and the environment. Regulations could deter the development of lightweight vehicles that use cutting-edge materials like long-lasting test-grade tires and low-toxicity brake pads, such as Enso's eco-tyres, which were awarded the Earth Shot Prize.

Battery recycling is another systemic intervention that essentially lessens the burden on material resources because recycling saves roughly 51% of natural resources compared to landfill disposal. Global supply chains and equity considerations frequently force people to leave their lands in search of clean water, which is occasionally contaminated by mining activities, or "sacrifice zones." Going forward, sustainable strategies must also include strict adherence to responsible sourcing guidelines and avenues for the actual voices of impacted communities.

Table 4. Summary Table (Key Interpretations)

Theme	Key Discussion Point
GHG Emissions	BEVs deliver 48–73% lifecycle GHG reductions in decarbonizing energy contexts
Production Burdens	Elevated resource and toxic emissions during battery production, especially with carbon-heavy energy

Non-Exhaust PM Trade-Offs	Regenerative braking helps; yet heavier weight increases tire/road PM—net cleaner in typical urban use
Policy & Lifecycle Strategies	Euro 7 regulations, sustainable materials, recycling, and lighter designs can mitigate impacts
Social & Supply Chain Equity	Rising mineral demand raises environmental justice concerns, calling for transparent, fair sourcing

Even though BEVs typically have better climate life-cycle performance, the issues are rooted in ethical supply chains, pollution dynamics that are emerging outside of the vehicle exhaust, and much more ontic production grounds. Therefore, to guarantee that electric vehicles fulfil their green props for Endom, an integrated policy of sustainability, justice, and innovation must be carved out.

6. CONCLUSION AND RECOMMENDATIONS

In order to compare electric vehicles (EVs), more especially battery electric vehicles, or BEVs, with conventional gasoline-powered vehicles (ICEVs), the LCA is carried out in this paper as much as is practical. The study concludes that a BEV is always superior from a life cycle perspective, especially as renewable energy sources become more integrated into the grid. According to the International Council on Clean Transportation, BEVs in Europe produce 73% fewer greenhouse gas emissions than gasolinepowered vehicles due to cleaner electricity and more efficient drivetrains.

This so-called "carbon debt" is usually paid off in relatively short distances (roughly 17,000 km) in decarbonised electricity cases because there are more emissions during the production phase, which are mostly caused by the production of energy-acting batteries. In fact, this highlights how clean power can help BEVs achieve greater environmental benefits.

The issue of non-exhaust particulate matter emissions is a little more complex. Research has shown that while regenerative braking can greatly reduce the production of brake-wear particles, a heavier vehicle may produce more tyre and road wear particles.

However, real-world modelling by Virginia Tech has demonstrated that BEVs produce fewer non-exhaust pollutants in situations with high traffic, particularly in places where 15% of driving takes place in an urban setting. However, if exhaust emissions are taken into account, net particulate pollution from EVs is still slightly lower than that from ICEVs, according to The Guardian, even though tyre particulates may be produced by EVs. The other area where standards will be improved concerns the unsheathing of the Euro 7 regulations starting in 2026. It will signal the beginning of a significant shift in the regulation of non-exhaust emissions, such as tyre wear particles and brake dust, which had previously been unregulated, as well as the tightening of battery lifespan requirements.

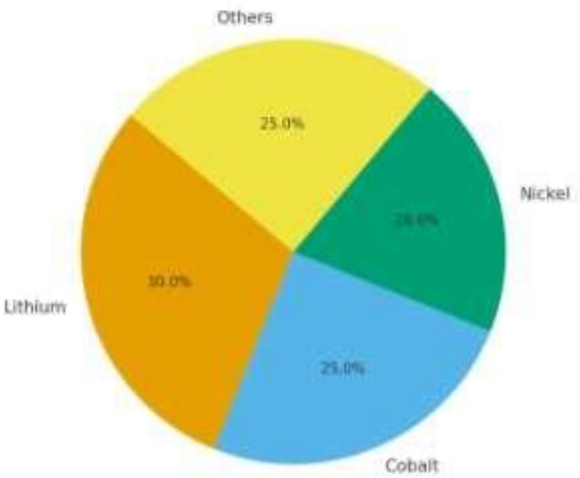

Figure 4. Battery Recycling & Circular Economy (Graph/Illustration)

Key Recommendations 1. Progressing with the Decarbonization of the Grid

Clean energy-powered electricity would have additional life-cycle benefits for BEVs. Policymakers should continue to advocate for clean energy infrastructure so that EV subsidies are treated equally with respect to the deployment of renewable energy. **2. Creating Novel Materials for Tires and EVs**

Regarding sustainable tire and brake technologies, such as low-wear versus biodegradable materials and light vehicle materials to prevent wear pollution, we may see an unanticipated panic today from a regulatory perspective on non-exhaust emissions. **3. Expanding Second Life and Battery Recycling**

Battery manufacturing's environmental impact is lessened when valuable materials are extracted. The circularity of resource scarcity and supply chain ethics could also be addressed by the circular economy and responsible sourcing initiatives. **4. Create Standards for Holistic Emissions**

The enforceable standards for exhaust and non-exhaust emissions may be Euro 7. After that, it would be gradually updated in accordance with driving behavior and technological advancements to maintain impact reduction.

5. Harmonizing Concepts in a Local Context

A hybrid or phased decarbonization approach would result in short-term savings while the renewable infrastructure matures in areas where the grid is carbon-intensive.

6. Raise Public Knowledge

Consumers, engineers, and city planners are among the stakeholders who need to be educated on the dynamics of the EV lifecycle and non-exhaust emissions. Demand-side awareness initiatives could help frame the need for environmentally friendly infrastructure and vehicle solutions.

Table 5. Summary of Policy & Lifecycle Strategies

Strategy	Environmental Benefit
Grid Decarbonization	Further reduces BEV lifecycle GHG emissions
Sustainable Tire & Brake Materials	Lowers non-exhaust PM emissions
Battery Recycling & Second Life	Cuts resource depletion & waste generation
Euro 7 & Similar Regulations	Monitors non-exhaust PM; enforces sustainability
Public Awareness & Education	Promotes adoption of sustainable EV practices

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