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Discussion Paper

Environmental Performance of Passenger Cars in the KSA: Comparison of Different Technologies via a Life Cycle Assessment Approach

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Abstract

Analyzing the environmental performance of alternative vehicle technologies in the current energy landscape of the Kingdom of Saudi Arabia (KSA) is very important given their expected role in future transportation systems. This study presents a comprehensive life cycle assessment (LCA) of sedans and sport utility vehicles (SUVs) powered by different propulsion systems to analyze their environmental performance in the KSA context. The LCA examines multiple impact categories, with a particular focus on global warming potential (GWP). The results reveal that hybrid electric vehicles (HEVs), fuel cell electric vehicles (FCEVs), and plug-in hybrid electric vehicles (PHEVs) consistently demonstrate the lowest GWP across both sedan and SUV vehicle classes, achieving reductions of approximately 30%, 28%, and 22%, respectively, compared with the baseline gasoline-powered internal combustion engine vehicles (ICEVs). Battery electric vehicles (BEVs) also exhibit lower GWP (approximately 16%) than do conventional ICEVs but to a lesser extent than do other advanced powertrains. The energy supply chain plays a crucial role for BEVs, including FCEVs and PHEVs, underscoring the importance of decarbonizing electricity and hydrogen (H_2) production to realize the full environmental advantages of these technologies in the KSA. In terms of deployment feasibility, PHEVs and HEVs have a distinct advantage over FCEVs, as they can leverage the existing electricity grid and fueling infrastructure, making them a more practical and readily available solution for reducing near-term emissions in the KSA transportation sector. Policymakers and industry stakeholders are encouraged to develop targeted incentives, regulations, and support mechanisms to accelerate the market penetration of these technologies while also considering strategies to address their multifaceted environmental implications.

Keywords: Vision 2030, Sustainable Mobility, Global Warming, Electric Vehicles, Saudi Arabi.

Abbreviations

BEV: Battery electric vehicle

CO_2: Carbon dioxide

EV: Electric vehicle

FCEV: Fuel cell electric vehicle

FU: Functional unit

GHG: Greenhouse gas

GWP: Global warming potential

HEV: Hybrid electric vehicle

ICEV: Internal combustion engine vehicle

IPCC: Intergovernmental Panel on Climate Change

LCA: Life cycle assessment

LIB: Lithium-ion battery

NMC: Nickel manganese cobalt

PHEV: Plug-in hybrid electric vehicle

PEM: Polymer electrolyte membrane (fuel cell)

RES: Renewable energy source

SMR: Steam methane reforming (hydrogen production)

SUV: Sport utility vehicle

WTW: Well-to-wheel

1. Introduction

The transportation sector is a significant contributor to global greenhouse gas (GHG) emissions and energy consumption, accounting for nearly a quarter of global carbon dioxide (CO_2) emissions (Ritchie 2020). Passenger cars alone are responsible for approximately 45% of the CO_2 emissions of the transportation sector. As the world has transitioned toward more sustainable mobility solutions, understanding the environmental impacts of different passenger vehicle technologies is crucial for informing policy and investment decisions. This situation is particularly relevant for countries in the Middle East and North Africa (MENA) region, which can be considered late adopters in the uptake of alternative passenger vehicles compared with China and countries in Europe and North America. However, interest and investment in sustainable mobility solutions are growing in the MENA region, as countries aim to diversify their economies and reduce GHG emissions.

As major players in the global energy landscape, the environmental impact of countries in the MENA region has far-reaching implications. Thus, addressing the environmental impact of the region's energy and transportation sectors is crucial in the global effort to mitigate climate change.

The Kingdom of Saudi Arabia (KSA) significantly contributes to the MENA region's environmental footprint. As a leading oil-producing nation, the KSA's transportation sector depends heavily on fossil fuels, resulting in substantial impacts on the environment and climate (Alajmi 2021). Currently, the KSA is facing the challenge of transitioning to sustainable transportation solutions, such as low-carbon vehicles and public transportation systems, to reduce emissions and promote cleaner air quality.

With this in mind, the KSA has undertaken various initiatives to promote alternative fuel vehicles and cleaner transportation, such as the Saudi Vision 2030 plan, which includes a target of achieving 30% electric vehicle (EV) penetration in Riyadh by 2030 (Alyamani, Pappelis, and Kamargianni 2024). These efforts are part of a broader strategy to reduce emissions and transition toward a less carbon-intensive energy mix. The Saudi Industrial Development Fund (SIDF) has also emphasized investments in EV production, the expansion of charging infrastructure, and incentives for alternative fuel vehicles to support this transition (SIDF 2022).

However, to effectively guide these initiatives and ensure that transitioning to low-carbon transportation yields environmental and climate benefits, a comprehensive understanding is necessary. Specifically, conducting a life cycle assessment (LCA) of the environmental performance of conventional vehicles and emerging options, such as battery EVs (BEVs), plug-in hybrid EVs (PHEVs), and hydrogen (H_2) fuel cell EVs (FCEVs), is needed within the context of the KSA's current energy landscape.

1.1 Summary of the Related Literature

LCA is widely utilized in the scientific literature to evaluate whether transitioning to low-carbon transportation genuinely yields environmental and climate benefits. LCA offers a holistic analysis of the environmental impacts associated with a product's entire life cycle, from raw material extraction through to manufacturing and use and finally to end-of-life disposal. This comprehensive approach ensures that all stages contributing to environmental burdens are considered when alternative transportation technologies are being assessed (Scott Matthews, Hendrickson, and Matthews 2014).

Building on this comprehensive approach, numerous studies have applied LCA methodologies to passenger vehicles, evaluating the environmental impacts of both conventional and emerging vehicle technologies. While alternative vehicles are widely considered promising technologies for decarbonizing the transportation sector, their actual environmental benefits are heavily dependent on the source or production pathways of the electricity/energy used to power them and the supporting infrastructure. For example, BEVs produce zero direct GHG emissions during operation, but their overall life cycle emissions depend strongly on the carbon intensity of the electricity grid (Cox et al. 2020; Koroma et al. 2022). In regions where electricity is generated primarily from fossil fuels, the emission savings of BEVs over conventional internal combustion engine vehicles (ICEVs) may be limited or even negligible. Conversely, in areas with a greater share of renewable or low-carbon electricity sources, BEVs have shown substantial emission reductions (Woo, Choi, and Ahn 2017; Shafique and Luo 2022; Marmiroli et al. 2018).

In addition to the importance of energy sources or fuel production pathways for alternative vehicles, Tolomeo et al. (2020) and Xia and Li (2022) emphasized the substantial environmental burdens associated with lithium-ion battery (LIB) production, particularly from raw material extraction and processing. Both studies underscore the necessity of recycling and developing more sustainable battery technologies to mitigate the associated impacts. Lewis et al. (2019) explored the environmental benefits of vehicle lightweighting and revealed that lightweighting can reduce emissions during the use phase. However, the production of advanced materials can offset some of these benefits because of increased environmental impacts. This finding is similar to those of other studies (Monteiro et al. 2022; Kawajiri, Kobayashi, and Sakamoto 2020).

