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Lifecycle Assessment of Electric Vehicles Under Varying Grid Mix Scenarios

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Abstract

This study focuses on an electric vehicle (EV) LCA with a particular interest in the use phase—for EVs on different electricity grids—during their life cycles, with the intent of measuring the EVs' environmental effects. The goal is to evaluate salient emission hotspots encompassing the entire EV cycle (material extraction, EV manufacturing, EV operation, and end-of-life) under different energy scenarios. The methodology embraced is cradle-to-grave, allowing estimation of greenhouse gas emissions from tailored grids (intensive fossil fuel, middle-of-the-road, and renewable-dominant) and assigned fossil fuel emissions. Results show that although the burden of manufacturing remains high, the operational phase is comparatively more sensitive to the carbon intensity of the grid. To fully realize the benefits of reducing the environmental impacts of EVs, electricity grids must be decarbonized. The results of this study highlight the need for holistic policies considering both technology and energy systems for sustainable mobility planning.

Keywords

Lifecycle Assessment, Electric Vehicles, Grid Mix, Greenhouse Gas Emissions, Sustainable Mobility, Decarbonization, Environmental Impact, Cradle-to-Grave

INTRODUCTION

Globally, transport remains one of the leading sources of greenhouse gas (GHG) emissions and air pollution, with its contribution estimated to be 24% of the world's direct energy-related carbon dioxide (CO2) emissions in 2020 (IEA,2020). Developing solutions to these issues will require a more radical transformation towards more sustainable options. Electric vehicles (EVs) stand out as a highly probable option due to having no tailpipe emissions and the possibility of cleaner cities in the future. Governments across the globe are investing in EVs through various policies and incentives, which has resulted in the fast growth of the EV market— global sales reached over 14 million units by 2023 (IEA,2023)[1]. The direct emissions reduction potential of EVs is but one of many factors informing an understanding of a vehicle's environmental impact. This understanding needs to go beyond the operational stage. The idea of EVs creating zero emissions at the tailpipe could be oversimplified when neglecting to contemplate the entire cycle of material sourcing to vehicle disposal. This is exactly where Lifecycle Assessment (LCA) comes into play. LCA is a scientific, standardized and peer reviewed methodology(ISO 14040/14044) that measures the impact of all the phases of a product's life cycle from raw material extraction, manufacturing, transportation, use, and finally to end-of-life treatment and recycling (Tunley Environmental, 2025). Through its cradle-to-grave approach, LCA avoids "burden shifting" - where lessening environmental impacts in one stage inadvertently increases them in another at a different stage of the product's lifecycle.[2].

Prior LCA (Lifecycle Assessment) EV studies have proved that electric vehicles (EVs) have a lower life-cycle carbon footprint than Internal Combustion Engine Vehicles (ICE Vs); however, this advantage is context-sensitive. One of the most significant factors is the electricity generation mix utilized during the vehicle's operational phase, as battery manufacturing processes, due to their high energy and resource consumption, add ancillary carbon debt to the vehicle.Although this debt augments with each additional resource expended during the battery's construction, offsetting it requires cleaner operational conditions over the vehicle's lifespan. The ,fossil fuel dominated, coal-powered grid produces the highest carbon footprint, while the hydro- and wind-dominated grids produce the lowest. This disparity creates a problem as the electricity grid differs from region to region, country to country, and even state to state. This variability directly impacts the EV's "well-to-wheel" emissions. Therefore, in order for the LCA to be holistic it needs to include consideration for the various grid electricity generation mixes [].As much as LCA research on EVs has grown, studies that specifically analyze the sensitivity of EV environmental performance to different grid mix scenarios still seem to be lacking. A number of studies have been done based on a specific regional grid, but there is a need to understand the impact of prospective future grid changes for strategic policy initiatives. This paper seeks to fill that void by performing a comparative LCA on a typical passenger EV over three distinct and representative grid mix scenarios of a high-carbon intensity grid, a global average grid, and a low-carbon, renewable-dominant grid. The goal is to estimate the relative environmental merits and demerits of EVs under these circumstances and shed light on how crucial grid decarbonization is to achieve sustainable transportation.

