Discussion Paper

Aligning Vehicle Electrification With Power Sector Transitions

Life Cycle Insights Across Diverse Grids



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Abstract

This study examines how the life-cycle greenhouse gas (GHG) emissions of battery electric vehicles (BEVs) vary across electricity systems with different carbon intensities, and how those emissions evolve in response to announced national energy transition initiatives. Using a temporal Life Cycle Assessment framework, we quantify BEV emissions across four regions – the European Union, the United States, China, and India – as well as the global average, while accounting for projected changes in electricity generation from 2022 to 2035.

We found that the climate performance of BEVs is impacted by the carbon intensity of the electricity used for charging. In low-carbon grid contexts, such as the EU, BEVs already provide substantial life-cycle emissions reductions. In contrast, countries with electricity systems still reliant on conventional energy sources exhibit more limited climate benefits in the near term; however, notable improvements are possible as the power sector transitions progress. Crucially, shifts in electricity systems are not treated as guaranteed outcomes but as trajectories dependent on policy and infrastructure, reflecting real-world uncertainty. Therefore, breakeven distances and total emissions savings vary widely across these geographies, with higher utilization rates and declining grid intensity emerging as critical drivers of BEV effectiveness.

Rather than advocating a uniform electrification pathway, this study underscores the importance of aligning vehicle deployment strategies with regional power sector trajectories, infrastructure capacity, and usage profiles. In contexts where clean electricity is limited, hybrid vehicles, system-level efficiency gains, and high-utilization deployments (e.g., fleets and transit) may offer greater near-term reductions in emissions. These life-cycle-based insights support a systems-oriented approach to sustainable transport planning, coordinating vehicle electrification with the evolving dynamics of national electricity systems.

Keywords: GHG Emissions, Climate Change, Vehicle Electrification, Energy Transition, Life Cycle Assessment

1. Introduction

In recent years, the global energy landscape has witnessed a significant shift in energy paradigms, often referred to as the global energy transition. This transition involves moving away from conventional energy sources toward renewable energy sources (RES), primarily wind, solar, and hydroelectric power. Driven by the urgent need to mitigate climate change and reduce greenhouse gas (GHG) emissions, decarbonizing electricity generation has become a cornerstone of this transition. According to Ember's fifth annual Global Electricity Review, the world achieved 30% renewable electricity in 2023, fueled by the increasing deployment of solar and wind technologies (Wiatros-Motyka et al. 2024). Similarly, the International Energy Agency (IEA) projected in its pledges scenario that renewable energy will account for nearly 40% of the global energy supply by 2035 and rise to 75% by 2050, underscoring the transformative potential of this shift (IEA 2024).

The energy transition also significantly influences the emissions performance of emerging technologies, particularly battery electric vehicles (BEVs). As BEVs gain traction as a sustainable transportation solution, understanding their life-cycle emissions (those generated during production, use, and end-of-life stages) becomes critical. A key factor in determining BEV emissions is the carbon intensity of the electricity used to charge them, measured in grams of CO_2 equivalent emitted per vehicle kilometer (gCO_2eq/vkm). For example, a BEV charged with coal-generated electricity will have a far higher emission footprint (over five times higher) than one powered by renewable energy (Zhang et al. 2023). Thus, the carbon intensity of national electricity grids plays a pivotal role in assessing the climate benefits of BEVs.

Carbon intensity varies significantly across regions, reflecting differences in energy systems and resource availability (Wiatros-Motyka et al. 2024; IEA 2024). Countries like Denmark and Germany have invested heavily in wind and solar energy, resulting in some of the lowest carbon intensities globally. In contrast, regions reliant on coal or natural gas face challenges in maximizing the climate benefits of electric mobility (Krishnan et al. 2024). This disparity highlights the need for context-specific analyses that consider local energy sources and their associated emissions.

Given the dynamic nature of the energy transition, it is crucial to examine how the GHG emissions of current BEVs may evolve over their lifespan as this transition unfolds. While motivations for BEV adoption differ across national contexts – for instance, initially driven by local air pollution control in China and currently by affordability and air quality concerns in India (Patel et al. 2024; Sierzchula et al. 2014; IEA 2020; Deka et al. 2023) – this study focuses specifically on the decarbonization dimension. As electricity grids decarbonize and carbon intensity decreases, the emissions associated with charging BEVs are expected to decline. However, the pace and extent of this change will depend on factors such as government policies, the political economy influencing those policies, technological advancements, and the adoption of renewable energy in the local context. A comprehensive understanding of these dynamics is crucial for accurately evaluating the long-term sustainability of BEVs.

To operationalize this understanding, it is necessary to quantify how geographical differences in grid decarbonization will shape the life-cycle emissions

trajectories of BEVs over time. Such analysis demands a temporal and spatially resolved approach, recognizing that the climate benefits of today's BEVs hinge not only on current energy mixes but also on how rapidly (and unevenly) electricity systems evolve and decarbonize. This study addresses that gap by systematically evaluating the decarbonization potential of BEVs in the European Union, the United States, China, and India, and comparing them to the global average.

The primary objective is to analyze the GHG emissions of current BEVs and investigate how these emissions may evolve during their lifespan in the context of the global energy transition at the country or entity level. The central research question guiding this study is: What are the life-cycle GHG emissions of current BEVs, and how might these emissions change over their lifespan in the context of the ongoing energy transition? By examining the outlooks of electricity generation in the assessed geographies and their projected carbon intensities, this research aims to increase understanding of the interplay between energy systems and BEV performance.

While this study focuses primarily on the emissions performance of BEVs, it does so in a comparative context. To benchmark BEV life-cycle outcomes, we also evaluate the GHG emissions of internal combustion engine vehicles (ICEVs) and hybrid electric vehicles (HEVs). ICEVs represent the conventional baseline, while HEVs serve as a transitional technology with potentially lower life-cycle emissions in regions where electricity decarbonization is still in progress. Including these reference technologies enables a more complete understanding of when and where BEVs offer meaningful climate advantages under evolving, carbon-intensive electricity system conditions.

This study has significant implications for policymakers, industry stakeholders, and consumers. For policymakers, insights into BEV GHG emissions under the current and evolving national electricity mix can inform regulations and incentives to promote effective transport decarbonization. For industry stakeholders, understanding the impact of energy transitions on BEV emissions can guide investment decisions and strategic planning. Likewise, this research provides consumers with a clearer understanding of the climate benefits of BEVs, taking into account geographical differences in grid intensity.

2. Literature Overview

Understanding the interplay between the carbon intensity of the electricity grid and the life-cycle performance of BEVs is essential for evaluating their true mitigation potential. This section reviews key literature in two parts: (1) the carbon intensity of electricity generation across different regions and its trajectory and (2) the environmental implications of BEVs from a life-cycle perspective.

