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Context matters: Life cycle emissions and policy implications of electric vehicles in evolving carbon-intensive energy systems

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ABSTRACT

Decarbonizing road transport is critical for climate targets, yet the benefits of electric vehicles depend strongly on local energy systems. In evolving carbon–intensive economies such as Saudi Arabia, the climate performance of battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) remains uncertain. This study applies an attributional, temporally resolved Life Cycle Assessment to compare the life cycle greenhouse gas (GHG) emissions of conventional vehicles, hybrid electric vehicles (HEVs), plug-in hybrids, BEVs, and FCEVs. The framework incorporates projected hydrogen and grid decarbonization up to 2035, including seasonal variability in generation and charging behavior. Results show that BEVs currently emit about 15 % more GHGs than HEVs due to the carbon intensity of Saudi electricity, but they provide the greatest long-term mitigation potential if the grid is decarbonized. BEV emissions vary by up to 45 % depending on charging profiles and season, while FCEV outcomes are highly sensitive to hydrogen production pathways. Sensitivity analysis shows that upstream electricity and hydrogen decarbonization drive greater variability (±12–16 %) than operational assumptions (±4–10 %). These findings challenge universal electrification narratives and underscore the need for context-specific, techno-agnostic strategies. Policy priorities for evolving carbon-intensive economies should include life cycle-based performance standards, smart charging infrastructure, and alignment of vehicle transitions with local energy sector decarbonization.

1. Introduction

Decarbonizing the transport sector is essential for mitigating climate change and remains a pressing global challenge for achieving net-zero targets. Road transport accounts for nearly one-quarter of global energy-related CO_2 emissions, and its rapid growth threatens to offset mitigation gains in other sectors [1]. Battery electric vehicles (BEVs) and hydrogen-based drivetrains are widely promoted as cornerstones of low-carbon transport transitions [2]. However, recent literature highlights that the climate benefits of these technologies are not universal. Life Cycle Assessment (LCA) studies increasingly show that the effectiveness of BEVs depends critically on the carbon intensity of electricity systems, while hydrogen (H_2) vehicles hinge on the production pathway of H_2 [3,4].

Recent studies have advanced understanding of the life cycle and contextual performance of electric and hydrogen vehicles, but they also reveal persistent methodological and geographic gaps. Dynamic LCA approaches show that BEV emissions vary substantially depending on temporal charging patterns and electricity mix, with reductions achievable only when charging aligns with a low-carbon supply [5,6]. Newer research underscores the same dynamics in carbon-intensive systems, demonstrating that misaligned charging can erode or even reverse expected climate benefits [7,8]. For hydrogen, prospective studies illustrate the sharp contrast between petroleum-based production pathways and renewable-powered electrolysis, with the former offering limited mitigation and the latter showing strong potential if scaled at cost [9,10].

However, most existing assessments concentrate on developed or highly decarbonized regions, while evidence for petroleum-reliant and Global South contexts remains sparse. Furthermore, the social and resource dimensions of battery and hydrogen supply chains, such as mineral scarcity, toxicity, and labor impacts, are only beginning to be systematically integrated [11,12]. Collectively, these insights emphasize that although electrification and hydrogen are central to climate strategies, their real-world performance is highly sensitive to context and requires more regionally grounded analysis. Significant knowledge gaps persist regarding the Global South's context and the evolving carbon-intensive economies, temporal assessments in LCA, and the

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integration of comprehensive policy levers, which urgently need to be addressed in ongoing and future research efforts. This leaves open the critical question of how current alternative vehicle technologies perform under evolving but still carbon-intensive energy systems, and how policy frameworks can realistically align mobility transitions with broader energy and local development priorities.

Saudi Arabia offers a strategically important case for examining these gaps. The Kingdom's transport sector accounts for roughly one-fifth of national GHG emissions, dominated by internal combustion engine vehicles (ICEVs) fueled by relatively affordable petroleum products [13,14]. At the same time, national energy policies are undergoing a profound transformation under Vision 2030, with ambitious targets for renewable electricity, hydrogen production, and diversification of the mobility sector [12,15]. Yet, the electricity grid remains heavily reliant on conventional fuel sources, creating a context in which BEVs may currently underperform relative to hybrids on a life cycle basis, and where the carbon benefits of H_2 depend on the pace of scaling green and blue pathways. Infrastructure constraints are equally significant: public charging networks remain sparse, and hydrogen refueling is still at a pilot stage [16]. This combination of carbon-intensive supply, limited infrastructure readiness, and rapid policy ambition makes Saudi Arabia an ideal testbed for evaluating the conditional performance of alternative vehicle technologies. Furthermore, the Kingdom's position as a global energy exporter means that insights from this case extend beyond its borders, offering lessons for other economies that rely on conventional fuels and are navigating early-stage energy transitions in Asia, Africa, and the Middle East.

In this light, this study addresses the question: To what extent do current and emerging passenger vehicle technologies deliver life cycle climate benefits under Saudi Arabia's evolving carbon-intensive energy system, and what policy frameworks can ensure context-appropriate decarbonization pathways? To answer this, we conduct a temporally resolved LCA of ICEVs, HEVs, PHEVs, BEVs, and FCEVs.. Our approach incorporates projected grid decarbonization, seasonal generation variability, and charging behavior through 2035, thereby moving beyond static assumptions common in prior LCA studies. By situating Saudi Arabia as a case study, the analysis highlights how the life cycle performance of electric vehicles is conditional on electricity and hydrogen pathways, infrastructure readiness, and charging practices. The findings advance three key contributions: (1) a temporal LCA framework that captures evolving grid dynamics throughout the vehicles' lifetime, (2) evidence for a techno-agnostic policy approach (approaches that avoid prescribing a single drivetrain technology) that prioritizes life cycle emissions rather than drivetrain mandates, and (3) policy-relevant insights for economies reliant on conventional energy sources where hybrids may deliver greater near-term climate benefits than BEVs. In doing so, the study reframes sustainable mobility as a regionally contingent transition rather than a universal prescription for electrification.

2. Literature review

2.1. Review of EV life cycle GHG emissions

Recent investigations have revealed that the life cycle emissions of BEVs are highly contingent upon the energy mix of the electricity grid used for charging. Studies demonstrate that in regions characterized by a high dependency on coal and other conventional fuels, the emissions from BEVs can exceed those from ICEVs during their operational phases [17,18]. Chen et al. [19] showed that the emissions benefits of BEVs are highly contingent on electricity grid composition, with life cycle reductions of roughly 50 % compared to ICEVs in the United States and European Union, but only around 32 % in China. Their analysis also draws attention to environmental justice concerns, as rural communities disproportionately bear the burden of power-sector emissions linked to urban EV use. Zhang et al. [20] extended this perspective by evaluating eleven lithium-ion battery chemistries, showing that lithium iron phosphate (LFP) batteries offer superior environmental performance compared to nickel manganese cobalt (NMC) types, yet stressing that production and end-of-life processes remain major emission sources. They further emphasized recycling as a key lever for reducing climate impacts, though their reliance on fixed assumptions about battery lifetimes and static grid structures constrains applicability across diverse contexts. Singh et al. [18] added a spatially explicit dimension by highlighting the critical role of regional grid carbon intensity in shaping BEV emissions. Their findings revealed that BEVs can deliver 60–70 % reductions in Brazil's hydro-dominated grid but may perform worse than hybrids in coal-reliant regions, aligning with broader evidence that electrification outcomes hinge on geography, travel patterns, and battery chemistries. Complementing these insights, Alatawneh and Torok [21] assessed ICEVs, BEVs, and autonomous vehicles (AVs) within the European Union's regulatory framework, finding that BEVs outperform ICEVs under cleaner grids, while AVs carry uncertain impacts depending on the number of vehicle kilometers traveled. Kavya and Yadav [22] highlighted that LCAs for EVs can yield unanticipated emissions outcomes in petroleum-dominant energy configurations, such as India's coal-heavy grid. They reveal that the entire life cycle emissions, including battery production and disposal, can exceed those of ICEVs under specific conditions, challenging the narrative that EVs are universally greener alternatives.