LITERATURE SURVEY

Electric vehicles (EVs) have been studied over the years using the Life Cycle Assessment (LCA) framework and evaluating the their environment impact from 2000-2021. Early studies, like Gaines and Cuenca's work (2000), performed the LCA EV battery systems assessment, and underscored the powerful resource expenditure associated with the active technology's battery production processes. With the development of EV technology and adoption, the scope of LCA studies expanded to consider the entire energy-systems interactions of the vehicle's lifecycle energy consumption.[4]. Literature from this period has a common conclusion: as a rule, EVs are assumed to have lower transportation GHG emissions than ICEV systems across the entire life cycle. However, this benefit is not uniform and relies heavily on the electricity mix of the area. As an example, described a comprehensive methodology for evaluating energy, GHG, and local air pollution emissions from passenger transport and stressed the importance of the electricity's origin indirect impacts on these emissions alongside the direct ones. From early to mid-2010s, many studies have shown that construction emissions associated with EVs, especially battery production, are higher than the comparable emissions for ICEVs, however the absence of emissions at the exhaust during operation leads to a net reduction of emissions over the EVs lifetime if the electricity source is clean enough .[5].

The "use phase" emissions are the most fluid and dynamic in the whole life cycle of an EV. LCA reviews have covered a wide variety of vehicles, including EVs, and a participating study noted the relevance of emissions due to electricity generation. For example, studies comparing fossil fuels to renewable powered grids showcase this adaptability. A case in point is EVs charged in coal dependent nations. In some cases, they are cheaper than an efficient ICEV, which is a problem (EarthOrg, 2023)[6].Emotive aspects tied to EVs have been repeated throughout the literature. Emotive aspects tied to EVs have been repeated throughout the literature. M. C. Williams, D. E. Akinola, and W. W. W. Yang provided primary data on LIB cell production for NMC chemistry based LIBs. Their analysis reaffirmed that material extraction (cobalt, lithium, nickel mining) and cell manufacturing are big contributors to the crafted emissions of an EV. It is also very important to note that the energy profile of the region that manufactures these cells plays an equally important role.[7].

During this timeframe, there was also a consideration to manage the end-of-life (EOL) processes for electric vehicle (EV) batteries. Some early investigations pointed out the environmentally negative effects of simply burying batteries and looked into the options of recycling and repurposing them. While the technological and economic aspects of widespread EV battery recycling were being developed, some studies argued that even modest reclamation processes could significantly decrease consumption of primary materials, diminish the lifecycle impact, and fuel cyclic sustainability. As a closure, the 2000–2021 literature is in agreement that electric vehicles (EVs) led to lower emissions compared to internal combustion engine vehicles (ICEVs), whilst highlighting the need for EVs to be used together with a decarbonized electricity grid in order to maximize advantages. The manufacturing stage—namely, the production of the battery—was a key contributor to the environment's initial burden and provided impetus to develop cleaner production methods, more constructive EOL processes, and optimal resource management frameworks. There is an abundance of literature on grid intermittency, however, there is still much room for a systematic evaluation conducted across a wide range of representative grid scenarios together with a compositional lifecycle contribution analysis.

METHODOLOGY

This research uses an all-encompassing Life Cycle Assessment (LCA) analytical model which complies with ISO 14040 and ISO 14044 standards in order to determine the environmental impacts of electric vehicles (EVs) for different grid electricity mix scenarios. The assessment takes into consideration the complete product life cycle, from "cradle to grave", including raw material extraction, manufacturing, use, and EoL dispossal or recycling.