2.1 Electricity Grid Carbon Intensity

The carbon intensity of electricity grids has been a focal point in the discourse surrounding energy transition and climate change mitigation. Numerous studies have highlighted the importance of understanding how the sources of electricity generation contribute to overall GHG emissions (Marmiroli et al. 2018; Khan 2018). The carbon intensity of electricity generation varies widely across different regions, influenced by the energy mix and technological advancements (IEA 2024; Wiatros-Motyka et al. 2024). Research indicates that transitioning to RES, such as wind, solar, and hydroelectric power, significantly reduces carbon intensity (Gielen et al. 2019).

The relationship between energy policies and carbon intensity has also been examined. For instance, a comprehensive analysis by Kök, Shang, and Yücel (2018) found that countries implementing robust renewable energy policies experienced a marked reduction in carbon emissions from electricity generation. However, the authors suggested that a one-size-fits-all approach would not be practical when transitioning to renewable energy. Policymakers and stakeholders should carefully analyze and adapt their strategies in response to local pricing mechanisms and market dynamics to effectively reduce carbon emissions through increased investments in renewables and low-carbon energy sources.

Yu et al. (2020) found that an increase in energy demand could undermine efforts to reduce emissions. Specifically, in regions where energy demand growth outpaced the integration of renewable energy sources, as continued reliance on conventional energy sources persisted. This reliance led to only a slight improvement in GHG reductions, despite the relatively high levels of renewable energy integration. Essentially, the increasing energy demand in these areas lessened the potential benefits of renewable energy, highlighting the complex relationship between energy consumption and emissions reduction efforts. This disparity underscores the pivotal role of governmental policies and incentives in shaping the energy transition.

Moreover, the temporal aspect of carbon intensity has attracted attention in recent research. Studies have shown that as countries invest in renewable technologies and improve grid efficiency, the carbon intensity of electricity can decrease over time (Gielen et al. 2019). The concept of a “carbon intensity trajectory” is gaining traction, wherein projections are made for future carbon intensities based on current trends and stated policies, such as the IEA Announced Pledges Scenario (IEA 2024). This trajectory is crucial for understanding how the emissions associated with alternative technologies, such as BEVs, will evolve in tandem with projected changes in electricity generation.

2.2 Environmental Implications of BEVs

As the adoption of BEVs continues to rise, considerable research has been focused on understanding their environmental implications (see Bhatt et al. 2025; Koroma et al. 2023; Lai et al. 2022; Marmiroli et al. 2018; Ricardo 2020; Ajanovic and Haas 2019, among others). A significant portion of this literature examines the life-cycle GHG emissions of BEVs, which include emissions from production, operation, and end-of-life disposal. Several of these studies have found that while BEVs produce zero tailpipe emissions, their overall environmental impact is heavily influenced by the carbon intensity of the electricity used for charging. For example, Kucukvar et al. (2022) found that the life-cycle emissions of BEVs can be significantly lower than those of conventional internal combustion engine vehicles (ICEVs), particularly in regions with low-carbon electricity sources. Conversely, in areas with high carbon intensity, the advantages of BEVs in reducing GHG emissions diminish, potentially shifting air pollutants from vehicle tailpipes to power plant smokestacks (Peters et al. 2020). This finding highlights the importance of context-specific assessments of BEV performance, taking into account local energy generation methods. Koroma et al. (2022) noted that further reductions in GHG emissions can reach nearly 10% when considering future changes in the EU electricity mix, such as projected increases in the share of renewable energy used for BEV charging. This suggests that strategic investments in renewable energy and electric vehicle infrastructure are crucial for achieving climate goals. It also highlights the need to integrate these elements into policy frameworks to maximize inclusive environmental benefits and support a sustainable energy transition.

In addition to their potential for reducing life-cycle GHG emissions, BEVs offer significant local environmental benefits, especially in urban settings where air quality is a pressing public health concern. BEVs produce no tailpipe emissions, contributing to reductions in urban concentrations of particulate matter ($PM_{2.5}$), nitrogen oxides (NO_x), and other pollutants associated with ICEVs. These reductions can lead to measurable improvements in respiratory and cardiovascular health outcomes, particularly in densely populated, traffic-affected cities (Peters et al. 2020). For many countries, including China and India, these public health and air quality co-benefits have been central to early EV adoption strategies (Patel et al. 2024; Sierzchula et al. 2014; IEA 2020).

However, the extent to which BEVs improve air quality critically depends on the carbon and pollution intensity of the electricity used for charging. In regions where conventional fuels, especially coal, dominate electricity generation, the environmental burden is not eliminated but merely shifted, from urban vehicle exhaust to the smokestacks of power plants, often located in rural or marginalized communities (Chen et al. 2024; Peters et al. 2020). This spatial redistribution of pollution raises concerns about environmental justice and regional inequality, as these communities may experience elevated levels of sulfur dioxide (SO_2), NO_x, and other harmful emissions without directly benefiting from the mobility advantages of electrification (Chen et al. 2024). Therefore, realizing the full air quality benefits of BEV adoption also necessitates a concurrent decarbonization of the power sector and deliberate policies to address the socio-spatial distribution of pollution impacts.

2.3 Contribution to Current Literature

Despite the growing research on the carbon intensity of electricity grids and BEVs, several gaps warrant further investigation. First, much of the existing literature examines either electricity carbon intensity or BEV emissions in isolation, with limited studies exploring the direct relationship between the two. A more integrated approach that examines how geographical differences in electricity dynamics influence BEV life-cycle emissions is essential for providing a comprehensive understanding of their universal climate impact and associated co-benefits.

Second, while there is a wealth of data on carbon intensity and BEV emissions, few studies have explored the temporal evolution of these metrics. Understanding how life-cycle emissions and carbon intensity may change over time, particularly in the context of current BEVs and the ongoing energy transition, is crucial for forecasting the long-term viability of BEVs as a climate-friendly transportation solution.

This study examined the electricity mixes across the different geographies, incorporating the increasing integration of renewables over the lifespan of the BEV. This approach represents a key contribution to the existing body of LCA research. Most previous LCA studies have assumed a static business-as-usual electricity mix or a static future energy mix, without accounting for the

evolution of energy shares during a BEV's lifetime. By incorporating the expected changes in the share of RES over the operational lifetime of the BEV, this work contributes to a more comprehensive and context-specific assessment of the GHG emissions associated with current BEVs under evolving energy scenarios.

Third, existing research often overlooks the role of integrated policy frameworks in shaping both the energy transition and BEV emissions. Investigating how different policy approaches can synergistically promote lower carbon intensity in electricity generation while enhancing the emissions performance of BEVs could yield valuable insights for policymakers and stakeholders.