The literature surrounding H_2 vehicles also reveals critical life cycle trade-offs, particularly depending on the source of H_2 production. Burchart and Przytuła [10] pointed out that H_2 produced through renewable sources can markedly reduce life cycle emissions, whereas H_2 from petroleum sources may exceed ICEVs emissions, presenting a significant trade-off in hydrogen's environmental viability as a fuel source. Ayca and Dincer's comparative studies illustrated that while H_2 vehicles may offer benefits, such as longer ranges and quicker refueling times, their overall sustainability hinges on decarbonizing H_2 production pathways [23]. Furthermore, the lack of comprehensive policy integration regarding the optimal methods for producing green H_2 remains a notable limitation in the current discourse, potentially hindering the wider adoption of H_2 technologies in transportation [24–26]. Overall, the majority of studies underscore that both BEVs and H_2 vehicles could play vital roles in future decarbonized transport systems, provided the energy mix in corresponding grids evolves towards greater renewable integration [10,27].

2.2. Review of temporal/dynamic charging impacts

Building on life cycle perspectives, the approach to temporal and dynamic charging has been shown to significantly influence the emissions profiles of EVs. The integration of dynamic charging schedules and the timing of energy consumption can optimize the emissions profile of these vehicles, allowing for reductions when paired with cleaner energy consumption [28,29]. For example, daytime charging when renewable sources are more prevalent could potentially lead to a significant reduction in emissions compared to charging during peak demand, when petroleum fuels are predominantly utilized [30]. Wang, Sasse, and Trutnevyte [30] examined home versus workplace charging within Switzerland's electricity system, showing that workplace charging aligns more closely with solar photovoltaic output, thereby reducing curtailment and facilitating the integration of renewable energy. Using the EXPANSE model, they demonstrated the potential for optimized charging to enhance grid flexibility, though the study's assumption of rigid user behavior and limited representation of regional diversity constrain its applicability to broader contexts. Complementing this work, Fungyai, Passey, and Yildiz [31] examined charging emissions in Australia across four strategies: Control Tariff, Timer, Solar Soak, and Convenience Charging. They found that aligning EV charging with high renewable availability can reduce GHG emissions by up to 67.3 % relative to peak demand charging. Yet, their analysis underplays interactions with regional grid disparities and equity issues in renewable deployment.

Together, these studies highlight the critical role of smart charging practices in enabling decarbonization and the integration of renewable energy, while also exposing the need for more detailed, behaviorally grounded, and regionally differentiated models as EV adoption scales globally. Bhatt et al. emphasize the necessity of incorporating these temporal factors into future policy frameworks to enhance the accuracy of EV emission assessments [4]. However, current literature often overlooks the integration of these dynamic charging strategies in LCAs.

2.3. Research gap

Existing studies show that the climate benefits of BEVs and FCEVs are highly dependent on upstream energy systems, with BEVs underperforming in carbon-intensive grids and FCEVs shaped by hydrogen production pathways. However, most LCAs assume static energy mixes and overlook temporal dynamics such as seasonal variability and charging behavior. Research on smart charging demonstrates significant potential for emission reductions, yet these strategies are seldom integrated into LCA models. Critically, evidence remains concentrated in developed economies, leaving a gap for temporally resolved, region-specific LCAs in petroleum-reliant economies such as the Middle East and North Africa.

3. Material and methods

This study follows the LCA methodology as standardized in ISO 14040 and 14044, adopting an attributional approach [32,33]. Attributional LCA quantifies the average environmental burdens directly associated with a product life cycle, under defined technological and energy system conditions. The method comprises four interconnected phases: (i) Goal and scope definition, where research objectives, the functional unit, system boundaries, and assumptions are established; (ii) Life cycle inventory (LCI) analysis, which compiles data on material and energy inputs, emissions, and waste flows; (iii) Life cycle impact assessment (LCIA), where inventory flows are converted into environmental impact indicators, with global warming potential (GWP100) as the primary focus in this study; and (iv) Interpretation, where results are analyzed, uncertainties explored, and findings contextualized relative to the study goals. The analytical steps are organized under subheadings that follow the four phases of the LCA framework.

3.1. Goal and scope definition

The goal of this study is to assess and compare the life cycle greenhouse gas (GHG) emissions and environmental trade-offs of electric, petrol, hybrid, and hydrogen passenger vehicles in the context of Saudi Arabia's evolving energy landscape. The assessment aims to quantify the influence of current and projected electricity and hydrogen production pathways on the relative performance of these technologies, and to derive policy-relevant insights for transport decarbonization strategies in evolving carbon-intensive economies.

The functional unit (FU) is defined as one vehicle-kilometer (vkm) traveled over a vehicle lifetime of 250,000 km (10 years $\times$ 25,000 km/year), consistent with Saudi annual VKT evidence [34,35]. This FU ensures consistency across the different powertrain technologies and provides a meaningful basis for comparison.

The geographical scope reflects a hybrid model approach, where vehicle and battery production are modeled using global averages. This reflects Saudi Arabia's current dependence on imported vehicle technologies and the absence of a large-scale local auto manufacturing base. In contrast, the use phase is localized to the Saudi context, incorporating its specific energy mix, climate conditions, and an estimated real-world fuel consumption based on the literature [36,37]. This localization ensures that the environmental impacts during vehicle operations are contextualized.

The system boundary follows a cradle-to-grave approach (Fig. 1), including.

- Vehicle production, covering the glider, drivetrain, and battery/fuel cell components.
- Energy production and supply, including crude extraction, refining, fuel distribution, electricity generation (with transmission and distribution losses), and hydrogen production and compression.
- Vehicle use phase, covering fuel or electricity consumption, exhaust and non-exhaust emissions (tire, brake, and road wear), and maintenance.
- End-of-life (EoL) management, including dismantling, waste treatment, and disposal, modeled under the Ecoinvent cut-off approach.

The construction and maintenance of external charging station infrastructure, including Level 2 workplace/public chargers and Level 3 DC fast charging stations, are excluded from the system boundary. However, the on-board charger (typically equivalent to Level 1 residential charging capability) is accounted for within the vehicle production inventory, as it is an integral component of the EV drivetrain system. This choice ensures consistency across drivetrains, as analogous infrastructure for gasoline, diesel, and hydrogen refueling stations is also excluded. Prior studies indicate that charging infrastructure contributes less than 5 % of total life cycle emissions [38,39], whereas vehicle production and energy supply processes have the most significant impact on the results. We therefore focus our analysis on vehicle and energy system processes, while acknowledging the environmental impacts of charging/fueling infrastructure as an important area for future region-specific LCAs [40].

Two temporal scopes are considered.

1. Static baseline (2024): life cycle results under the current Saudi energy mix.
2. Temporal average (2024–2035): life cycle results reflecting the average grid decarbonization and hydrogen production pathways expected over the vehicle's operational lifetime.

Additionally, hourly and seasonal variations in electricity generation are modeled separately as part of a sensitivity analysis to assess their impact on emissions during the use phase.