While numerous LCA studies on passenger vehicles exist globally, few studies have focused specifically on the life cycle environmental performance of vehicle technologies in the KSA. Additionally, LCA studies examining the effects of policy implementation in those countries in the MENA region are scarce. One notable exception is a recent well-to-wheel (WTW) analysis of GHG emissions for passenger vehicles in the MENA region (Ankathi et al. 2024). Ankathi et al. employed both technology-normalized and fleet-representative modeling approaches and reported WTW emissions of approximately 308.01 g CO_2eq/km for ICEV gasoline vehicles on the basis of a fleet-representative fuel economy of 10.46 km/L in the KSA. The technology-normalized approach of Ankathi et al. revealed emissions of 109 g CO_2eq/km and 117.5 g CO_2eq/km for small and midsize sport utility vehicles (SUVs), respectively, assuming technology-specific fuel economies of 16.58 km/L and 15.39 km/L. The variation in the above results underscores the importance of accounting for regional differences in factors such as fuel economy when evaluating vehicle emission performance. However, the WTW-only approach utilized by Ankathi et al. offers a limited perspective on the overall life cycle impacts of vehicles in the KSA and the MENA region.

Given that the KSA has been a late adopter of alternative passenger vehicles, comprehensive LCA studies comparing conventional and alternative passenger vehicles within the country are lacking. This absence highlights the following critical research gap: the need for context-specific LCA studies that encompass all life cycle stages of both conventional and alternative vehicles in the KSA. Addressing this gap is essential for accurately assessing the potential environmental benefits of transitioning to low-carbon transportation options and informing effective policy implementation in the KSA and the broader MENA region.

1.2 Study Objective

This study attempts to fill the abovementioned research gap by conducting a comprehensive LCA of current and emerging passenger vehicle technologies within the KSA context. The aim is to establish a baseline for the environmental performance of these technologies, providing critical insights to inform policy and consumer choices toward more sustainable mobility solutions. Specifically, the study objectives are as follows:

1. Perform a comprehensive LCA of conventional and alternative passenger vehicles in the KSA.
2. Evaluate and compare environmental impacts, including GHG emissions, across the full life cycle of

ICEVs, BEVs, hybrid EVs (HEVs), PHEVs, and FCEVs under the KSA's current energy landscape.

3. Identify the key areas for emission reduction within the vehicle life cycle.
4. Inform sustainable transportation policies with evidence-based recommendations.

The remainder of this paper is organized as follows. Section 2 provides the methodological details and life cycle inventory for vehicle technologies, fuel production pathways, and energy mixes, including data sources, system boundaries, and assumptions. Section 3 presents the full life cycle results and discussion, covering the environmental impacts and global warming potential (GWP) of the assessed passenger vehicle options. The concluding section summarizes the key findings and offers insights to guide policymakers, industry, and consumers toward more sustainable mobility solutions in the KSA.

2. Method, Data, and Assumptions

Assessing the environmental impacts of passenger vehicles requires a comprehensive life cycle perspective, considering both the use phase and the upstream supply chains for vehicle production and fuel or electricity. These impacts vary significantly depending on the powertrain technology and fuel production pathways. In addition, vehicle drivetrain technologies exhibit varying maturity levels. For example, ICEVs are well established, whereas BEVs, HEVs, and PHEVs have recently gained mainstream traction, and FCEVs are in the early commercialization stage. This disparity necessitates a consistent comparative assessment framework. A robust comparison must capture the full life cycle of each system, from raw material extraction to end-of-life treatment. This comprehensive approach is essential for accurately comparing the environmental impacts of different powertrain options. Thus, this section outlines the approach to modeling vehicle performance as well as the details of the LCA model.

2.1 Energy Landscape

The LCA model was constructed for the business-as-usual (BAU) scenario, in which the current (2022) energy mix of the KSA was assumed to remain static throughout the analysis. In this scenario, the operational phase of the vehicles was modeled under the assumption that the energy mix would remain constant over time. Gasoline and diesel remain the predominant fuels for ICEVs, with the limited adoption of low-carbon transport technologies being carried out. Electricity generation was derived primarily from fossil fuels (natural gas and oil), with a small share of renewable energy sources (RESs) constituting approximately 1% of the total energy mix (Elshurafa, Petitet, and Felder 2023).

2.2 Uncertainty Analysis

We employed Monte Carlo analysis to calculate uncertain life cycle parameters for both current and emerging vehicle technologies. The model considered a range of sedan and SUV powertrains and sizes, from small to large, with the vehicle mass, battery capacity, and fuel/electricity consumption identified as the key uncertain parameters. The input assumptions for vehicle production, including the value ranges for these uncertain parameters, were calibrated via values from the literature.

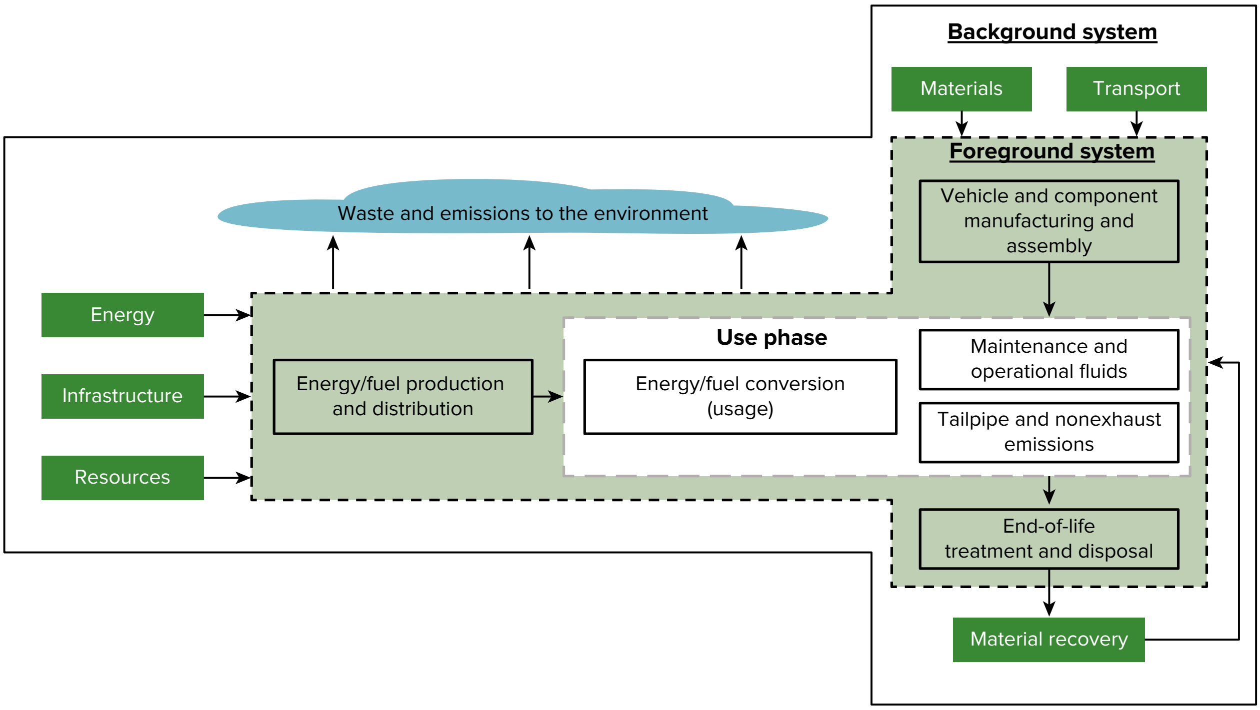
We defined triangular distributions[1] for the uncertain parameters[2], following similar assumptions to those of (Cox et al. 2018; 2020). A triangular probability distribution was chosen because comprehensive distribution data were not available. This distribution type requires only estimates of the minimum, mode, and maximum values, which were reasonably determined on the basis of literature data. Although detailed data to precisely define the distribution tails were lacking, triangular distribution offered a conservative approach by assigning relatively high probabilities to extreme values (values close to the minimum and maximum) within the parameter range (Kissell and Poserina 2017). Table S1 of the Supplementary Information (SI) section provides a complete list of the input parameters used and their distributions.