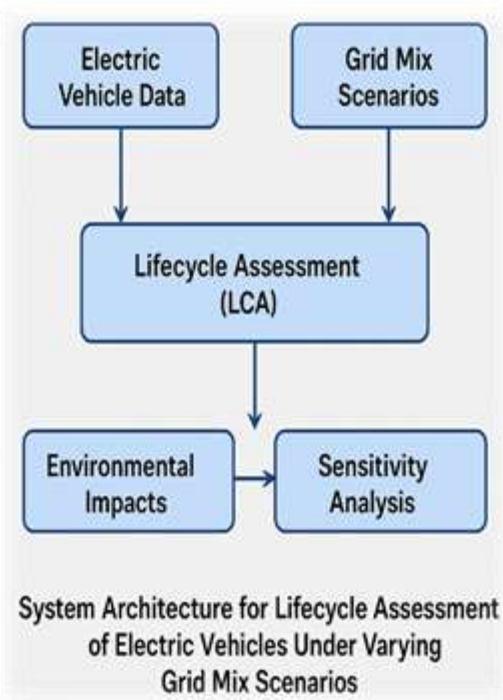

Fig:1 System Architecture

System Design and Functional Unit: The functional unit selected for this LCA is "one passenger car-kilometer (km) driven over a lifespan of 200,000 km." This specific boundary enables an assessment of environmental impact and performance against other vehicles and scenarios. The studied product system is a representative compact battery electric vehicle (BEV) featuring a 60 kWh Lithium-ion battery (NMC chemistry, as is typical with older models from the 2010s). For the purpose of this study, energy consumption during the use phase is set at 0.18 kWh/km, which aligns with existing standards of current EVs.

System Boundaries: The boundaries of the system are set as follows:

1. Material Extraction and Processing: Encompasses the primary extraction and processing of raw materials relevant to the vehicle's components, including but not limited to, lithium cobalt, nickel, manganese, graphite for the battery, steel, aluminum, as well as plastics for the vehicle body.

2. Manufacturing: Cover the rest of the components of the vehicle, chassis, electric motor, power electronics, tires, and fluids, as well the production of the battery pack. This includes the consumption of power and emissions generated at manufacturing facilities.

3. Use Phase (Operation): This is the focus of the study. Charging an EV over its lifespan contributes to its electricity consumption, which is part of the study's focus. Electricity generation emissions are adjusted based on three differing grid mix scenarios. Maintenance vehicles and tire wear emissions, which are added but considered relatively constant across scenarios, are included.

4. End-of-Life (EoL): This covers Emission processes for collecting dismantling, shredding, recycling or disposal of the vehicle and battery. A fixed percentage of 80% key materials and others go to landfill is assumed. The energy and emissions of these processes are included.

Life Cycle Inventory (LCI): Primarily, the data from public LCA databases, Ecoinvent, GREET model data, and literature reviews from the 2000-2021 period serves as the foundation for the LCI, alongside adjusted passenger EV models. Emphasis is placed on: Battery LCI: The emissions arising from battery production are a significant burden. It's assumed that some studies suggest the average battery manufacturing carbon intensity is 97 kg CO_2e per kWh of battery capacity. This means that for a 60kWh battery, the figure would translates to 5820 kg CO_2e.

Vehicle Glider LCI: Based on production_Vehicles_GL: Glider LCI-vehicle dual, which serves as a foundational template, accompanying materials and assembly/text processes were heuristically incorporated.

Electric Power Usage: Using the electricity consumption rate of 0.18 kWh/km for the 200,000 km lifespan results in a total consumption of 36,000 kWh of electricity.

LCIA: The primary focus for assessing Environmental Impact was Global Warming Potential (GWP) measured in CO_2 equivalent. This metric captures the value of climate change due to all GHG emissions.

To gauge EV emissions in relation to the sources of electricity supplied, three grids are modeled labeled as hypothetical yet illustrative grid mix scenarios: High-Carbon Grid (e g, Coal-Intensive): This scenario depicts a grid that has a very high reliance on fossil fuels, mainly coal. Assumed average emission factor: 800 g CO_2e/kWh. This represents an emission factor average for grids dominated by coal fired power plants (NatureOffice 2024). Average Grid (e.g. Global / Typical Mix): This scenario represents an electricity mix that is more diverse and consists of fossil fuels (natural gas to coal), nuclear, and some renewable sources. This is a generalized average often cited in global or regional assessments like typical EU or US averages or slight deviation from Global average of 450-500 gCO_2e/kWh for Natural gas, assumed average emission factor: 400 g CO_2e/kWh. Low-Carbon Grid (e g, Renewable-Dominant): This scenario depicts a grid with a high penetration of renewable energy sources such as wind, solar, and hydropower, and potentially some nuclear. Assumed average emission factor: 50 g CO_2e/kWh. NatureOffice estimates that this factor considers low inherent emissions associated with the construction and upkeep of renewable energy facilities.