3.2. Life cycle inventory analysis

Primary and secondary data were utilized that represent average "market" values under Saudi-specific conditions, where available. Inventory data are divided into foreground and background processes. Foreground data correspond to the specifications of the vehicles assessed, and cover glider and drivetrain components, battery and fuel cell systems, fuel and electricity consumption, and the Saudi electricity generation mix for both a static baseline year (2024) and a temporal average throughout the vehicles' lifetime (2024–2035). Background data captured all other upstream and supporting processes required to fully define the system, including material extraction, global vehicle manufacturing supply chains, and energy production pathways not specific to Saudi Arabia. These background processes are modeled using the Ecoinvent v3.10 database, ensuring consistency across all vehicle technologies and life cycle stages.

3.2.1. Vehicle production

Vehicle production is divided into two modules: (i) the 'rest of car' (comprising the glider (chassis and non-powertrain systems) and the drivetrain components without the traction battery), and (ii) the traction battery system (cells + modules + pack housing + Battery Management System (BMS) + cooling system). Table SI1 in Supplementary Information (SI) provides the data used for key vehicle parameters and their corresponding uncertainty distributions.

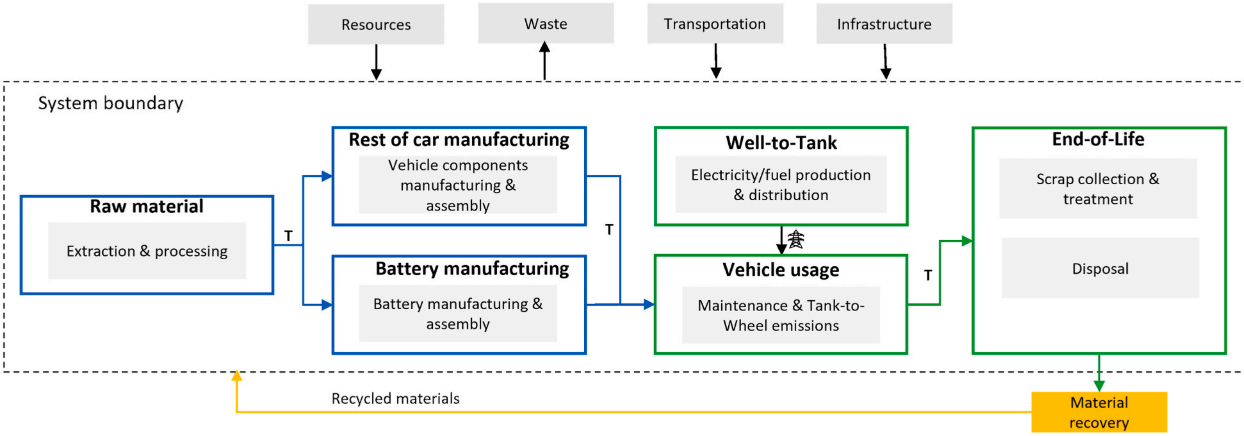

Fig. 1. System boundary and associated life cycle stages.
Source: Authors. Blue arrows represent life cycle stages or processes modeled using global averages, and green arrows indicate Saudi average values. T = transportation

The glider inventory is based on the Ecoinvent process "glider production, passenger car GLO", which is then scaled to the estimated mass of a sedan and SUV. To reflect modern vehicles, the base glider dataset is supplemented with a 10-inch infotainment tablet, modeled using the Ecoinvent dataset for mobile devices ("consumer electronics production, mobile device, tablet GLO").

The drivetrain components, excluding the traction battery, vary by technology. ICEVs, HEVs, and PHEVs share a common internal combustion engine core, scaled to match engine power and vehicle class. This follows a similar approach to that utilized in Candelaresi et al. [41]. The electric drivetrain for BEVs and PHEVs (excluding the traction battery) includes a single-speed transmission, electric motor, onboard charger, DC/AC inverter, DC/DC converter, and power distribution unit. Adjustments were made for HEVs and FCEVs compared to the BEVs' drivetrain: HEVs exclude the single-speed transmission, onboard charger, and DC/DC converter, while FCEVs incorporate a polymer electrolyte membrane (PEM) fuel cell system (modeled using inventory data in Ref. [42]), and exclude the onboard charger. Most processes used to model the drivetrain component are sourced from the Ecoinvent database. However, the single-speed transmission is modeled based on Koroma et al. [43].

The traction battery systems are modeled based on battery chemistry and vehicle technology, with BEVs, PHEVs, and FCEVs utilizing NMC 811 battery packs that have a pack energy density of 0.149 kWh/kg. The LFP battery pack is utilized in HEVs, featuring a pack energy density of 0.089 kWh/kg. The ecoinvent processes "market for battery, Li-ion, NMC811, rechargeable, prismatic GLO" and "market for battery, Li-ion, LFP, rechargeable, prismatic GLO" were utilized. Inventory for their manufacturing was primarily based on the work of Dai et al. [44, 45] and Winjobi et al. [46], covering raw material extraction, cell manufacturing, and pack assembly. Battery mass is calculated based on required energy capacity and battery chemistry-specific energy density.

3.2.2. *Fuel and electricity production*

The life cycle inventory includes upstream emissions associated with the production, distribution, and supply of gasoline, diesel, electricity, and hydrogen fuels used in vehicle operation. All energy pathways are modeled using Saudi Arabia-specific processes, where available, reflecting the unique characteristics of the Kingdom's energy system and its evolving transition targets [47,48].

Gasoline and diesel pathways were modeled using a Well-to-Tank (WTT) and Tank-to-Wheel (TTW) approach. The WTT stage includes (i) crude oil extraction and associated flaring and venting, (ii) transport of crude oil to Saudi refineries, and (iii) refining and blending processes to produce gasoline and diesel. Baseline process data were drawn from Ecoinvent v3.10 inventory for "petrol production, low-sulfur" and "diesel production, low-sulfur", with region-specific adjustments applied using the Archie Initiative refinery emission data to better reflect Saudi operations [49]. These adjustments included higher shares of crude oil–based feedstock (relative to natural gas liquids), refinery configuration differences (hydroskimming and cracking units), and regionally reported energy intensities [50–52].

Electricity generation is modeled using both static (2024) and average carbon intensity between 2024 and 2035 based on decarbonization targets in Vision 2030 and Saudi Net-zero aspirations [47]. Fig. 2 (a) shows the projected grid mix and average carbon intensity for 2024 and 2024–2035. The baseline year (2024) electricity mix is derived from the KAPSARC Power Sector Model (KPM) [9], which includes generation shares from natural gas, crude oil, and emerging renewables. Life cycle GHG intensity for each electricity generation technology (infrastructure) is calculated using technology-specific life cycle emission factors from the Ecoinvent database. Saudi-based fuels (natural gas and oil) were used as feedstock in the generation plants. Inventory for methane leak and fugitive emissions from Saudi-based natural gas was based on [53, 54], which was ~73 % lower than those reported by the IEA. For the average grid intensity for 2024–2035, annual projections through 2035, reflecting Saudi Arabia's announced pledges for fuel mix diversification, including a growing share of solar PV and natural gas, as well as the anticipated phase-out of crude oil combustion in power generation, are considered. Distribution and transformation losses, estimated at an average of 7 %, are also considered. Table SI3 shows the annual average electricity generation mix during the vehicles' lifetime, from 2024 to 2035.

Hydrogen (H_2) used in FCEVs is also modeled using both static (2024) and average carbon intensity for the period from 2024 to 2035 (Fig. 2 (b)). H_2 in 2024 is assumed to be produced via steam methane reforming (SMR) using natural gas, the current dominant production pathway in Saudi Arabia. The model includes methane leakage, reforming emissions, compression, and local transport of H_2 to refueling stations. Emissions are estimated using Saudi-specific data from the ecoinvent database and modeled as delivered H_2 at 700 bar. Green H_2 production was modeled assuming a Saudi portfolio of 30 % wind and 70 % solar sources. An alkaline electrolyzer (AE) is considered for the electrolysis process, based on the findings of Alhadhrami et al. [15], which indicates its expected dominance in Saudi Arabia green H_2 production due to its lower cost, despite the higher efficiencies of other electrolyzer types. The inventory utilized for green H_2 infrastructure and production process is reported in Refs. [55,56], respectively. An extra step for H2 compression to 700 bar was included in the model using the inventory reported in Cox et al. [42].