2.3 Goal and Scope Definitions

The goal of this LCA is to estimate and compare the life cycle environment impacts of current and emerging passenger vehicle powertrains in the context of the KSA's current energy landscape. We assessed the following powertrains for sedans and SUVs operating in the KSA: gasoline ICEVs, diesel ICEVs, HEVs, PHEVs, BEVs, and FCEVs.

The scope represents a cradle-to-grave approach, covering the full life cycle of the different passenger vehicle powertrains. Figure 1 shows the system boundary[3] covering the background and foreground system. The foreground system includes vehicle and component production, fuel/energy generation and supply, vehicle use, and disposal (treatment) at the end of life. The background system considers all additional model inputs, such as transportation, infrastructure, recovered materials, and energy and material resources. A global scope was assumed for vehicle and battery production because the KSA does not produce its own cars or batteries, as they are typically imported. The use phase, however, was limited to the KSA to reflect the local energy mix and usage conditions. The temporal scope covered the current state (2022) of the technologies, specifically the local energy mix, during vehicles' lifetimes.

Figure 1. Scope and system boundary of the LCA in this study.



Source: Authors.

The functional unit (FU) is defined as the number of vehicle kilometers (vkm) traveled to ensure a consistent basis for comparison among the different vehicle technologies. The lifetime vkm was assumed to range from 200,000 km to 350,000 km (most likely a value of 250,000 km). This most likely lifetime vkm is based on the average performance of vehicles in the KSA, as reported by Sheldon and Dua (2021).

2.4 Fuel/Energy Production

The fuel/energy cycle or well-to-tank stage of a transport LCA covers the processes involved in producing, transporting, and distributing the fuel or energy source used to power the vehicle. This includes the extraction and processing of raw materials, conversion into usable fuels or energy carriers, transportation and distribution to end users, and storage/dispensing at refueling stations. Evaluating this stage is critical because the environmental impacts of fuel- and energy-related processes can significantly contribute to the overall impact of the vehicle. These impacts strongly depend on the energy source, the production pathways, and the efficiency of production and distribution.

2.4.1 Gasoline and Diesel Production

Gasoline and diesel fuel production begins with the extraction and processing of crude oil from onshore and offshore wells. In the KSA, approximately 35.7% of oil is extracted offshore, whereas 64.3% is extracted onshore (Meili, Niels, and Wenzel 2023). During the extraction stage, associated natural gas is coproduced. According to the ecoinvent data, 53% of this co-extracted natural gas is combusted onsite to generate power for extraction operations, 15% is flared, and 32% is vented. In addition to natural gas use, the oil extraction stage relies on 31% grid electricity and 1% onsite diesel generators to meet the power requirements. A simplified flow diagram of the well-to-tank stages for gasoline and diesel is shown in Figure 2. We assume that the extracted crude oil is transported to petroleum refineries in the KSA via pipelines, where it undergoes a series of distillation and conversion processes to yield various petroleum products, including gasoline and diesel. The specific inventories, including energy, infrastructure, and emission data associated with crude oil extraction, transportation to local refineries, and conversion to low-sulfur gasoline and diesel in the KSA, were obtained from the ecoinvent v3.10 database and the Archie Initiative (Meili, Niels, and Wenzel 2023; ecoinvent 2023; Archie Initiative 2021).

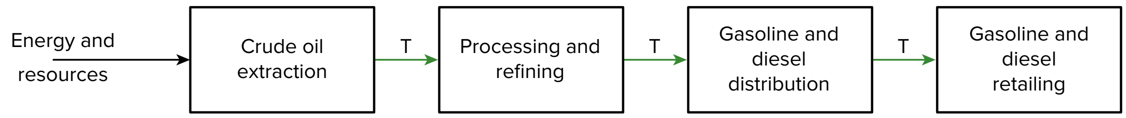
2.4.2 Electricity Production

Electricity generation is based on the King Abdullah Petroleum Studies and Research Center (KAPSARC) Energy Model (Elshurafa, Petitet, and Felder 2023). The KSA electricity mix for 2022 comprises approximately 80% natural gas, 18% oil, and 2% wind and solar energy sources. The carbon intensity of the mix was estimated to be 735.2 gCO_2-eq/kWh via the Intergovernmental Panel on Climate Change (IPCC) 2021 impact assessment method according to the GWP100 timeframe (IPCC 2021).

2.4.3 H_2 Production

Hydrogen (H_2) under the current energy landscape of the KSA is produced from natural gas steam methane reforming (SMR) with CO_2 venting. The production process for H_2 from natural gas SMR was derived from the ecoinvent process “hydrogen production, steam reforming RoW,” pressurized to 200 bar. Natural gas served as both the feedstock for the reaction and the fuel for the furnace. The natural gas origin is adjusted to align with the KSA context, using the ecoinvent process “market for natural gas, high pressure SA.” The technical details of the SMR process that was used to model this dataset are presented in Antonini et al. (2020). An extra

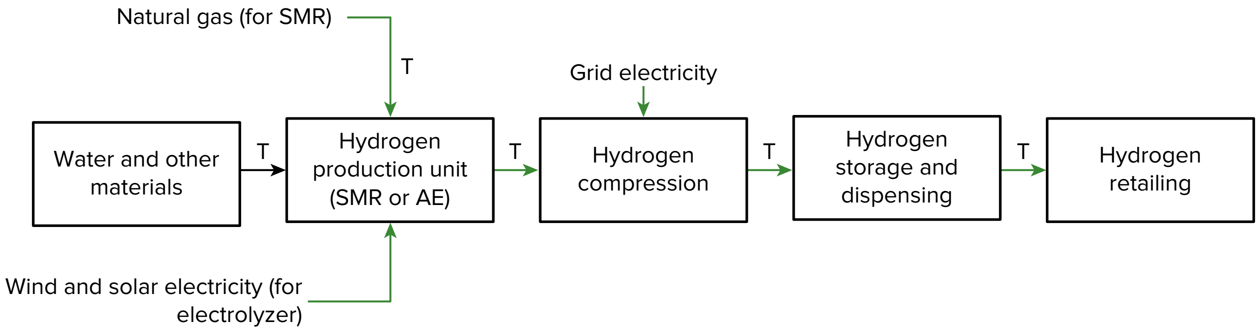
Figure 2. Flow diagram and system boundary of gasoline and diesel production.



Note: Here, T = transportation, and the green and black arrows = fuel and material flows, respectively.

Source: Authors.

Figure 3. Flow diagram and system boundary of H_2 production pathways.



Note: Here, T = transportation, and the green and black arrows = fuel and material flows, respectively.

Source: Authors.

step for H_2 compression to 700 bar is incorporated into the model, following the dataset presented in (Cox et al. 2020). Figure 2 shows the flow diagram and system boundary covering raw material extraction, electricity and natural gas production and distribution, and equipment and power plant construction, including H_2 production, compression, and distribution steps.

2.5 Vehicle Production

We assumed that the gasoline and diesel vehicle models had the same underlying design and components, with the differences in their weights reflecting the varied component sizes required for different vehicle classes. The analysis used the "passenger car production" process from the ecoinvent database as the starting point. This dataset is structured into two distinct modules – the "glider" and "drivetrain" modules – based on average passenger car technologies spanning 2000-2010 (Schweimer and Levin 2000; Habermacher 2011). We assume that these average values are representative of passenger cars today, in addition to the evolution of automotive infotainment systems that come with added environmental impacts (Meixner et al. 2017; Koroma et al. 2022). Thus, the production of a 10-inch tablet as a proxy for advancement in in-vehicle infotainment systems was added to the glider dataset using the ecoinvent dataset for "consumer electronics production, mobile device, tablet GLO." The production dataset for a kg of glider is assumed to be common for all the vehicle technologies assessed. Similarly, a common production dataset for kg of ICEV drivetrain is assumed for all vehicle technologies with conventional engines (i.e., HEVs and PHEVs). For the detailed parameters of the components and their respective ecoinvent processes, see Table S2.