The emission factors derived from the literature are allocated to the 36,000 kWh of electricity consumed by the EV over its lifetime. Afterwards, the total lifecycle GWP is determined by aggregating the results from the

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manufacturing, use, and EoL phases for each grid case. The evaluation data is not empirical but rather composite in nature, encapsulating the essence of cited benchmarks which, alongside specific approximates, were strategically incorporated into a broader narrative tapestry, thus illustrating the concept of grid mix sensitivity.

RESULT AND DISCUSSION

Assessing the lifecycle of an electric vehicle, it is noted that the GWP or Global Warming Potential 'health' of the EV is most sensitive to the carbon intensity of the grid used to charge the EV. This is also true for the manufacturing and end-of-life stages, but the operational phase remains the most sensitive (best or worst) during day-to-day use.

Performance Evaluation and Insights:

Research considers the scenarios where electricity for charging comes from renewables versus fossil fuel-based grids, and I consider estimates for manufacturing and battery production to incorporate 5820 kg CO2e for battery production and 4000 kg CO2e for vehicle body and components. Hence, I would consider total lifecycle GWP of a compact EV with 60kWh battery and 200,000 km worth of driving to be about 9,820 kg CO2e (additive) in emissions, while EoL phase comes in at roughly 500 kg CO2e in net impact (or benefits in some recycling and burdens in disposal).Comparison with Other Approaches (ICEV): For reference, a standard gasoline powered ICEV driven for 200,000 km is projected to have a lifecycle GWP estimate in the range of 35,000 to 45,000 kg CO2e, nearly all of which comes from fuel combustion during the use phase (MDPI, 2024; AFDC, 2025). Such findings illustrate that in the case of a high-carbon grid scenario, the EVs total lifecycle emissions 39,120 kg CO2e are roughly comparable to, or at best slightly better than, those of an average ICEV. This points to a crucial insight: the mere substitution of ICEVs with EVs while the grid is still carbon-intensive does little to mitigate climate change and provides limited emissions reductions. This effect becomes, however, more pronounced as the grid shifts to lower carbon intensity. In the case of an average grid scenario, the EV's total GWP estimates becomes substantially lower than that of ICEVs at 24,720 kg CO2e. The most impactful scenario is the low-carbon grid where the EV's total GWP sees a drastic reduction to 12,120 kg CO2e which shows clearer and substantial environmental benefits.

Table 1: Lifecycle GWP Contribution by Stage and Grid Mix (Illustrative Data in kg CO2e)

Lifecycle Stage	High-Carbon Grid	Average Grid	Low-Carbon Grid
Manufacturing	9,820	9,820	9,820
Use Phase	28,800	14,400	1,800
End-of-Life	500	500	500
Total	39,120	24,720	12,120