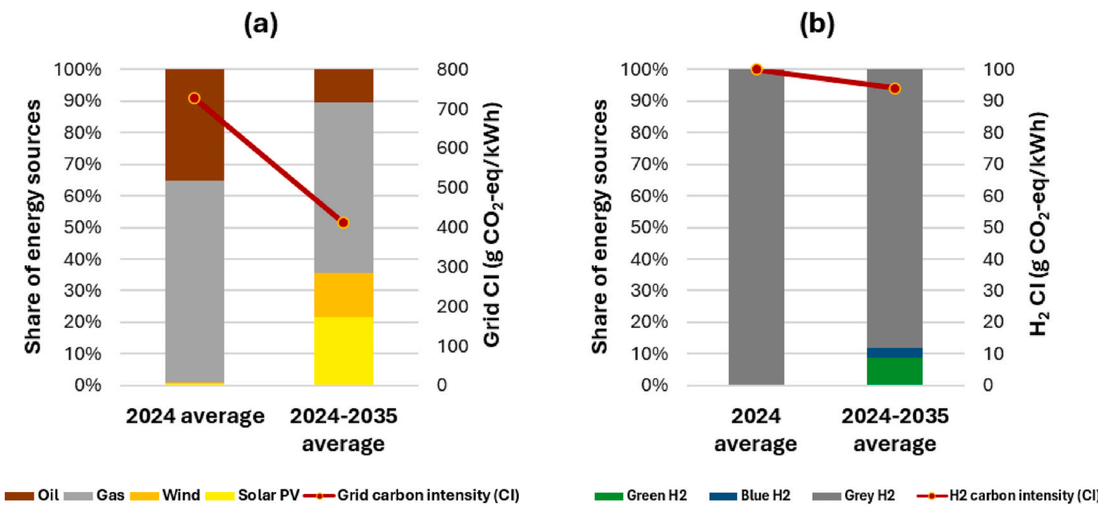

Fig. 2. (a) Projected grid mix and average carbon intensity, and (b) Projected H_2 mix and average carbon intensity.

The projected mix of hydrogen production pathways for 2024–2035 is informed by recent literature [12,57]. By 2035, green H_2 is expected to supply ~22 % of total production, supported by expanding renewable capacity and falling costs. Blue H_2 is projected to contribute ~10 %, though its role is likely to diminish as renewables become more competitive. The remaining share will be grey H_2, but this fraction is expected to decline steadily as cleaner pathways scale up. Table SI7 in the Supplementary Information provides the projected market mix and carbon intensity between 2024 and 2035 for compressed H_2 in this study.

3.2.3. *Vehicle use*

The use phase incorporates fuel or electricity consumption, exhaust and non-exhaust emissions, vehicle maintenance activities, and impacts associated with road infrastructure usage. To reflect real-world conditions, we adjusted manufacturer-reported energy consumption values upward by 25 % in the central case (Table 1). This aligns with empirical studies showing that actual on-road consumption typically exceeds laboratory values by 15–40 % [36,37]. To assess robustness, we conducted a sensitivity analysis with adjustment factors of +15 % and +35 %, capturing the lower and upper ends of this observed range.

Exhaust emissions for vehicles with internal combustion engines were modeled based on their adjusted fuel consumption using emission profiles consistent with the EURO 5 emission standards available in the Ecoinvent 3.10 database. Non-exhaust emissions, specifically from road surface wear, tire abrasion, and brake wear, were quantified using emission factors derived from Ref. [59]. Vehicle and infrastructure maintenance impacts were adapted from Ref. [60], originally specified for a 1240 kg vehicle with a lifetime of 150,000 km. These impacts were scaled proportionally according to the specific vehicle weights and lifetime mileages analyzed in this study.

Table 1
Adjusted fuel consumption (MJ/km) data.

Body type	Powertrain	Energy use (MJ/km)
Sedan	ICEV- gasoline	3.014
	ICEV- diesel	2.729
	BEV	0.870
	PHEV-series (ICE)	1.877
	HEV	1.776
	FCEV	1.580
SUV	ICEV- gasoline	3.354
	ICEV- diesel	3.035
	BEV	0.985
	PHEV-series (ICE)	2.093
	HEV	1.996
	FCEV	1.777

Source: Author's estimations based [42] and the manufacturer's website [58].

For BEVs, brake wear emissions were reduced to 20 % of those associated with ICEVs, reflecting the reduced mechanical braking demand enabled by regenerative braking systems. This follows the methodology proposed by Del Duce et al. [61]. For HEVs and PHEVs, vehicle maintenance impacts were conservatively accounted for by modifying ICEV maintenance profiles in the Ecoinvent database to explicitly consider petrol engine maintenance requirements.

Battery lifetime mileage is subject to substantial uncertainty due to variability in charging behavior, operational conditions, and battery management systems. Consequently, battery lifespan was modeled with a range of 100,000–250,000 km, using a central estimate of 160,000 km based on prevailing warranty benchmarks from leading EV manufacturers [62,63]. Importantly, the modeling approach acknowledges that high ambient temperatures, common in hot climates such as Saudi Arabia, can accelerate battery degradation by affecting cell chemistry and thermal management efficiency, among other factors. However, recent advances in battery thermal management systems, including liquid cooling and active temperature regulation, have significantly mitigated these effects in newer EV models [64,65]. To reflect this uncertainty, the model allows for potential battery replacements using the ratio between the vehicle's lifetime mileage and the assumed battery lifespan. Indicators for the central estimate are reported in the main text, and sensitivity bounds are illustrated as error bars in Figure SI1 of the Supplementary Information.

3.2.4. *End-of-life management*

End-of-life (EoL) management of vehicles was modeled using the Ecoinvent cut-off system approach, which accounts exclusively for the environmental burdens associated with dismantling, treating, and disposing of waste materials generated during vehicle decommissioning. In alignment with the cut-off modeling principle, material recovery and the associated recycling benefits were excluded to avoid double-counting [66,67]. This is consistent with the Ecoinvent cut-off system, as the production phase of vehicle components already includes recycled materials as burden-free inputs, thereby reflecting the recycled content without assigning upstream impacts related to recycling activities.

3.3. *Life cycle impact assessment*

The LCIA was performed using SimaPro 9.6 software, utilizing the Ecoinvent v3.10 database for background processes and emission factors. Life cycle GHG emissions were assessed using the ReCiPe 2016 (Midpoint, Hierarchist) method [68], with a primary focus on the Global

Warming Potential (GWP100) indicator, reported in grams of CO_2-equivalent per vehicle-kilometer (gCO_2-eq/vkm). GWP includes emissions of CO_2, CH_4, and N_2O, weighted by their 100-year radiative forcing impact [69].

Additional indicators, including particulate matter formation, photochemical smog, human toxicity, and resource depletion, are also calculated and reported in the Supplementary Information (Table SI9–SI.13). These indicators are not emphasized in the main results due to their limited policy relevance in this study context of decarbonization and climate policy. However, in the sustainable mobility transition lens, these indicators offer valuable co-benefit insights as discussed in section 3.2.

3.3.1. Uncertainty analysis

To assess the robustness of the life cycle emissions estimates and identify key sources of variability, a Monte Carlo simulation was conducted using triangular probability distributions for selected input parameters. Triangular distributions were chosen due to their suitability when empirical data is limited, but expert judgment allows for defining minimum, most likely, and maximum values [42]. This approach offers a transparent and conservative means of representing uncertainty. The key distribution parameters used in the analysis are summarized in Table SI1 of the Supplementary Information. The Monte Carlo simulation was run using the SimaPro 9.6 software with 1000 iterations per vehicle configuration. For each iteration, the life cycle GHG emissions per vehicle-kilometer (vkm) were recalculated using randomly drawn parameter values from specified distributions.