The electric drivetrain for BEVs and PHEVs comprises the following six main components: a single-speed transmission, an electric motor, an onboard charger, a DC/AC inverter, a DC/DC converter, and a power distribution unit (pdu). We modeled a modified electric drivetrain for HEVs and FCEVs. Specifically, FCEVs excluded the onboard charger, whereas HEVs excluded the single-speed transmission, onboard charger, and DC/DC converter. The production datasets for these components were modeled according to their equivalent processes in the ecoinvent database, in addition to the single-speed transmission that was modeled following the dataset derived from Koroma et al. (2023). Similarly, the production datasets for the lithium-ion battery (LIB) packs used in BEVs, PHEVs, FCEVs, and HEVs were also based on the ecoinvent database, with inventories derived from Dai et al. (2019), Winjobi, Dai, and Kelly (2020), and Dai et al. (2018). For BEVs, FCEVs, and PHEVs, we assumed the installation of a lithium nickel manganese cobalt (NMC) oxide (LiNi0.8Mn0.1Co0.1O2) LIB pack, referred to as NMC 811, with an energy density of 0.149 kWh/kg. Conversely, HEVs were assumed to use a lithium iron phosphate (LiFePO4) LIB pack, referred to as LFP, with an energy density of 0.089 kWh/kg.

In addition to the modified electric drivetrain, FCEVs are powered by a hybrid powertrain consisting of a polymer electrolyte membrane (PEM) fuel cell and a power-optimized LIB. The PEM fuel cell serves as the primary power source, providing continuous electrical output to drive the vehicle's propulsion and auxiliary systems. The LIB is integrated into the hybrid configuration to supplement the fuel cell during periods of peak power demand, leveraging the high power density capabilities of the LIB. The inventory data for the PEM fuel cell system are based on the work of Cox et al. (2020), who reported a power area density of 700-1100 milliwatts per square centimeter (mW/cm^2) (most likely a value of 900 mW/cm^2) and a platinum loading range of 0.114 to 0.178 g/kW (most likely a value of 0.139 g/kW), assuming a 1 m^2 (10,000 cm^2) active fuel cell area for current fuel cell technologies (Cox et al. 2020). The power of the PEM fuel cell system was assumed to range from 80 to 130 kW (the most likely value was 114 kW).

2.6 Vehicle Use

The use phase covers factors such as fuel/electricity consumption, exhaust emissions, nonexhaust emissions, vehicle maintenance, and road infrastructure impacts. To accurately reflect conditions in the KSA, it is essential to analyze how region-specific factors, such as driving behaviors and climate conditions, affect the actual fuel economy of passenger vehicles compared with official manufacturer values. In the KSA, high ambient temperatures lead to the increased use of air conditioning, significantly increasing fuel consumption by up to 20% (Alani et al. 2022; Farrington and Rugh 2000). Additionally, local driving habits, including faster highway speeds, frequent stop-and-go urban traffic, and aggressive acceleration and braking, further reduce fuel efficiency (Mohammadnazar, Khattak, and Khattak 2024). As a result, actual fuel consumption in the KSA often surpasses manufacturer values, which are based on standardized tests that do not account for these regional factors. In addition, studies have shown that real-world fuel consumption can exceed official values by 20% to 40% (Fontaras, Zacharof, and Ciuffo 2017; Wu et al. 2020; Mock et al. 2012). Given the limited data on actual vehicle performance under real-life conditions in the KSA, assuming a 25% to 30% increase over official fuel consumption values is a realistic approach to account for these differences. By incorporating this real-world performance gap, this analysis aims to provide a more representative assessment of the use phase impacts in the region. Table 1 shows the adjusted fuel consumption data for the vehicles assessed.

Exhaust emissions for vehicles with conventional engines are modeled on the basis of their fuel consumption

Table 1. Adjusted fuel consumption (WTW energy, MJ/km) data for the vehicles in this study.

Body type and powertrain	Uncertainty distribution	Mode	Minimum	Maximum
Sedan				
ICEV-p	Triangular	3.014	2.495	3.598
ICEV-d	Triangular	2.729	2.258	3.259
BEV	Triangular	0.870	0.708	1.041
PHEV-series (ICE)	Triangular	1.877	1.595	2.139
HEV	Triangular	1.776	1.520	2.074
FCEV	Triangular	1.580	1.324	1.874
SUV				
ICEV-p	Triangular	3.354	2.678	3.849
ICEV-d	Triangular	3.035	2.423	3.479
BEV	Triangular	0.985	0.778	1.166
PHEV-series (ICE)	Triangular	2.093	1.706	2.470
HEV	Triangular	1.996	1.601	2.381
FCEV	Triangular	1.777	1.409	2.110

reported in Table 1 and the EURO 5 emission standard[4] following representative datasets in the ecoinvent database. Nonexhaust emissions, such as those from road surface wear and wear from road vehicle tires and brakes, were quantified via emission factors from (Ntziachristos and Boulter 2023), as implemented in the ecoinvent database. Vehicle and road maintenance impacts were based on values reported by (Spielmann and Althaus 2006) for a 1,240-kg vehicle with 150,000 km lifetime mileage. To account for the differences in the parameters in this study, the parameters were scaled proportionally to vehicle mass and lifetime mileage. However, brake wear emissions for EVs were modeled considering only 20% of their ICEV counterparts because regenerative braking following a similar approach to that in Del Duce et al. (2013). Similarly, a conservative approach was taken for HEV and PHEV maintenance, modifying the ecoinvent dataset for ICEVs to account for petrol engine maintenance.

The battery lifetime vkm is highly uncertain and influenced by factors such as charging cycles, aging, charging power, temperatures, and battery management. Therefore, the battery lifetime mileage was assumed to range from 100,000 km to 250000 km, with the most likely value being 160,000 km following EV manufacturers' warranties (Tesla 2020; Nissan 2019). This finding implies that battery replacement accounts for the ratio of the vehicle lifetime vkm to the battery lifetime vkm in the model.

2.7 Vehicle and Battery End of Life

Following the ecoinvent cutoff modeling approach,[5] we considered only the efforts to dismantle, treat, and dispose of waste flows at vehicles' end of life, which implies that the recycling of relevant minerals and metals was excluded at this stage of the model because of limited access to reliable material recovery data for the KSA context. However, the use of recycled (recovered) materials is burden free in the production stage of vehicle components, as implemented in the ecoinvent cutoff modeling database (Ekvall et al. 2020; ecoinvent 2023).

2.8 Impact Assessment

LCA was performed via Simapro 9.6 and ecoinvent v3.10 life cycle inventory database (PRé Sustainability 2022; ecoinvent 2023). The ReCiPe 2016 impact assessment method at the midpoint level was used to compute vehicle performance across several indicators (Huijbregts et al. 2016). The midpoint indicators discussed covered health and GWP, resource consumption, ecosystem damage, and air pollution categories.

3. Results and Discussion

An impact assessment of different vehicle technologies, including BEVs, PHEVs, ICEVs, FCEVs, and HEVs, is presented in this section. The analysis considers key process categories, covering the production, use, and end-of-life stages of the vehicles. The results are reported at the midpoint level, and six impact categories are selected to demonstrate the potential environmental damage resulting from different vehicle types.