Overall, while the literature on electricity grid carbon intensity and BEVs is extensive, there is a need for research that bridges the gaps between these two areas, particularly regarding their interdependence and the implications for policy and practice. By addressing these gaps, this study aims to contribute to a deeper and refined perspective on how the ongoing energy transition can enhance the climate performance of BEVs and ultimately support a just energy transition.

3. Methodology

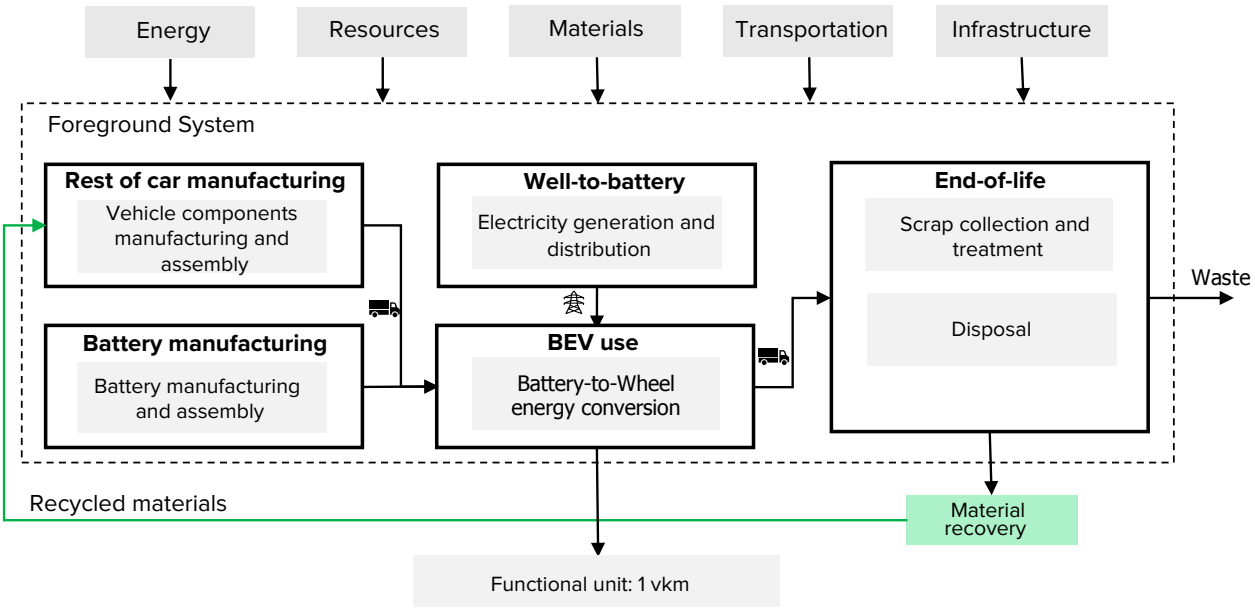
The primary objective of this study is to analyze the life-cycle emissions of current BEVs and evaluate how these emissions evolve over their lifespan, considering the dynamics of the global energy transition.

To achieve this, we have applied an attributional LCA methodology in accordance with ISO 14040 and 14044 standards (ISO 2020b; 2020a). The system boundary, illustrated in Figure 1, encompasses all key process categories that are environmentally significant throughout the BEV lifetime. These include BEV manufacturing, grid-to-battery (GTB), BEV usage, and end-of-life (EOL) management. The GTB category addresses the processes from electricity production and transmission to charging the BEV battery. In contrast, BEV usage focuses solely on battery-to-wheel (BTW) energy conversion, which reflects the process of transforming stored electrical energy in the battery into kinetic energy that propels the vehicle.

The EOL category considers the treatment and disposal of the BEV at the end of its life. Material recovery (recycling) is outside the foreground system, meaning that only the impacts from virgin materials are included in the direct assessment of the BEV (Steubing et al. 2016).

The functional unit is 1 vehicle-kilometer (vkm), selected to ensure comparability across different vehicle types and geographic regions. All GHG emissions are reported in grams CO_2-eq./vkm and include both direct and indirect emissions associated with each life-cycle stage.

Figure 1. System boundary and key process categories for BEV.



Source: Authors.

3.1 Key Assumptions

The analysis incorporates data from four distinct geographic regions: the European Union, the United States, China, and India, alongside the global average. To reflect realistic driving conditions, vehicle energy consumption values are adjusted to include a 25% increase from official manufacturer test values, based on documented real-world deviations (Fontaras, Zacharof, and Ciuffo 2017; Wu et al. 2020; Mock et al. 2012). Vehicle lifetime mileage is assumed to be 250,000 km, with an annual usage rate of approximately 19,231 km/year, reflecting mid-sized SUV usage patterns (Cox et al. 2020). Battery lifetime is estimated at 160,000 km, corresponding to typical warranty conditions provided by leading BEV manufacturers (Nissan 2019; Tesla 2020), which necessitate battery replacement within the vehicle's lifetime. Battery cell production is assumed to occur predominantly in China, utilizing the average Chinese electricity grid mix to reflect current global lithium-ion battery (LIB) cell production capacity distributions (Lebedeva, Di Persio, and Boon-Brett 2016). The BEV use phase is projected to begin in 2022 and extend until its EOL in 2035.

To model the evolution of grid carbon intensity from 2022 to 2035, this study relies on region-specific electricity scenarios that reflect current policies, nationally endorsed strategies, and announced pledges. For the European Union, we used projections from WindEurope and ETIPWind (2021), aligned with the Fit for 55 package and broader EU decarbonization directives. For the United States, electricity trajectories were based on the U.S. EIA Annual Energy Outlook 2023 reference case (EIA 2023). China's pathway reflects the "Current Policy Scenario" developed by Abhyankar et al. (2022), while India's generation mix is derived from the "Constrained Renewables Scenario" in Rodrigues et al. (2023), developed by The Energy and Resources Institute (TERI). Finally, global average trajectories are derived from the IEA's Announced Pledges Scenario (IEA 2024). Linear interpolation is used to estimate intermediate yearly grid compositions between available data points.

We acknowledge the variation in ambition levels across scenarios. To facilitate a fair comparison, our results are presented in both absolute and relative terms, focusing on directional insights rather than precise interregional rankings.

Vehicle Life Cycle Model

Vehicle manufacturing includes glider, powertrain, and LIB pack assembly, modeled using global-average datasets from the ecoinvent v3.10 database. The LCA model captures material and energy flows for each component and accounts for energy consumption, component mass, and manufacturing inputs (Table 1).

Table 1. Inventory data for key vehicle components.