3.3.2. Sensitivity analysis

To evaluate the robustness of the results, a sensitivity analysis was conducted on parameters identified as key sources of uncertainty in literature. These include assumptions about real-world vehicle energy consumption, the pace of grid decarbonization, battery lifetime, and the future hydrogen production mix. Table 2 summarizes the parameters, central assumptions, variation ranges, and supporting references. The analysis quantifies how changes in these inputs affect the life cycle GWP100 indicator and tests whether the comparative ranking of drivetrain technologies remains consistent across plausible scenarios.

In addition to structural parameters such as energy consumption adjustments, battery lifetime, and hydrogen production mix, we explicitly test the influence of charging behavior and seasonal variation on life cycle results (Table 2). Charging profiles are modeled to reflect the Saudi context, where nighttime home charging (20:00–06:00, Level 1) is contrasted with daytime workplace/public charging (09:00–19:00, Level 2/3). This captures the effect of time-of-use variation in grid carbon intensity, as nighttime charging coincides with lower renewable penetration and higher petroleum generation. Seasonal variation is also assessed by comparing winter (December–February) and summer (June–August) grid profiles, which differ substantially due to cooling loads and dispatch decisions. Together, these additions enable a more granular understanding of how charging practices and seasonal demand patterns shape BEV life cycle emissions under Saudi-specific conditions.

Table 2
Parameters included in the sensitivity analysis and their variation ranges.

Parameter	Central value/ assumption	Variation tested	Rationale/Source
Real-world energy consumption adjustment	+25 % vs. manufacturer values	+15 % (low), +35 % (high)	Empirical evidence of a 15–40 % gap between lab and on-road use [36,37]
Grid decarbonization (2024–2035 temporal average)	Vision 2030-aligned projection (AGI = 411.8 gCO_2/kWh)[a]	Slower (+25 %), Faster (−25 %)	Reflects uncertainty in renewable build-out and fuel switching trajectories in practice
Battery lifetime	160,000 km (central, ~1 replacement per 250,000 km vehicle life)	100,000 km (shorter), 250,000 km (longer)	Manufacturer warranties and literature ranges [62,63]
Hydrogen decarbonization market mix (2024–2035 temporal average)	Authors projection (AMI = 108.8 gCO_2/kWh)[b]	Slower (+25 %), Faster (−25 %)	Uncertainty in scale-up of renewable hydrogen and CCS deployment [57]
Charging profile	2030 AGI = 281.0 gCO_2/kWh	Homebase (80 %) = 386.9 gCO_2/kWh vs. Work/public (80 %) = 267.2 gCO_2/kWh	Captures time-of-use variation in Saudi grid carbon intensity [9]
Seasonality	2030 AGI = 281.0 gCO_2/kWh	Winter = 338.9 gCO_2/kWh vs. Summer = 404.3 gCO_2/kWh	Captures seasonal variation in Saudi grid carbon intensity due to cooling loads and dispatch changes [9]

[a] AGI = Average grid intensity.
[b] AGI = Average mix intensity.

4. Results and discussion

4.1. Comparison of life cycle GHG emissions

Fig. 3 presents the life cycle greenhouse gas (GHG) emissions of various vehicle technologies—ICEVs, HEVs, PHEVs, BEVs, and FCEVs—in Saudi Arabia based on the 2024 electricity and hydrogen mix, along with the expected reductions throughout their lifetime (average between 2024 and 2035). The bar chart represents the emissions intensities under the static 2024 conditions, expressed in grams of CO_2-equivalent per vehicle-kilometer (gCO_2e/vkm), while the green arrows indicate the potential emission reductions when considering the average energy mix over the vehicle lifetime (2024–2035).

Using our baseline assumptions, ICEVs exhibit the highest life cycle emissions, ranging from 347 to 383 gCO_2eq/vkm for sedans and SUVs, respectively. These high values are mainly driven by tailpipe emissions from fuel combustion. HEVs show moderate improvements, with emissions ranging between 244 and 269 gCO_2eq/vkm for sedans and SUVs, respectively. These reductions relative to the ICEVs stem from HEVs' increased fuel efficiency and partial electrification, consequently reducing their tailpipe emissions.

BEVs underperform relative to HEVs under Saudi Arabia's current energy landscape: BEVs' life-cycle emissions are 15 %[1] higher than HEVs (sedans: 281 vs 244 gCO_2eq/vkm; SUVs: 310 vs 269 gCO_2eq/vkm). This is primarily due to Saudi Arabia's current carbon-intensive grid used for charging. This finding contrasts with global perceptions of BEVs as universally low-emission vehicles and underscores their local dependency to meet expected climate benefits. FCEVs also exhibit relatively high life cycle emissions, in the range of 252–277 gCO_2eq/vkm, largely because current hydrogen production is reliant on natural gas reforming pathways, which remains a carbon-intensive process.

Under a projected decarbonized grid scenario, substantial differences emerge, particularly for BEVs and PHEVs. BEVs exhibit the highest absolute GHG reductions (around 76.1 gCO_2eq/vkm for sedans and 86.2 gCO_2eq/vkm for SUVs), representing an average 28 % improvement compared to their 2024 baseline. This highlights the strong climate mitigation potential of BEVs as the grid decarbonizes. A similar pattern

[1] Sedan: (281−244)/244 = 15.2 %; SUV: (310−269)/269 = 15.2 %.

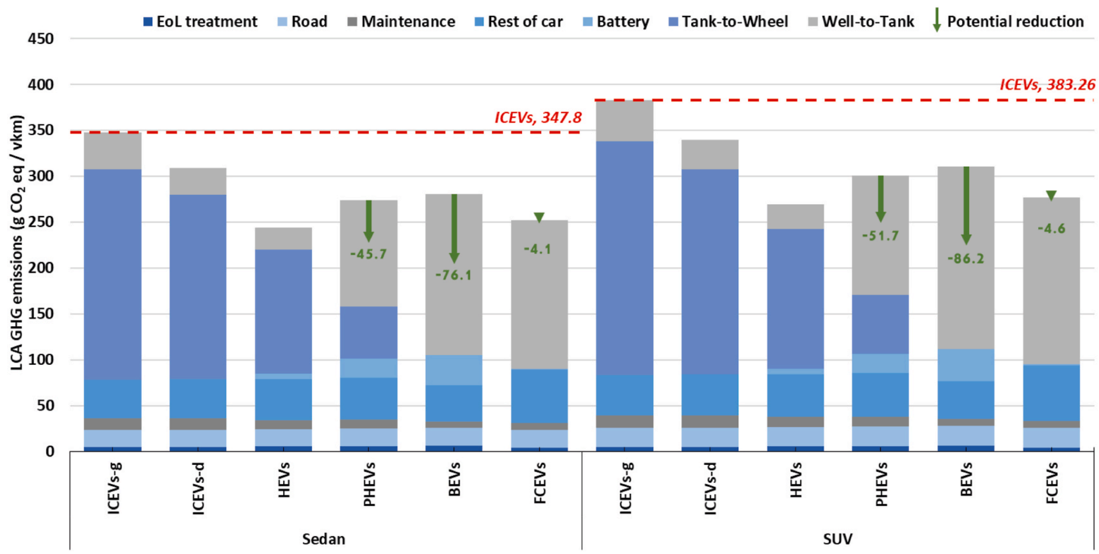

Fig. 3. Life cycle GHG emissions with potential reductions.
Note: Green arrows indicate the potential emission reductions between 2024 and the 2025–2035 period, reflecting projected grid decarbonization over the vehicle's lifetime. ICEVs-g are gasoline-powered and ICEVs-d are diesel-powered.

is observed for PHEVs. FCEVs see only modest improvements (4.1–4.6 gCO_2eq/vkm) unless green hydrogen pathways are aggressively pursued.