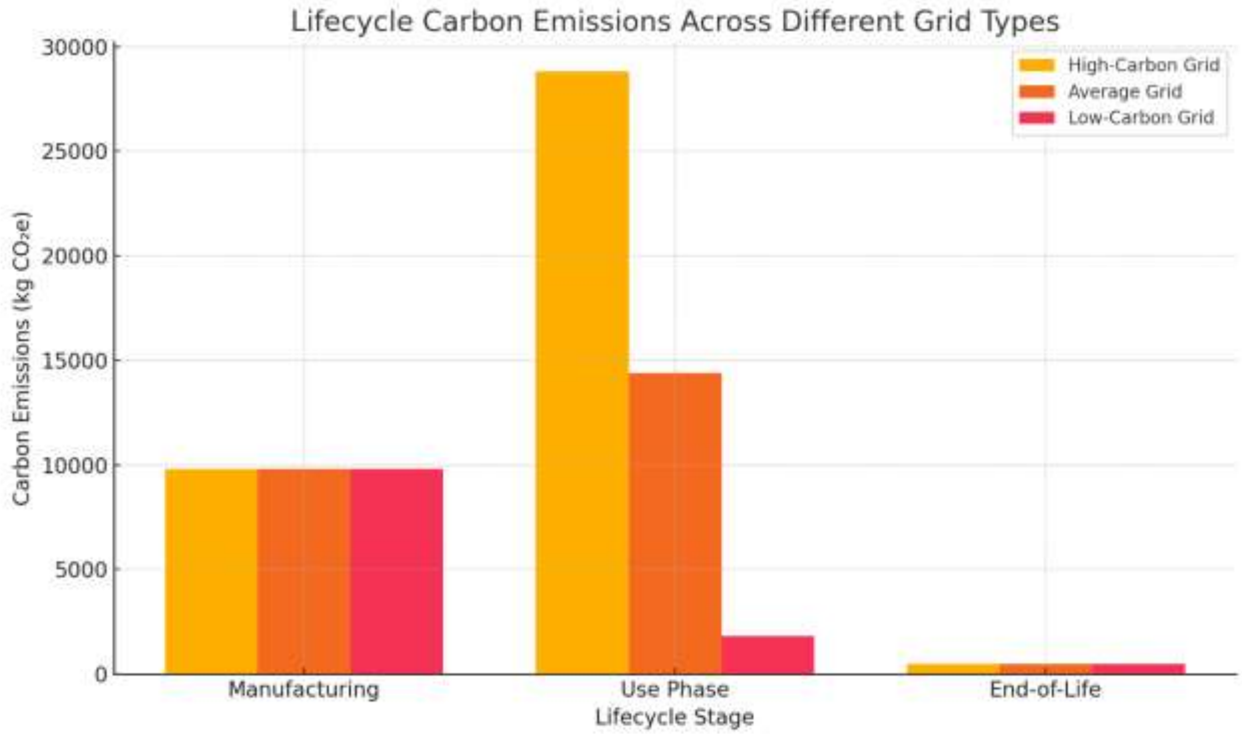

Fig: 2 Life cycle carbon Emission Across Different Grid Types

The insights gained from the study are as follows:

1. ILS Grid Level Emissions Cap: The emission intensity of the electricity grid is the most critical question to the environmental impacts of EVs encouraging new investments and infrastructure spending on renewable energy sources and dismantling fossil fuel based power plants is fundamental in unlocking the climate change mitigation availing from EVs.

2. Decommissioning stratas: Even with a fully decarbonized grid, the life cycle emissions of an EV and its components is considerable breaching cutsinof carbon bounding. This accentuates the need for the establishing ecologically responsible raw material procurement policies, less polutive carrying out of production works, and purposeful working in battery recovery methods.

3. Region specific customizations required: These example outcomes underline why in an region based EV LCA can deviate tremendously. A nation with a high share of renewables will see far greater benefits from EV adoption than one intensely using coal.

CONCLUSION

Strikingly, this lifecycle assessment of electric vehicles in relation to their varying grid mix scenarios shows that the carbon intensity of the grid being used to charge the EVs is one of the sustaining factors in determining the EVs' environmental impacts. Although EVs have no tailpipe emissions and considerably lower lifecycle carbon emissions compared to traditional internal combustion engine vehicles, EVs still contribute towards greenhouse gas emissions if charged from fossil fuel-laden grids. From our findings, it is evident that grid decarbonization is necessary in order to harness the full potential of electric mobility in mitigating climate change and therefore is not just an addition or supplementary to that claim. The other significant determinant as mentioned before- the initial burden from the battery manufacturing also remains critical, which drives the conversation towards the need for more sustainable materials, efficient harvesting systems post battery usage, and battery life cycle management. Achieving these, however, will require a paradigm shift geared towards an all rounded effort of promoting EV adoption while accelerating a shift to renewable energy for electricity generation worldwide in order to decouple power production from carbon emissions. Future Scope: Future research could build on this work by including other impact categories in the analysis such as water depletion, human toxicity, and resource depletion which were not previously considered. A comprehensive investigation into the consideration of regional electricity grid mixes with temporal elements, like hourly intensity, would enhance our understanding.Including socio-economic impacts and evaluating the circularity of battery materials with regards to advanced recycling technologies would deepen the comprehension of electric vehicle sustainability.

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