All	Lifetime mileage (km)	250,000	Authors' estimate; Cox et al. (2020)
All	Annual mileage (km)	19,231	Authors' estimate
BEV	Battery lifetime (km)	160,000	Authors' estimate; Nissan (2019); Tesla (2020)
All	Glider mass (kg)	1,317	Authors' estimate; Cox et al. (2020)
BEV	Converter mass (kg)	4.5	Del Duce, Gauch, and Althaus (2014); ecoinvent (2023b)
BEV, HEV	Inverter mass (kg)	9	BRUSA (2019); ecoinvent (2023a)
BEV	Charger mass (kg)	6	BRUSA (2019); ecoinvent (2023a)
BEV, HEV	Power distribution unit mass (kg)	4	BRUSA (2019); ecoinvent (2023b)
BEV, HEV	Electric motor mass (kg)	60.6	Authors' estimate; Cox et al. (2020)
BEV, HEV	Electric motor mass per power (kg/kW)	0.52	Authors' estimate; Cox et al. (2020)
BEV	Single-speed transmission (kg)	23.8	Koroma et al. (2023)
BEV	LIB pack energy (kWh)	62.7	Typical of the average mid-sized electric SUV
HEV	LIB pack energy (kWh)	9.7	Typical of the average mid-sized hybrid SUV
BEV, HEV	Pack specific energy (kWh/kg)	0.1492	NMC 811 cells based on Dai et al. (2018); ecoinvent (2023a)
ICEV	Engine power (kW)	110	Authors' estimate; Cox et al. (2020)
HEV	Combined power (kW)	100	Authors' estimate; Cox et al. (2020)
HEV	Engine power (kW)	60	Authors estimate; Cox et al. (2020)
HEV	Motor power (kW)	40	Authors estimate; Cox et al. (2020)
HEV	Combustion power share	0.75	Authors estimate; Cox et al. (2020)
BEV	Battery-to-wheel energy (MJ/km)	0.985	Typical of the average mid-sized electric SUV, considering a 25% increase in manufacturer value Fontaras, Zacharof, and Ciuffo (2017); Wu et al. (2020)
HEV	Tank-to-wheel energy (MJ/km)	1.996	Typical of the average mid-sized hybrid SUV, considering a 25% increase in manufacturer value
ICEV	Tank-to-wheel energy (MJ/km)	3.354	Typical of the average mid-sized ICEV SUV, considering a 25% increase in manufacturer value

Operational impacts incorporate electricity use for BEVs (GTB and BTW) and fuel combustion for ICEVs and HEVs. Maintenance and part replacements are scaled by lifetime mileage and adjusted for vehicle type and drivetrain complexity. The use phase is based on electricity generation data for the regions assessed (see Section 3.3). Analysis of electricity mixes for different geographies incorporated the increasing integration of RES within the energy mix over the lifespan of the BEV. This approach represents a key contribution to the existing body of LCA research.

Following the ecoinvent cut-off modeling approach, we considered only the efforts to dismantle, treat, and dispose of waste flows at the end of the vehicle's life. Material recovery is excluded at this model stage to avoid double counting, since recycled materials are used burden-free in the production stage of the vehicle components (Ekvall et al. 2020; ecoinvent 2023a).

Table 2. Data sources for electricity generation mix (2022-2035).

Entity/country	Source for 2022 generation mix	Source for 2023-2035 projections
European Union	Ember (2023)	Aligned with the Fit for 55 package and broader EU decarbonization directives (WindEurope and ETIPWind 2021)
United States	Ember (2023)	EIA Annual Energy Outlook 2023 (EIA 2023)
China	Ember (2023)	Abhyankar et al. (2022) – Current Policy Scenario
India	Ember (2023)	Rodrigues et al. (2023) – Constrained RE Scenario
Global	Ember (2023)	IEA Announced Pledges Scenario (IEA 2024)

3.3 Fuel/Energy Cycle

The fuel/energy cycle encompasses all processes involved in the production, transportation, and distribution of the fuel or energy source used to power a vehicle. This includes the extraction and processing of raw materials, their conversion into usable fuels or energy carriers, transportation and distribution to end-users, and storage or dispensing at refueling stations. For gasoline production, this study utilizes the global average dataset from the ecoinvent database to ensure a consistent benchmark for assessing the performance of BEVs relative to ICEVs and HEVs across the different geographies. Evaluating the fuel and energy cycle is critical, as fuel and energy-related processes can significantly contribute to the vehicle's overall life-cycle impact.

Since feedstock for electricity generation is highly varied across regions, its GHG impacts strongly depend on the energy source, production pathways, and the efficiency of national or entity generation and transmission systems. In this context, electricity generation is a key focus of this study. Table 2 shows that the generation shares for 2022 were primarily sourced from Ember (2023).

The future electricity grid trajectories modeled in this study are based on country- or entity-specific projections aligned with officially stated policy commitments and announced national-level decarbonization targets and initiatives as of 2023/24.

3.3.1 Electricity Grid Evolution and Scenario Design

While these scenarios are not all directly equivalent – for example, IEA's Announced Pledges Scenario differs in structure and ambition from India's Central Electricity Authority outlook or China's Current Policy scenario in Abhyankar et al. (2022) – they share a common methodological foundation. They are built from current policies, pledges, and announced initiatives, rather than suggested net-zero trajectories. As such, they represent plausible mid-term energy futures under existing political and institutional conditions, rather than idealized or normative net-zero pathways.

By integrating these evolving mixes into the use-phase emissions, the study provides a more contextually comprehensive estimate of current BEV lifetime emissions than traditional LCA approaches, which often assume static grid intensities.

3.4 Exhaust and Non-Exhaust Emissions

Exhaust emissions for the ICEV and HEV are estimated based on fuel consumption data provided in Table 1 and the EURO 5 emission standard, utilizing relevant

datasets from the ecoinvent database. Non-exhaust emissions, including those from tire and brake wear and road surface wear, were calculated using emission factors from Ntziachristos and Boulter (2023) as implemented in the ecoinvent database. Vehicle and road maintenance impacts were derived from the values reported by Spielmann and Althaus (2006), which are based on a reference vehicle weighing 1,240 kg and a lifetime mileage of 150,000 km. To align with the study's specifications, these values were scaled proportionally to reflect the mass and lifetime mileage (250,000 km) of the analyzed vehicles.

For BEVs, brake wear emissions are assumed to be only 20% of those associated with ICEVs due to the regenerative braking system, following an approach similar to that of Del Duce et al. (2013). Maintenance impacts for HEVs are modeled conservatively by adapting the ICEV maintenance profile to reflect the hybrid drivetrain structure. Specifically, we assume that HEVs require maintenance for both the internal combustion engine and the electric components (e.g., battery, motor) but at reduced intensity for each system. As such, the ICEV maintenance burden is reduced by 25% to reflect the ICE powertrain size in hybrid operation, while a partial BEV maintenance profile is introduced to account for the electric subsystem. This blended approach captures the dual-maintenance nature of HEVs while avoiding double counting.