These results underscore the transformative potential of energy sector decarbonization in Saudi Arabia. While BEVs currently face relatively high life cycle emissions under the petroleum-dominated grid, their comparative climate performance improves significantly as the grid carbon intensity declines over time. This shift is primarily driven by reductions in upstream emissions from electricity generation, which significantly lower BEV use-phase emissions.

The findings reinforce that the environmental advantage of BEVs is not fixed but strongly linked to the scale of electricity decarbonization. Furthermore, these findings imply that in regions where power sector reforms are slower, hybrid vehicles may remain more effective in the near term. This local and temporal sensitivity of EVs highlights the importance of aligning transport electrification strategies with national energy transition pathways.

4.2. Environmental co-benefits, tradeoffs, and uncertainty analysis

Adopting alternative energy vehicles (AEVs) such as BEVs, PHEVs, HEVs, and FCEVs introduces significant environmental co-benefits and trade-offs, extending beyond reductions in GHG emissions alone. As shown in Table 3, these vehicles offer meaningful improvements in local air quality, particularly through reduced emissions of Particulate Matter ($PM_{2.5}$), Nitrogen Oxides (NO_x), and Volatile Organic Compounds (VOCs) during the use phase, thereby contributing to lower public health burdens related to respiratory and cardiovascular diseases.

However, under Saudi Arabia's current energy mix, primarily petroleum fuel-based, these benefits are partially offset by upstream emissions from power and hydrogen generation. This results in the relocation of air pollution from urban centers (tailpipes) to areas surrounding electricity and hydrogen production facilities (smokestacks), highlighting a spatial redistribution of environmental impacts.

Other critical trade-offs arise from the manufacturing stage, especially for BEVs and PHEVs, where lithium-ion battery production leads to increased mineral resource scarcity and toxicity-related impacts. Similarly, FCEVs impose additional environmental burdens due to the production of fuel cells and the extraction of rare metals such as platinum. Furthermore, the energy supply chain remains a dominant contributor to fossil resource depletion and acidification potential, particularly for BEVs and FCEVs, whose electricity and hydrogen inputs are derived from natural gas. These trade-offs underscore the importance of decarbonizing the electricity and hydrogen sectors to fully realize the environmental advantages of AEVs.

The robustness of these findings is further evaluated through uncertainty analysis. As detailed in the Supplementary Information (Figures SI1–SI6 and Tables SI8–SI.12), considerable variability is observed in several impact categories, especially human carcinogenic toxicity. These variations are primarily driven by differences in vehicle lifetime mileage and size/class (e.g., glider mass, battery size, and energy consumption). Uncertainty in the background inventory data and the impact assessment of critical mineral supply chains also significantly influence the estimated outcomes, particularly for toxicity and resource depletion indicators. This highlights the need for improved data quality and methodological transparency in future assessments to better support

Table 3
Summary of environmental co-benefits, trade-offs, and key uncertainties by vehicle type.

Impact category	BEVs	PHEVs	HEVs	FCEVs
Co-benefits	Zero tailpipe emissions; Improved urban air quality	↓ Tailpipe pollutants; Partial electric drive	↓ GHG and air pollutants vs ICEVs	Zero tailpipe emissions; Improved urban air quality
Trade-offs: vehicle Manufacturing	↑ Li-ion battery impacts; Mineral scarcity; Carcinogenic toxicity	Battery impacts are lower than BEVs	Small battery; Minor impacts	Fuel cell production; Precious metals (Pt)
Trade-offs: energy supply chain	Fossil electricity → ↑ upstream emissions	Fossil electricity + fuel → mixed emissions	Fossil fuel combustion	Fossil-based H_2 → ↑ GHG, toxicity
Uncertainty sources	Lifetime mileage, battery size, and electricity mix	Lifetime mileage, Fuel/electricity ratio, battery mass	Lifetime mileage, Fuel efficiency variability	Lifetime mileage, H_2 production variability, fuel cell size
High uncertainty impact Areas	Toxicity, mineral scarcity	Toxicity, mineral scarcity	Fossil resource scarcity	Toxicity, mineral scarcity

policymaking.

4.3. Sensitivity of results

Sensitivity analysis was carried out for BEVs and FCEVs (Fig. 4), as these technologies are most dependent on upstream energy pathways (electricity and hydrogen, respectively) and therefore represent the highest uncertainty and policy relevance under Saudi Arabia's evolving carbon-intensive context. The results, benchmarked against vehicles' climate performance under the average 2024–2035 grid and hydrogen mix, show that operational assumptions have modest effects: varying the real-world consumption adjustment between +15 % and +35 % changes life cycle GHG emissions by ±4–5 %, while battery lifetime variation shifts BEV emissions by +9 to −6 %. In contrast, upstream decarbonization dominates outcomes: a ±25 % change in average grid intensity alters BEV emissions by ±12–13 %, while a similar variation is observed for FCEV. A ±25 % variation in hydrogen decarbonization shifts results by ±16 %, underscoring that production pathways are decisive for climate performance. This finding aligns with Saudi Arabia's hydrogen ambitions, where scaling blue hydrogen in the near term and expanding green hydrogen in the longer term will critically shape the viability of FCEVs. These findings demonstrate that while efficiency and durability assumptions influence results, the comparative climate performance of BEVs and FCEVs is primarily determined by the pace of electricity and hydrogen decarbonization.

4.3.1. A2030 outlook on the impact of charging time and seasonality

Fig. 5 shows the impact of different home-based (nighttime) charging shares on WTW emissions. Globally, around 80 % of EV charging occurs at home [2], primarily due to convenience, lower costs, and access to residential infrastructure. In the Saudi context, this trend may increase implications for the electricity sector. Residential electricity demand is already elevated due to extensive cooling loads, especially during summer. When home charging coincides with these high-demand periods, when the grid is typically powered by gas generators, it could increase emissions.

Well-to-wheel (WTW) emissions increase significantly with greater reliance on home charging, rising from 64.7 to 93.6 gCO_2eq/vkm for sedans and from 73.2 to 106.0 gCO_2eq/vkm for SUVs as the share of home charging grows from 20 % to 80 %. The higher emissions are attributed to low renewable generation at night and increased petroleum-based marginal generation. Public charging, by contrast, is more aligned with daytime solar availability and offers relatively lower emissions intensity. These findings underscore the critical influence of charging time and associated electricity supply characteristics on the climate benefits of EV deployment.

Seasonal variation in electricity demand further compounds this effect. Fig. 6 present BEV WTW emissions for peak summer and winter conditions. In the Saudi context, higher cooling demand is typically experienced during the summer months, resulting in a surge in electricity consumption. As a result, the grid is relying more on natural gas to meet the extra cooling load. This increases the BEV charging emissions to 97.8 gCO_2eq/vkm for sedans and 110.8 gCO_2eq/vkm for SUVs. By contrast, in winter, reduced cooling loads and relatively lower overall demand allow for a relatively low-carbon generation mix, resulting in lower emissions of around 82.0 and 92.9 gCO_2eq/vkm, respectively. This seasonal shift in emissions intensity highlights the importance of adjusting charging patterns to reflect seasonal variations in grid carbon content.