3.1 Climate Change Impact

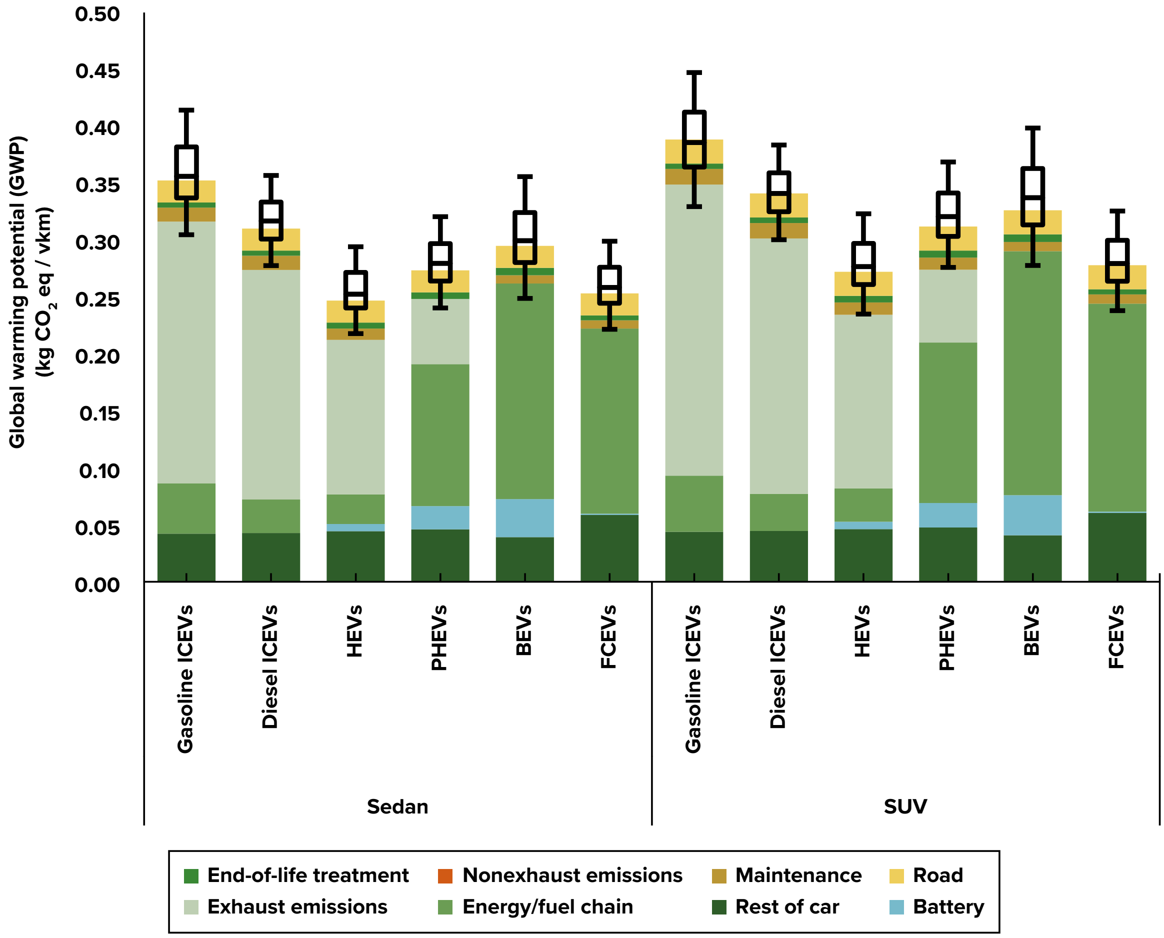
This indicator assesses the contribution of vehicle technologies to climate change and considers the effects of GHG emissions that contribute to global warming and the subsequent climate change. Figure 4 shows the GWP of the different vehicle technologies assessed, expressed in kg of CO_2 equivalent per vehicle kilometer driven (kgCO_2eq/vkm) averaged over the vehicles' lifetime. The stacked bars indicate the most likely vehicle performance, and the error bars represent the uncertainty and variability associated with the background and foreground datasets.

The GWP impacts of the different vehicles and technologies follow a consistent trend across both the sedan and SUV categories. HEVs present the lowest overall GWP, closely followed by FCEVs. PHEVs have the third-lowest GWP, followed by BEVs and diesel ICEVs. Gasoline ICEVs have the highest GWP and are used as a baseline for comparison with the other technologies. Compared with sedan gasoline ICEVs, which have the highest GWP for the sedan category, the relative reductions for the other sedan vehicles are approximately 30% for HEVs, 28% for FCEVs, 22% for PHEVs, 16% for BEVs, and 12% for diesel ICEVs. A similar pattern is observed for the relative reductions in GWP for these technologies as those for SUV gasoline ICEVs.

This consistent trend across the sedan and SUV categories highlights the environmental benefits of advanced powertrain technologies, with HEVs and FCEVs demonstrating the lowest overall GWP impacts under the current energy landscape of the KSA. This finding highlights the significant environmental benefits that can be realized through the widespread deployment of these advanced powertrain solutions. Policymakers and industry stakeholders should therefore collaborate to develop targeted incentives, regulations, and support mechanisms to accelerate the market penetration of these technologies in the KSA.

When deployment feasibility in the short to medium term is considered, PHEVs and HEVs have a distinct advantage over FCEVs, as they do not require the establishment of a comprehensive H_2-fueling infrastructure. The existing electricity grid and fuel infrastructure can readily support the rollout of PHEVs and HEVs, making them a more practical and readily available solution for near-term emission reductions in the KSA transportation sector. In contrast, the widespread adoption of FCEVs necessitates significant investments in H_2 production, storage, and distribution facilities, which may pose greater logistical and financial challenges in the short to medium term. Similarly, deploying BEVs faces significant challenges because of the need for extensive charging infrastructure. Widespread adoption requires substantial investments in the construction of a comprehensive network of charging stations and upgrading of the electrical grid to handle increased demand. These infrastructural developments

Figure 4. Life cycle climate change impacts of sedan and SUV passenger vehicles.



Note: The stacked bars indicate the most likely vehicle performance. The boxplots show the uncertainty of the results, with the whiskers denoting the 5th and 95th percentiles, the box representing the interquartile range, and the line marking the median performance. Legend: Rest of car + Battery sums up the production stage of the vehicles, and Energy/fuel chain + Exhaust emissions + Maintenance + Road sums up the use phase contribution.