4. Results and Discussion

This section presents an analysis of electricity generation mixes and their associated carbon intensities across the selected geographies, examining their impact on the life-cycle GHG emissions of BEVs. We first evaluate the current status and projected evolution of electricity grids, providing insights into geographical disparities in renewable energy adoption and reliance on conventional fuels. Subsequently, we compare our modeled carbon intensity results to officially reported grid emissions, validating our comprehensive life-cycle approach. Finally, we assess the emissions performance of BEVs relative to ICEVs and HEVs, highlighting geographic-specific emission break-even points, lifetime emission savings, and critical considerations for policy and infrastructure development aimed at maximizing the climate benefits of transport electrification.

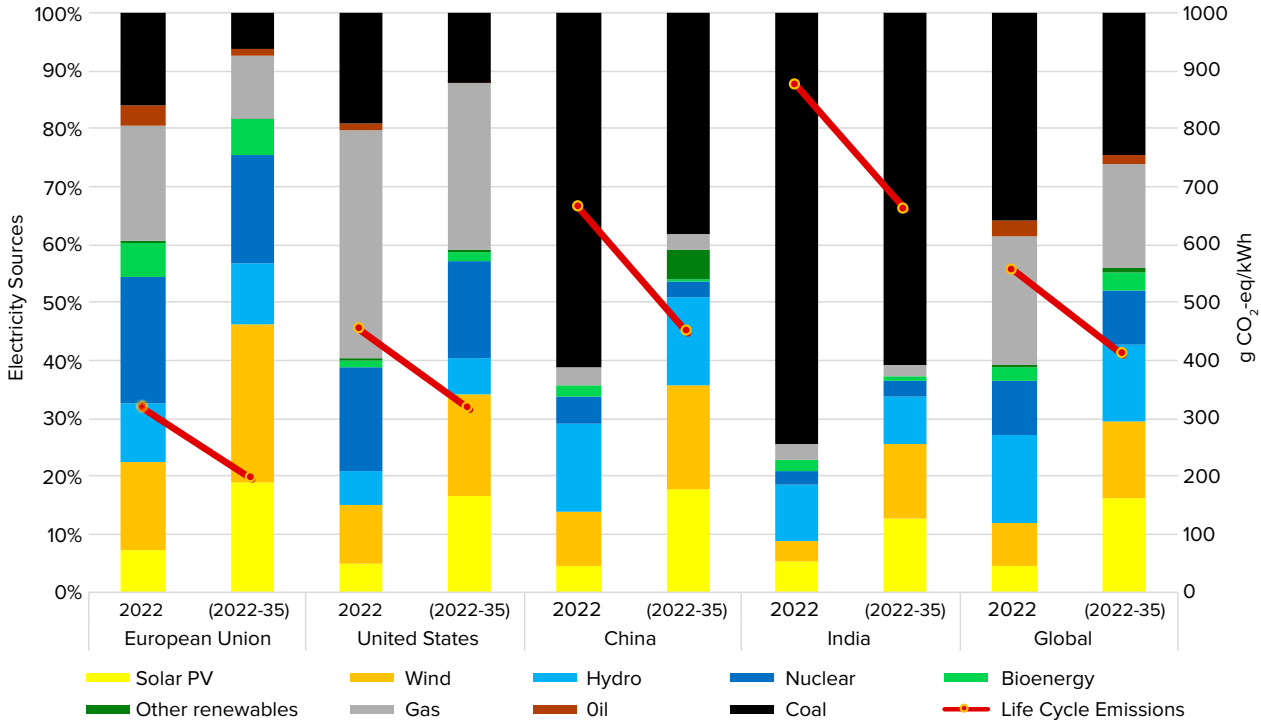
4.1 Electricity Analysis

The global electricity sector is undergoing a transformation, with RES increasingly replacing conventional fuels. However, the pace and scale of this transition vary significantly across regions, affecting the local climate impact of technologies like BEVs. Figure 2 illustrates the electricity mixes and carbon intensity for 2022 and the 2022-35 average of the regions assessed. It examines the electricity generation profiles of the EU, the U.S., China, India, and the global average, focusing on the share of various energy sources and their associated carbon intensity. This analysis provides critical insights into how the different nations are transitioning to cleaner energy sources and reducing GHG emissions.

The data for 2022 reveals significant variations in the electricity generation landscape across the regions assessed. For solar PV, the EU had a generation share of 7.29% in 2022 and is projected to average 19% between 2022 and 2035. India, China, and the United States showed potential for growth in solar electricity generation share, but with relatively lower current shares. Like solar, the EU again showed advanced deployment with a generated wind energy share of 15% in 2022, forecasted to average 27.9% between 2022 and 2035. The United States and China also demonstrated significant wind contributions, with current generation shares of around 10.11% and 9.3%, respectively.

China stood out with a 15% share in hydropower generation in 2022, with a slight increase projected between 2022 and 2035. The EU and India also rely on hydro, indicating its importance in the global energy mix. Nuclear energy is also evident, with the EU having the highest generation share of nuclear energy at around 22% in 2022. However, its average between 2022 and 2035 is forecasted to decline.

Figure 2. Electricity generation mixes and carbon intensity for 2022 and 2022-35 average.



Source: Author's estimations based on sources in Section 3.3 and the ecoinvent database. 2022 implies average grid intensity for 2022, and 2022-35 implies average grid intensity between 2022 and 2035 (the BEVs' lifespan).

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In 2022, coal remained a significant source of electricity generation, particularly in India and China, at around 75% and 61% of the generation share, respectively. However, the average between 2022 and 2035 is projected to decrease significantly. For natural gas, the U.S. had a notable contribution from gas (around 39.5% for 2022), reflecting its role in the current global electricity generation landscape.

The life-cycle GHG emissions for 2022 highlight stark contrasts in carbon intensity across regions. The EU boasts one of the lowest life-cycle carbon intensities, at 317 gCO2-eq/kWh, projected to average 195 gCO2-eq/kWh between 2022 and 2035. Similarly, the United States exhibited a carbon intensity of 451 gCO2-eq/kWh in 2022, with a projected average of 315 gCO2-eq/kWh between 2022 and 2035, reflecting an ongoing transition towards low-carbon energy sources. Conversely, China's and India's current carbon intensities of 663 and 874 gCO2-eq/kWh raise potential concerns for the adoption of BEVs as a climate strategy in the near term, although projected averages of 447 and 660 gCO2-eq/kWh are expected

over the period between 2022 and 2035, respectively. This indicates a slow but necessary shift for China and India, particularly given their heavy dependence on coal.

Analyzing the disparity in electricity mix and carbon intensity forecasts reveals a diverse landscape of energy generation and emissions profiles. While progress is evident, particularly in the EU, significant disparities remain, especially in regions that are just starting to diversify their electricity generation sources. However, the average forecasts between 2022 and 2035 show the expected evolution of electricity mixes and a reduction in carbon intensity. All assessed geographies, including the global average, are expected to increase the share of solar and wind energy, which will be essential for reducing carbon intensity. The EU is projected to lead this growth (in terms of its direct impact on GHG emissions), followed by the United States and China.