These results emphasize that the climate performance of BEVs cannot be decoupled from the temporal dynamics of electricity supply. Aligning EV charging with periods of low-carbon electricity availability is crucial for maximizing emission savings. Deploying smart grids and integrating renewable energy into public charging stations presents an opportunity to better manage this alignment. For instance, solar-enabled public parking infrastructure can leverage daytime solar output for cleaner charging while also mitigating grid peaks. Although such infrastructure entails upfront costs and logistical complexity, evidence from international case studies suggests that long-term environmental and operational gains justify the investment [70–72].

4.4. Limitations and future research suggestions

This study offers a comprehensive LCA of emerging passenger vehicle technologies in Saudi Arabia, integrating temporal grid dynamics and environmental trade-offs. Several limitations, however, must be acknowledged.

First, the analysis relies on projected changes in the national energy mix to 2035. While grounded in policy targets and scenario modeling, these projections remain uncertain; delays in decarbonization, technological constraints, or geopolitical shifts could alter the comparative performance of EVs. Future work should employ stochastic or adaptive scenario modeling to capture a wider range of pathways.

Second, charging behavior is represented through simplified home versus public charging and seasonal variation. In practice, charging access and timing vary by income, urban form, dwelling type, and

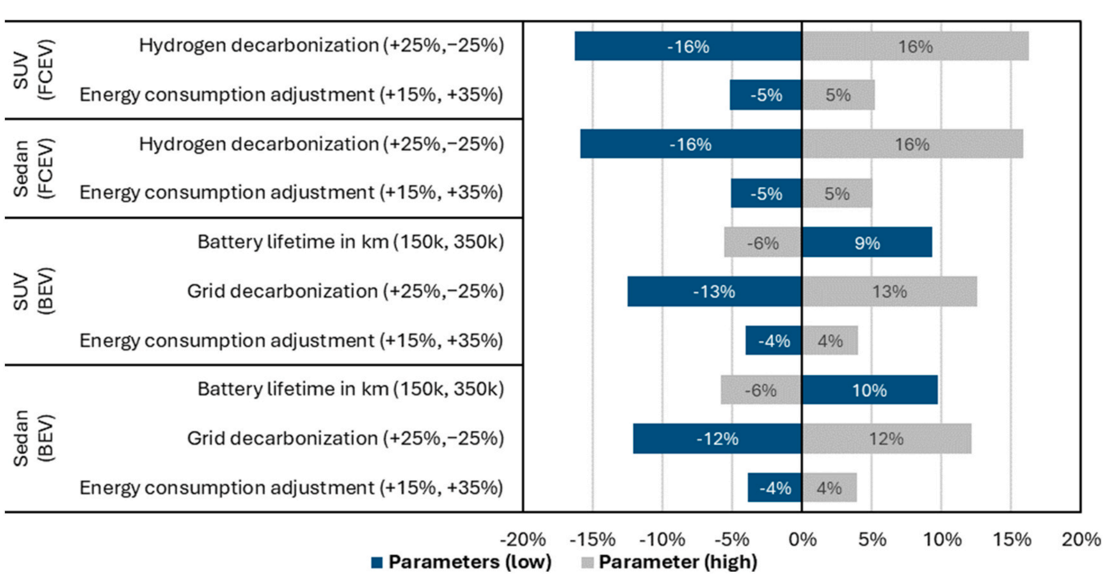

Fig. 4. Sensitivity of BEV and FCEV life cycle GHG emissions under the 2024–2035 average mix to key parameters.

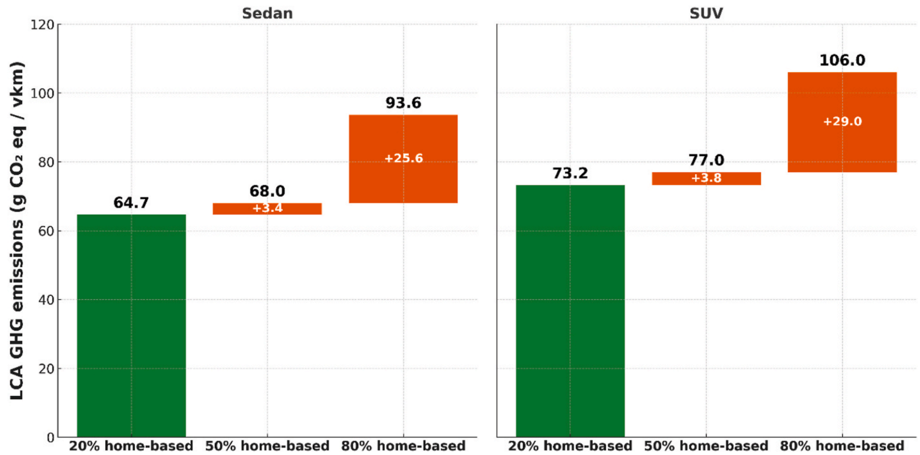

Fig. 5. Estimated well-to-wheel GHG emissions by home-based (nighttime) charging share in Saudi Arabia.
Note: Home-based charging share refers to the proportion of charging performed at home during night-time. The values of 20 %, 50 %, and 80 % represent different shares of home-based charging and illustrate the corresponding potential environmental impact.

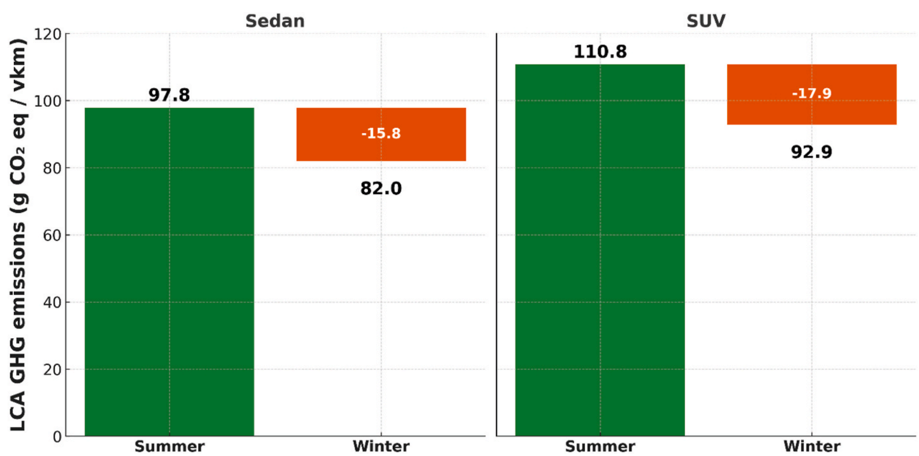

Fig. 6. Seasonal variation in BEV well-to-wheel GHG emissions in Saudi Arabia.
Note: Seasonal emissions" refer to the impact of electric vehicle charging under different electricity mixes. The values for summer and winter represent seasonal variations in grid intensity and show how these differences influence the environmental performance of EVs.

infrastructure availability. Incorporating agent-based or spatially disaggregated behavioral models would improve accuracy and policy relevance. Distributional equity including charging access and affordability for renters and low-income households is outside this LCA's scope; future work should assess levers such as bill-payment protections, subsidized public charging, access requirements, and renter-focused financing.

Third, vehicle manufacturing inventories are largely drawn from global databases. These may not fully capture supply chains relevant to Saudi imports, introducing uncertainty in categories such as mineral extraction and upstream manufacturing emissions. Developing Gulf-specific datasets is therefore a key priority.

Finally, this study focuses on environmental outcomes without addressing cost-effectiveness or macroeconomic impacts. Future research should integrate techno-economic metrics, including total cost of ownership, industrial spillovers, and employment effects, to ensure transitions are both just and feasible.

Collectively, these limitations highlight the need for regionally contextualized, interdisciplinary approaches that combine behavioral, economic, and environmental perspectives to guide sustainable mobility in the Global South.