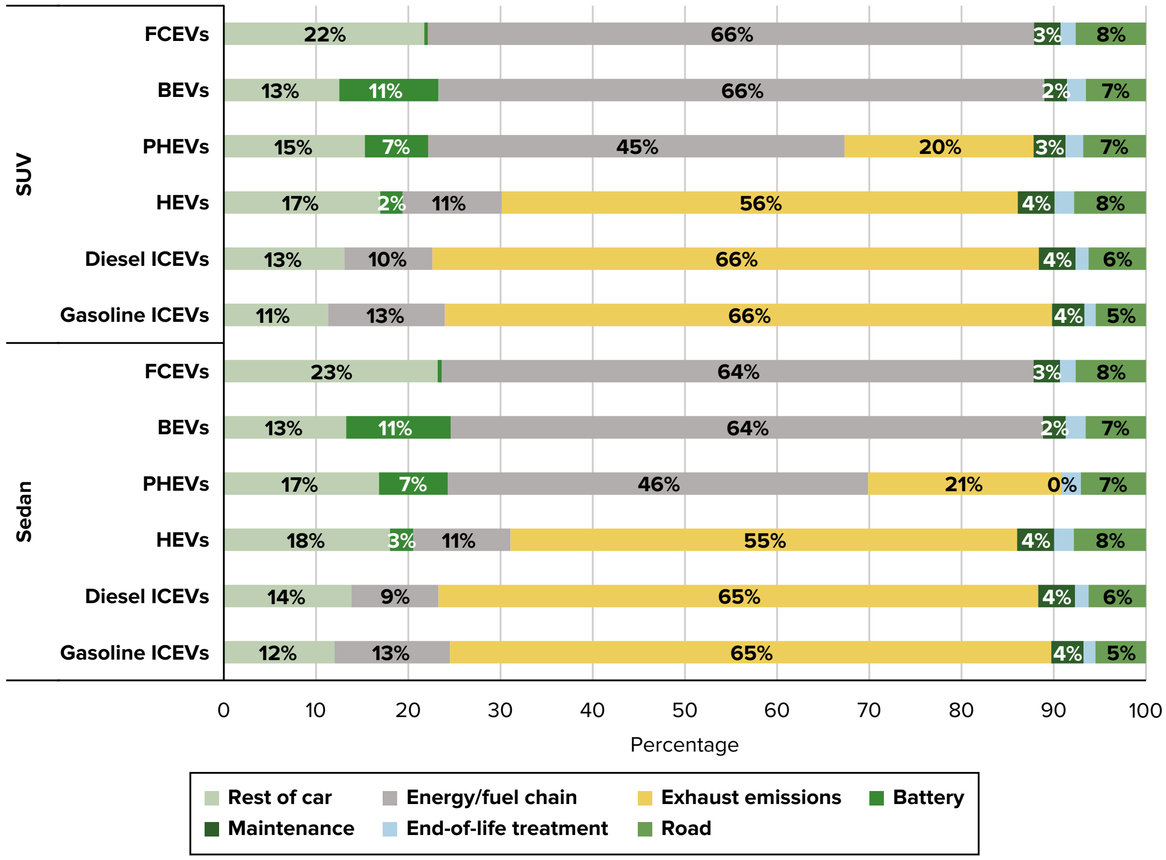
Source: Authors' estimation.

involve considerable financial and logistical efforts, posing challenges in the short to medium term (Melaina, Sun, and Bush 2014).

The production stage of vehicles (Rest of car + Battery from Figure 5) account for 11% to 25% of their total life cycle GWP impacts across both the sedan and SUV categories. Gasoline ICEVs have the lowest GWP during the production stage, closely followed by diesel ICEVs. This finding suggests that the manufacturing processes for ICEVs and their components are relatively more optimized and less carbon intensive than are those of emerging powertrain technologies. HEVs have the third-lowest production-stage GWP, indicating the extra climate burden for producing the additional components required for the hybrid system, such as electric motors and power electronics. FCEVs and PHEVs are on par in terms of production-stage GWP, ranking fourth among the evaluated technologies. BEVs have the highest GWP impacts during their production stage compared to other vehicles types.

The results highlight the increased production impact of emerging vehicle technologies, such as BEVs and PHEVs. This impact is attributed primarily to the manufacturing of their battery components, which alone accounts for approximately 7% and 11% of the total life cycle

Figure 5. Contribution analysis of the life cycle climate change impacts for sedan and SUV passenger vehicles using the most likely performance data from the stacked bars in Figure 4.



Note: Legend: Rest of car + Battery sums up the production stage of the vehicles, and Energy/fuel chain + Exhaust emissions + Maintenance + Road sums up the use phase contribution.

Source: Authors.

GWP impacts for PHEVs and BEVs, respectively; this finding translates to approximately 31% and 46% of their production-stage GWP impacts. Similarly, the production of fuel cell stacks for FCEVs contributes significantly to their overall environmental footprint, which is on par with the impacts associated with battery manufacturing for PHEVs. This situation underscores the energy-intensive nature of the upstream processes involved in producing these advanced powertrain components. These findings emphasize the importance of addressing production-stage emissions to enhance the overall sustainability of the transportation sector. Automakers and their suppliers should focus on decarbonizing manufacturing processes and supply chains for all vehicle technologies, with a particular emphasis on battery and fuel cell production.

Figure 5 also shows that the use phase (Energy/fuel chain + Exhaust emissions + Maintenance + Road) represents the most significant contributor to GWP for the vehicles assessed, contributing approximately 77% for HEVs, 75% for FCEVs, 74% for PHEVs, 73% for BEVs, and 86% for ICEVs, of their life cycle GWP. For HEVs and ICEVs, much of their use phase impact is linked to exhaust emissions during usage. For example, for SUV gasoline ICEVs, exhaust emissions contribute approximately 66% of their total GWP, with a similar trend observed for sedans. In contrast, the GWPs of FCEVs, BEVs, and PHEVs are significantly influenced by the electricity and H_2 supply chains. For example, approximately 65% of sedan BEVs' climate impacts are linked to their electricity supply chain, with a similar pattern observed for SUV BEVs.

The use phase results underscore the importance of vehicles' operational phase and emphasize the critical role of decarbonizing the energy supply chains that power electric and H_2-based vehicles. A substantial portion of the life cycle GWP of electric and H_2-based vehicles is attributed to their energy production pathways. Addressing these energy-related emissions is thus crucial in further enhancing the climate performance of these emerging vehicle technologies within the KSA context. Therefore, strategies to promote the deployment of renewable and low-carbon energy sources and green H_2 production should be prioritized to align with the broader sustainability goals of the KSA (Amran et al. 2020).

The GWP impacts from the end-of-life stage of the vehicles are relatively weak compared with those from their production and use stages, accounting for approximately 2% or less of the total life cycle impacts (Figure 5). The reason for this is that the analysis considers only the impacts of the treatment and disposal of the vehicle's components and does not include other potential end-of-life factors, such as recycling, reuse, or energy recovery from vehicle components. However, there is an opportunity to explore circular economy approaches that maximize the reuse, recycling, and recovery of vehicle components at this stage. The literature has shown that establishing robust end-of-life vehicle management systems can lead to additional reductions in the degree of overall life cycle environmental impacts, especially for emerging vehicle technologies (Koroma et al. 2022).

3.2 Human Carcinogenic Toxicity (HCT)

The life cycle impacts of the HCT[6] of the various vehicles assessed are shown in Figure 6, expressed in kg 1,4-dichlorobenzene (1,4-DCB) equivalent per vehicle kilometer (kg 1,4-DCB eq/vkm). These results provide important insights for sustainable transportation, although the uncertainty range for HCT impacts is substantial.

For both the sedan and SUV categories, conventional ICEVs have the lowest HCT impacts, closely followed by HEVSs, PHEVs, and BEVs. FCEVs have the highest HCT impacts among the powertrains assessed. The majority of HCT impacts are attributed to the vehicle production stage, accounting for more than 80% of the total impacts across all powertrains, except for FCEVs, where it is approximately 65%. The fuel/energy chain also makes a significant contribution, particularly for FCEVs, which accounts for approximately 28% of their total HCT impacts. The relatively high HCT impact from the FCEV energy chain is linked to the infrastructure for H_2 refueling and storage at high pressure, mostly due to the use of aluminum, carbon fiber, copper, and other metals. The higher level of uncertainty in terms of HCT is due to variability in emissions, the limited amount of specific data, and the complexity of modeling health impacts. These factors make it difficult to produce precise estimates in LCAs.

These results are similar to the findings of other studies (Maniscalco et al. 2024), highlighting the importance of addressing the environmental impacts associated with the manufacturing and energy supply processes for alternative vehicle technologies. Strategies to optimize production processes, increase metal recycling, and transition to low-carbon energy sources can contribute to reducing the HCT impacts on the transportation sector.