Additionally, the analysis underscores the importance of understanding context-specific dynamics. While the EU sets a strong example with low carbon intensity and high renewable shares, other regions face substantial and diverse challenges that require tailored strategies for an effective energy transition that aligns with energy security constraints, among others (Karunathilake et al. 2022; Chipangamate and Nwaila 2024). Therefore, as countries strive to meet energy security and climate targets, effective policy frameworks, technological advancements, and carefully structured financing mechanisms will facilitate a sustainable transition.

4.2 Comparative Analysis of Grid Intensity Estimates

This study's modeled 2022 grid carbon intensity estimates are broadly consistent with values reported by national regulatory agencies and energy authorities (Table 3), while reflecting systematically higher values due to the adoption of a full life-cycle assessment boundary. For the EU, our estimate of 317 gCO_2/kWh moderately exceeds the 275 gCO_2/kWh reported by the European Environment Agency (EEA 2025), which is consistent with including upstream emissions in our model. The projected 195 gCO_2/kWh for 2022-2035 aligns with expectations of increased renewable energy deployment and reduced reliance on coal.

Table 3. Comparison of modeled vs. reported grid carbon intensities (2022) across key geographies.

Entity/country	2022 LCA-based estimate (this study)	2022 reported grid carbon intensity (gCO_2/kWh)	2035 LCA-based estimate (this study)	2022-2035 average LCA-based estimate (this study)
European Union	317	275 (EEA 2025)	104	195
United States	451	375 (EPA 2024)	246	315
China	663	537 (MEE 2024)	375	447
India	874	716 (CEA 2023a; CEA 2023b)	604	660

In the United States, our estimate of 451 gCO_2/kWh in 2022 aligns with the 375 gCO_2/kWh reported by the U.S. Environmental Protection Agency's eGRID (EPA 2024), which only reports Scope 1, point-of-generation emissions. The projected 315 gCO_2/kWh for 2022-2035 aligns with observed declines driven by fuel switching and the growth of renewable energy (EIA 2023).

In China, our estimate of 663 gCO_2/kWh aligns well with the 537 gCO_2/kWh (which also does not account for upstream emissions) published by the Ministry of Ecology and Environment (MEE 2024), considering the high share of coal and the additional emissions from upstream fuel processes. The projected 447 gCO_2/kWh for the 2022-2035 average is consistent with China's shift toward renewable energy and carbon-neutral targets (Tian et al. 2024; Abhyankar et al. 2022).

Similarly, India's modeled intensity of 874 gCO_2/kWh reflects upstream coal mining and transport emissions, whereas the 716 gCO_2/kWh reported by the Central Electricity Authority (CEA 2023a; CEA 2023b) captures direct combustion emissions only for 2022. India's significant reliance on coal supports its high emissions intensity, while the projected 660 gCO_2/kWh for the 2022-2035 average reflects decreasing trends due to projected renewable energy expansion (Rodrigues et al. 2023; CEA 2023a).

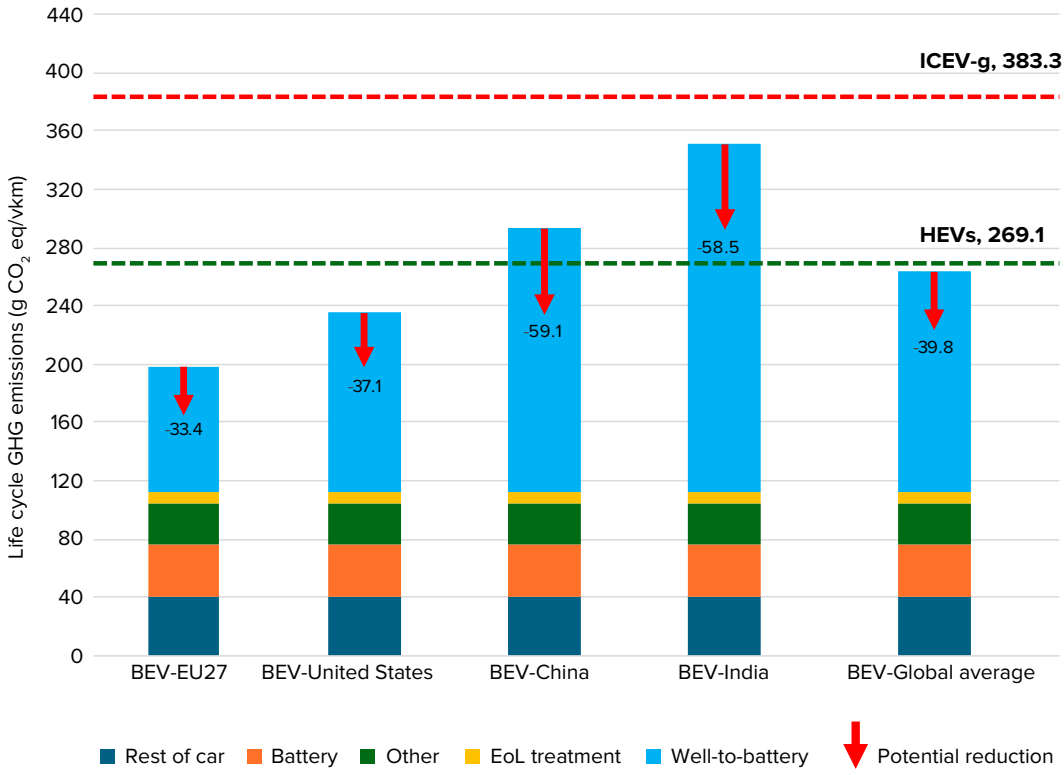
The differences in our 2022 estimates and the reported sources underscore the importance of transparent system boundaries when comparing grid intensities across geographies. The higher values estimated in this study are consistent with the expected uplift from accounting for fuel cycle and infrastructure-related emissions, thereby enhancing the credibility of the life-cycle modeling approach applied in BEV emission assessments across the assessed geographies.

4.3 BEVs Life Cycle Emissions Analysis

The life-cycle GHG emissions of BEVs vary significantly depending on the country's or context's electricity mix. Regions with a high share of renewable energy, such as Europe, exhibit substantially lower emissions from BEV operations compared to those that rely on conventional energy sources. This variation in emissions highlights the importance of assessing BEV performance within the broader context of the energy transition and electricity decarbonization. The LCA breakdown includes components such as battery production, end-of-life (EoL) treatment, and other vehicle materials, providing a more comprehensive picture of life-cycle emissions across the vehicle's lifespan (Figure 3).