5. Conclusions and policy implications

The analysis provides compelling evidence of the climate implications of transitioning to alternative energy vehicles in Saudi Arabia. Our study highlights a significant regional divergence from global trends, with BEVs initially demonstrating higher life cycle GHG emissions than HEVs under the Saudi Arabia's current carbon-intensive electricity grid. However, substantial emission reductions are evident for current BEVs, averaging up to a 28 % reduction during their lifespan if the electricity grid is decarbonized in line with the Kingdom's targets and initiatives. This highlights the transformative climate mitigation potential of BEVs, contingent upon ongoing decarbonization of the energy sector. Additionally, environmental co-benefits, notably improvements in local air quality, accompany the deployment of AEVs, but are tempered by environmental trade-offs related to battery production and the shifting of pollution sources from tailpipes to electricity generation sites. The sensitivity analysis confirms that upstream electricity and hydrogen decarbonization drive greater variability (±12–16 %) than operational assumptions (±4–10 %). Furthermore, it emphasizes that BEV emissions are significantly influenced by temporal aspects, such as charging behavior and seasonal electricity demand, underscoring the need for integrated transport-energy policy frameworks in Saudi Arabia.

5.1. Policy prescriptions

Based on our results, we offer policy recommendations to support a sustainable and context-aware transition in the passenger vehicle sector.

1. Technology-neutral GHG performance standards with life cycle thresholds

This policy prescription suggests introducing technology-agnostic life cycle GHG performance standards for all vehicles, rewarding the best life cycle performers (e.g., HEVs today, BEVs in the future) regardless of drivetrain type. The rationale from our results shows that HEVs outperform BEVs in life cycle emissions under Saudi Arabia's current energy landscape. This result highlights the importance of outcome-based rather than technology-prescriptive policies, a trend that contradicts prevailing international policy assumptions. The following key implementation levers are suggested.

- Regulate based on life cycle gCO_2eq/vkm rather than tailpipe-only standards. To ensure feasibility, implementation should be phased: beginning with voluntary reporting, then progressing to mandatory thresholds as supply chains adjust.
- To operationalize for vehicle production stage emissions, certified LCA disclosure should be required as part of vehicle registration, encouraging Original Equipment Manufacturers (OEMs) to optimize upstream supply chains for Saudi-bound fleets. Enforcement can be achieved by requiring certificates of conformity that include detailed life cycle GHG data as a prerequisite for customs clearance.
- To operationalize for use stage emissions, provide tax incentives for any vehicle model that has proven lower WTW emissions compared to the incumbent ICEVs by meeting a verified life cycle carbon threshold adapted to the Saudi energy mix.
- Integrate life cycle standards with existing Saudi Standards, Metrology and Quality Organization (SASO), and Gulf Standardization Organization (GSO) import certification processes to streamline compliance.

2. Time and grid-responsive electrification policies:

This policy prescription promotes linking alternative EVs and charging incentives to grid carbon intensity. Instead of promoting blanket EV adoption, policymakers should implement time- and location-sensitive electrification policies that align alternative EV incentives with local life cycle emissions and grid carbon intensity. In addition, charging behavior with periods of low grid carbon intensity, daytime solar peaks, or shoulder seasons with higher renewable shares should be incentivized. The rationale from our results shows that alternative EV emissions strongly depend on the carbon intensity of the energy system. In addition, BEV emissions vary by nearly 40–50 % depending on charging time and season. This regional insight suggests that simply increasing EV uptake, without decarbonizing the energy system, and coordinating when and where charging occurs, may undermine the potential of BEVs to reduce GHG emissions. The following key implementation levers are suggested.

- Smart meter integration with dynamic electricity pricing that penalizes high-emission nighttime residential charging.
- Deploy solar-canopied public and workplace chargers as preferred charging nodes.
- Launch a public campaign promoting "smart charging" behavior tailored to local grid decarbonization patterns.

To illustrate feasibility, consider initiatives in regions with hot, arid climates comparable to Saudi Arabia. In the UAE, Cabinet Resolution No. 81 (2024) standardized EV charging rates (AED 0.70/kWh for slow AC and AED 1.20/kWh for fast DC, plus VAT), while encouraging off-peak home charging via timers to leverage lower electricity tariffs, reducing costs and grid strain during peak hours [73]. In Australia, the South Australian government's $3.2 million EV Smart Charging Trials (2022–ongoing) tested dynamic pricing: Chargefox's Rapid DC Time-of-Use Pricing Trial adjusted rates based on electricity market events, shifting charging to off-peak periods and demonstrating up to 20 % demand reduction; AGL's trial used price signals to alter fleet charging behavior, integrating with solar for renewable-optimized sessions [74]. These examples highlight how time-varying incentives can align charging with low-carbon periods; however, Saudi-specific trials are needed to refine for local energy mixes.

3. Equity-focused access and affordability measures

To ensure environmental gains translate into real-world adoption, complementary equity measures, such as bill-payment protections, subsidized public charging in underserved areas, access requirements, and renter-friendly financing, can address documented charging access gaps for low-income and multifamily households.

A successful transition requires rethinking "clean mobility" beyond the one-size-fits-all electric vehicle model. Institutional coordination between the Ministry of Energy, the Ministry of Transport, and Vision 2030 industrial clusters is vital. Enabling conditions include accelerated investment in renewable energy, carbon capture integration, smart grid infrastructure for real-time emissions monitoring, and targeted fiscal support for proven low-emission vehicles. Social acceptance can be bolstered through public communication around charging behavior and by ensuring affordable mobility options across income groups.

6.2 Applicability to global context.

The findings and policy recommendations emerging from this Saudi-focused assessment hold significant implications for global climate and transport policy, especially for petroleum-fuel reliant, emerging economies navigating the early stages of energy transition. First, this study challenges the dominant global narrative that equates vehicle electrification with universal GHG mitigation. Instead, it advances a context-aware and techno-agnostic paradigm, emphasizing that climate benefits from EVs are not inherent but are conditional on energy system characteristics, infrastructure readiness, and charging behaviors.

Globally, many countries in the Global South share structural similarities with Saudi Arabia: petroleum-dominated electricity grids, limited public charging infrastructure, and constrained fiscal space for large-scale BEV incentives. In these settings, hybrids and transitional technologies may offer greater near-term GHG reductions per dollar invested than BEVs, especially when life cycle emissions are considered. By showing that HEVs can currently outperform BEVs in Saudi Arabia on a life cycle basis, this study provides an evidence base for recalibrating vehicle policy targets away from drivetrain-specific mandates toward outcome-based, life cycle emission performance standards. Such frameworks allow nations to chart their own decarbonization trajectories, aligned with national energy profiles, social equity needs, and economic structures.

Moreover, the results on temporal charging sensitivity and seasonality reinforce the global relevance of coupling EV deployment with smart charging infrastructure and renewable-aligned mobility planning. This is especially salient for tropical, desert, and monsoonal climates where cooling or heating loads create large intra-annual variability in grid carbon intensity. Countries like India, Indonesia, Nigeria, or China can draw from these insights to design dynamic, grid-responsive charging strategies that mitigate the risk of emissions rebound from poorly timed electricity use.

Finally, the Saudi case illustrates that sustainable mobility transitions need not hinge solely on EV adoption, but on a techno-agnostic approach to reducing climate emissions. By proposing transitional pathways, such as hybrid deployment when the electricity mix is still carbon-intensive, this study offers a template for nations starting their energy transition journey. These strategies support broader goals of technology diversification, industrial upgrading, and energy sovereignty, demonstrating that the global transition must embrace plural mobility futures if it is to be truly inclusive, just, and effective.

CRediT authorship contribution statement

Abdulrahman Alwosheel: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology. **Michael Samsu Koroma:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2025.138845.

Data availability

Data will be made available on request.

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