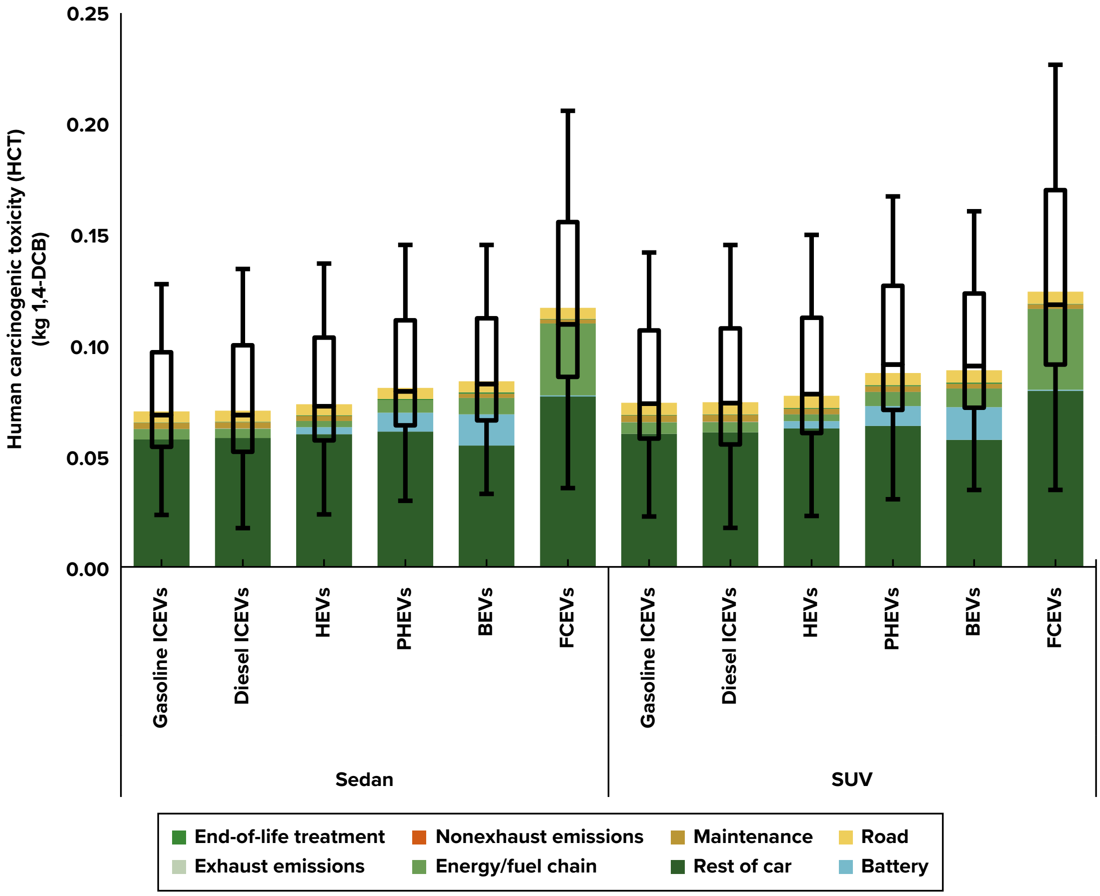
3.3 Fine Particulate Matter (FPM) Formation

Figure 7 shows the formation of FPM measured in kg PM2.5 equivalent per vehicle kilometer (kg PM2.5 eq/vkm). This impact category assesses the impact of different vehicles on air quality.

Across the sedan and SUV categories, BEVs have the greatest impact, followed by PHEVs, FCEVs, and diesel ICEVs. Gasoline ICEVs and HEVs are on par and have the lowest values. Compared with BEVs across both vehicle categories, gasoline ICEVs and HEVs present an approximately 42% reduction, diesel ICEVs present an approximately 32% reduction, FCEVs present an approximately 28% reduction, and PHEVs present an approximately 18% reduction in FPM formation.

The production stage is the most significant contributor for most of the vehicles, except for ICEVs, for which the use stage is the dominant contributor. Generally, the manufacturing of various vehicle parts and components, such as the body, chassis, and electrical systems, can involve welding, painting, and machining, which release FPM. In addition, the mining and processing of raw materials, such as lithium, cobalt, nickel, and platinum

Figure 6. Life cycle HCT impacts of sedan and SUV passenger vehicles.



Note: The stacked bars indicate the most likely vehicle performance. The boxplots show the uncertainty of the results, with the whiskers showing the 5th and 95th percentiles, the box representing the interquartile range, and the line marking the median performance. Legend: Rest of car + Battery sums up the production stage of the vehicles, and Energy/fuel chain + Exhaust emissions + Maintenance + Road sums up the use phase contribution.

Source: Authors' estimation.

group metals, can also contribute to FPM formation. This situation can be linked to the extra burden of producing powertrain components for alternative vehicles. For EVs, the production of LIB cells and other battery cells generates FPM emissions, particularly during electrode coating, drying, and cell assembly processes. For FCEVs, the production of fuel cell stacks and H_2 storage systems, including catalyst layers, membranes, carbon fiber-reinforced polymers, and bipolar plates, can generate FPM emissions during processes such as coating, drying, and assembly. Addressing these drivers through process optimization, emission control measures, and the use of cleaner manufacturing technologies can help reduce the FPM impacts associated with the production of these advanced vehicle technologies.

The fuel/energy chain drives most of the use phase formation of FPM, except for diesel-powered ICEVs, for which exhaust emissions are the dominant contributor. This finding is linked to the burning of fossil fuels, such as coal, natural gas, and oil, in power plants, particularly from the incomplete combustion of these fuels. Likewise, the combustion of natural gas or other fuels used to generate the high temperatures required for the SMR process for H_2 production contribute to FPM emissions. The nickel-based catalysts used in the SMR process also generate FPM emissions during the catalyst preparation and activation stages. Addressing these drivers via cleaner fuels, improved combustion technologies, efficient emission control systems, and sustainable catalyst manufacturing processes can help mitigate the FPM impacts associated with fuel/energy production.

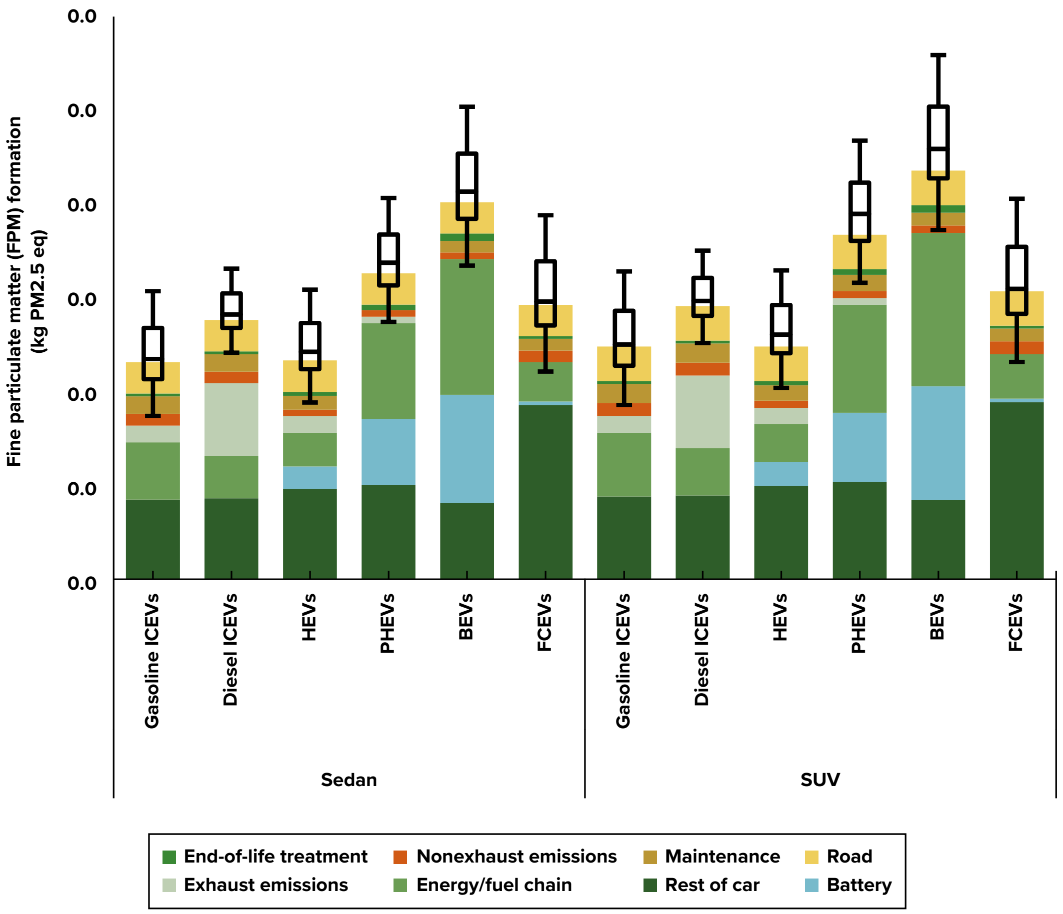
3.4 Terrestrial Acidification (TA)