Figure 3 shows the life-cycle GHG emissions of BEVs across the different regions assessed, using both the static emissions intensity for 2022 (shown as wheel-to-battery) and the projected reduction in average emissions when expected changes in the electricity sector are considered between 2022 and 2035 (shown as potential reduction in the red arrow). The analysis highlights significant geographical differences in the potential emissions reductions achievable through projections for decarbonized electricity grids by 2035 (in line with announced and ongoing sectoral initiatives/policies).

Figure 3. Life-cycle GHG emissions of BEVs across regions with potential reductions (2022-2035).



Source: Author's estimations. Others – emissions from vehicle maintenance and road infrastructure.
Note: Emissions are calculated with average grid intensity; marginal factors can differ and would reflect dispatch/capacity effects rather than attributional accounting.

The global average life-cycle emissions for BEVs are estimated at 263 gCO_2eq/vkm under the 2022 electricity emissions intensity. This value could drop to 223 g CO_2eq/vkm when considering the average emissions intensity over the vehicle's lifetime (2022-2035), reflecting a 15% reduction. Among the analyzed regions, Europe showed the lowest GHG emissions, averaging 198 g CO_2eq/vkm in 2022 and decreasing to 165 g CO_2eq/vkm during its lifespan (2022-2035). This achieves about a 17% reduction in lifetime GHG emissions, primarily driven by the EU's sustained integration of renewables, particularly wind and solar.

In contrast, India presented the highest emissions for BEVs under the 2022 static electricity mix, at 351 CO_2eq/vkm, yet, BEVs still outperform ICEVs. China and India demonstrated moderate reductions of 20% and 17%, respectively, while the United States achieved a 16% reduction. The relatively lower reduction in absolute values for China and India is linked to the share of coal, and for the U.S. it is attributed to its use of natural gas, which, although cleaner than coal, still contributes to substantial GHG emissions, partly driven by relatively higher methane leaks (Sherwin et al. 2024; Howarth 2024).

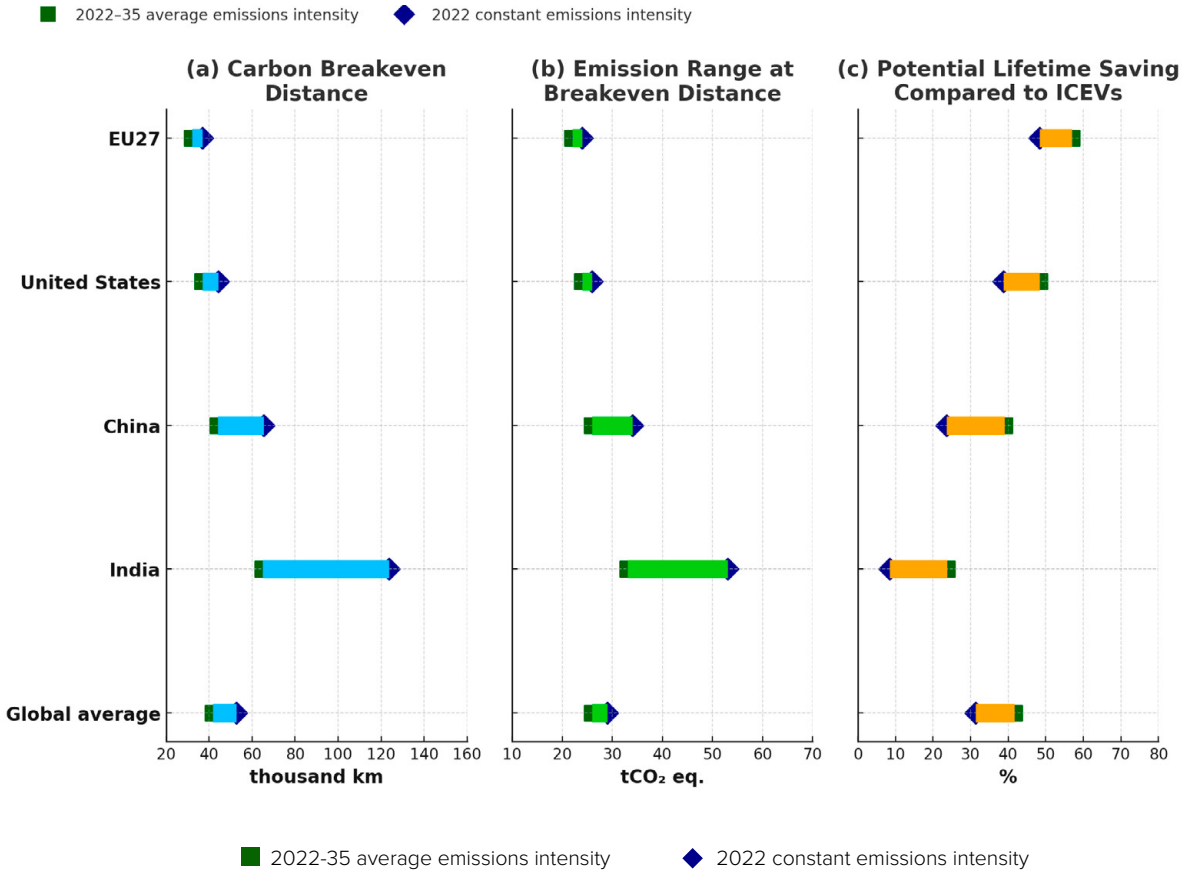
For comparison, HEVs produced approximately 269.1 gCO_2eq/vkm, which makes them more carbon-efficient than BEVs in high-carbon electricity regions like China and India. However, BEVs in Europe and the United States outperform HEVs in total life-cycle emissions. These results suggest that HEVs can be a relatively low-emission option where grid decarbonization lags behind prevailing in 2022. The figure also contextualizes these results against ICEVs, which emit approximately 383.3 gCO_2eq/vkm. This comparison highlights that current BEVs, especially in low-carbon grids, can offer a 30% to 50% reduction in life-cycle emissions relative to ICEVs. However, this depends strongly on local electricity system conditions.

4.4 Lifetime Emissions Performance

The lifetime climate performance of BEVs varies significantly by region, primarily driven by the carbon intensity of local electricity grids. To better understand the dynamics underlying geographical differences in BEV climate performance, we assessed three key metrics: (i) breakeven driving distance, defined as the number of kilometers a BEV must be driven before its cumulative emissions fall below those of an ICEV; (ii) emission savings at breakeven distance, which quantifies the net GHG reduction achieved at the point of breakeven; and (iii) total potential lifetime GHG savings, calculated over a fixed 250,000 km of lifetime mileage. These indicators were derived using geographically specific life-cycle carbon intensities and global average vehicle manufacturing emissions and assume consistent driving profiles across technologies. These values are summarized in Figure 4.

In Figure 4a, BEVs in the EU reached breakeven rapidly, after approximately 32,000-37,000 km, reflecting the region's relatively low-carbon electricity mix. Globally, the average breakeven distance ranged from 42,000 to 53,000 km. Conversely, in regions with carbon-intensive grid infrastructure prevailing in 2022, such as India, BEVs required substantially longer distances (65,000-124,000 km, respectively) to offset higher production and grid (use phase) emissions.

Figure 4. Carbon breakeven point and emissions savings of BEVs.



Source: Authors' estimations.

Cumulative emissions at the breakeven point also exhibited significant geographical differences (Figure 4b). In the EU, BEVs emitted approximately 22-24 tCO_2-eq by breakeven, whereas emissions at breakeven in India ranged significantly higher, between 33-53 tCO_2-eq, respectively. Thus, in countries or contexts with a high-carbon intensity mix, achieving meaningful climate benefits from BEVs necessitates intensive utilization over their lifetime.

Over a full vehicle life-cycle of 250,000 km, BEVs consistently delivered substantial emissions reductions compared to ICEVs, although these reductions varied significantly by context (Figure 4c). Our results indicated that the EU achieved emissions reductions of 48% to 57%, the U.S. realized reductions of 39% to 48%, and China saw improvements ranging from 24% to 39%. In contrast, the climate benefits in regions with evolving, carbon-intensive systems, such as India, were lower yet still notable, achieving emissions reductions of 9% to 24%.

These findings underline three critical insights. First, the breakeven distance for BEVs is highly variable and improves markedly with low-carbon electricity generation. For instance, India could halve their breakeven distances over the vehicle's life if planned low-carbon energy targets are realized. Second, long-term emission savings from BEVs are still achievable even in regions reliant on conventional energy sources, but only if vehicles and their batteries are used at high mileage and accompanied by sustained power sector transformation. Third, the climate performance of BEVs is not universal and is strongly dependent on the local grid mix. While BEVs are highly effective in renewable-rich grids, they may not be the optimal solution everywhere when compared to HEVs.

Therefore, regions with limited access to clean electricity may benefit more from deploying conventional hybrid vehicles in the short to medium term while investing in a low-carbon electricity system. In addition, fuel efficiency improvements and investments in low-emission public and shared transport can further enhance transportation emissions in grid-intensive regions. This reinforces the need for national or context-specific policy frameworks that align transport electrification with broader energy transition goals, infrastructure readiness, and socioeconomic realities.

6. Conclusion and Implications

This study underscores a critical insight: while BEVs hold significant potential to reduce transportation emissions, their climate performance is neither universal nor guaranteed. It is strongly conditioned by the carbon intensity of the electricity used for charging. In regions with a high share of renewables, such as the European Union, BEVs deliver substantial reductions in emissions. However, in countries with grids reliant on conventional energy sources, the benefits of BEV adoption are highly dependent on the credibility, speed, and scale of electricity system transitions.

Therefore, promoting BEVs in isolation is unlikely to yield the desired climate outcomes. What matters is not just electrification but which electrons power the vehicles. If additional electricity demand is met through conventional energy sources, the emissions savings from BEVs may be lower than alternative technologies, such as hybrids. Accordingly, this study does not assume grid decarbonization as a given but emphasizes that any emissions reductions attributed to BEVs must be interpreted within the evolving and often uncertain context of the energy system.

Rather than advocating for a single technology, this study promotes a technology-agnostic and system-aware strategy to decarbonize transportation. Effective emissions reduction requires a portfolio of solutions, including energy efficiency improvements, modal shifts to active and shared mobility, and context-appropriate deployment of BEVs, hybrids, and fuel cell vehicles. These approaches should be embedded within broader efforts to redesign mobility systems that are inclusive, equitable, and aligned with the Sustainable Development Goals (Sovacool, Martiskainen, et al. 2019; Sovacool, Kester, et al. 2019; Lowans et al. 2023).

For countries with relatively clean electricity grids, BEVs can make meaningful contributions to climate targets. In contrast, countries with high grid carbon intensity may initially achieve greater climate gains through hybrid technologies or system-level interventions while working to decarbonize their electricity supply. Importantly, this sequencing should reflect local energy realities rather than assuming uniform readiness for full electrification.

At a global scale, reducing transport emissions will require co-evolution between vehicle electrification and power sector transformation, along with efficiency and behavioral shifts across all modes of transport. The transition to cleaner energy sources, if and when realized, will amplify the climate benefits of BEVs. Yet this outcome is not automatic; it must be supported by credible policy implementation, infrastructure planning, and governance reforms.

Policymakers should therefore adopt a technology-neutral, context-sensitive approach that allows for flexibility in different national pathways. This means aligning investments in charging infrastructure, grid modernization, and renewable deployment with a country's institutional capacity, energy mix, and socioeconomic priorities. Such an approach enables both high-income and emerging economies to pursue low-carbon mobility pathways that are environmentally effective, economically viable, and socially just.

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Appendix

Appendix 1. List of Inventory Datasets Used for BEV Production

Components	Ecoinvent dataset name	Location
Glider	Production for glider, passenger car	GLO
Charger	Production for charger, electric passenger car	GLO
Converter	Production for converter, electric passenger car	GLO
Electric motor	Production for emotor, electric passenger car	GLO
Inverter	Production for inverter, electric passenger car	GLO
Power distribution unit	Production for power distribution unit, electric passenger car	GLO
Cable	Market for cable, three-conductor cable	GLO
IC engine powertrain	Production for internal combustion engine, passenger car	GLO
Li-ion battery	Battery production, Li-ion, NMC811, rechargeable, prismatic	RoW
Maintenance BEV	Market for maintenance, passenger car, electric, without battery	
Maintenance ICEV	Market for passenger car maintenance	GLO
BEV dismantling	Market for manual dismantling of used electric passenger car	GLO
ICEV dismantling	Market for manual dismantling of used passenger car	GLO

About the Authors



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Abdulrahman Alwosheel is a Lead Transportation and Infrastructure expert at KAPSARC. Prior to that, he was a Lecturer at the College of Engineering at Muhammad Ibn Saud University. He also worked as a Traffic Engineer on the Riyadh Metro project. His interests include transport demand modeling, aviation transport, life-cycle analysis, alternative fuels, and energy demand. Abdulrahman holds a master's in Transportation Planning and Engineering and a B.S. in Civil Engineering.



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About the Project

The “Evaluating Decarbonization Pathways in Passenger Vehicles in KSA Using an Integrated Lifecycle Analysis Approach” project aims to assess the sustainability aspects of current and future passenger road vehicles in KSA. The project seeks to understand and mitigate the environmental impact of transportation in the country. Using an Integrated Lifecycle Analysis approach, the project examines decarbonization pathways by considering energy generation sources, infrastructure development, and regional disparities. It also aims to identify key sustainability hotspots and trade-offs to inform policy decisions and drive the transition towards a more sustainable transportation sector in Saudi Arabia.

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