The life cycle impacts of TA are shown in Figure 8, expressed in kg SO_2 equivalent per vehicle kilometer (kg SO_2 eq/vkm). This impact category assesses the potential of different vehicles to contribute to acid rain formation, which can negatively affect ecosystems.

BEVs and PHEVs have the highest TA impacts across both sedans and SUVs, followed by FCEVs and diesel ICEVs. Compared with BEVs, gasoline ICEVs and HEVs have the lowest TA impacts, with approximately 50% reductions. The production phase, particularly the manufacturing of batteries in BEVs and PHEVs, is the primary cause of TA impacts, contributing approximately 46% of the total impacts. This finding is a result of emissions generated during the extraction and processing of raw materials, along with the energy-intensive nature of manufacturing processes.

For ICEVs, the energy/fuel chain and exhaust emissions during the use phase are notable contributors to TA,

Figure 7. Life cycle FPM impacts of sedan and SUV passenger vehicles.



Note: The stacked bars indicate the most likely vehicle performance. The boxplots show the uncertainty of the results, with the whiskers showing the 5th and 95th percentiles, the box representing the interquartile range, and the line marking the median performance. Legend: Rest of car + Battery sums up the production stage of the vehicles, and Energy/fuel chain + Exhaust emissions + Maintenance + Road sums up the use phase contribution.

Source: Authors' estimation.

especially in diesel vehicles, where they make up as much as 37% of the total impact. The use of low-sulfur fuels and advanced emission control technologies in ICEVs can mitigate these impacts. However, their effectiveness is limited by high emission levels during the fuel production phase.

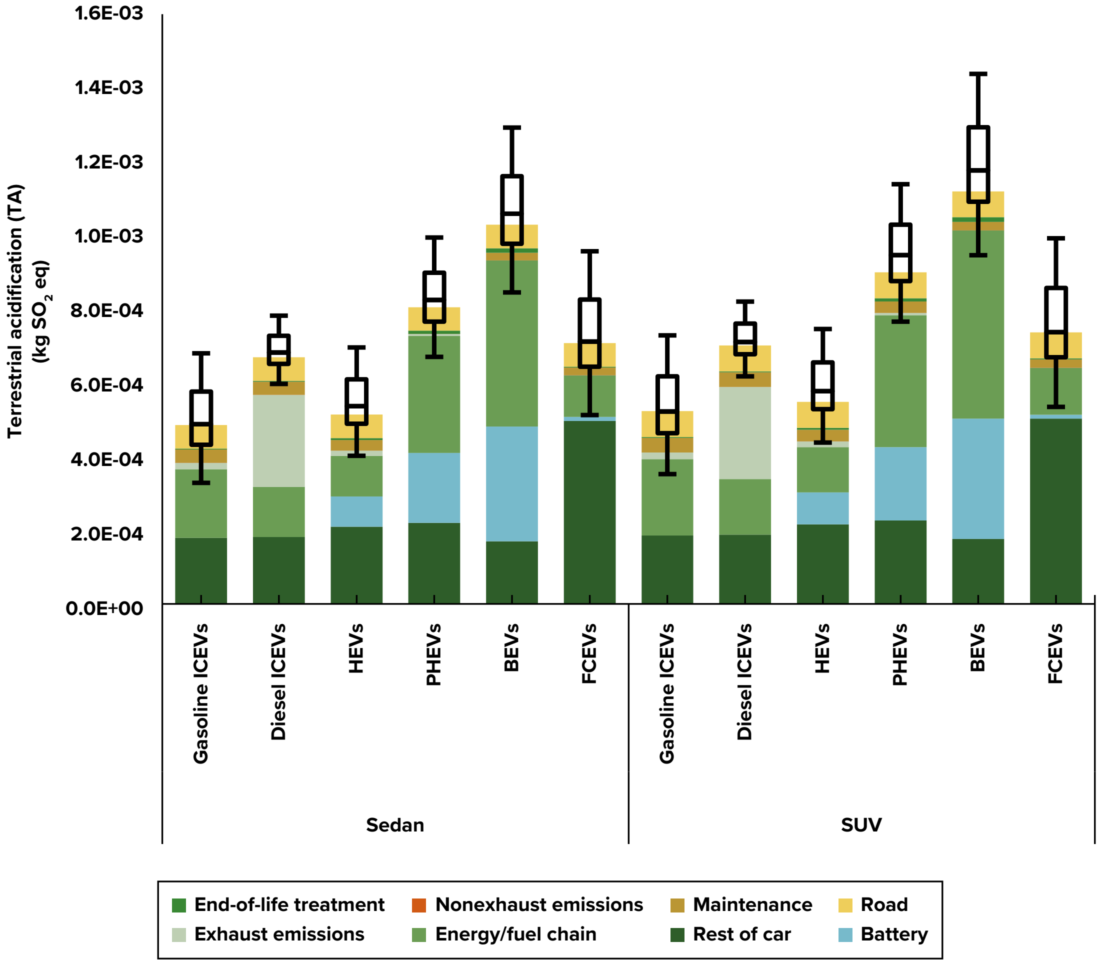
Reducing the impact of TA requires cleaner production technologies, improved fuel efficiency, and the use of low-sulfur fuels in energy generation. Additionally, optimizing battery production processes and increasing the recycling of materials can further reduce the acidification potential of advanced vehicle technologies.

3.5 Mineral Resource Scarcity (MRS)

The life cycle impacts of MRS are shown in Figure 8 and are measured in kg Cu equivalent per vehicle kilometer (kg Cu eq/vkm). This impact category assesses the strain on mineral resources due to vehicle production and operation.

BEVs and PHEVs create a significant demand for scarce minerals, due primarily to the battery production phase,

Figure 8. Life cycle TA potential impacts of sedan and SUV passenger vehicles.



Note: The stacked bars indicate the most likely vehicle performance. The boxplots show the uncertainty of the results, with the whiskers showing the 5th and 95th percentiles, the box representing the interquartile range, and the line marking the median performance. Legend: Rest of car + Battery sums up the production stage of the vehicles, and Energy/fuel chain + Exhaust emissions + Maintenance + Road sums up the use phase contribution.

Source: Authors' estimation.

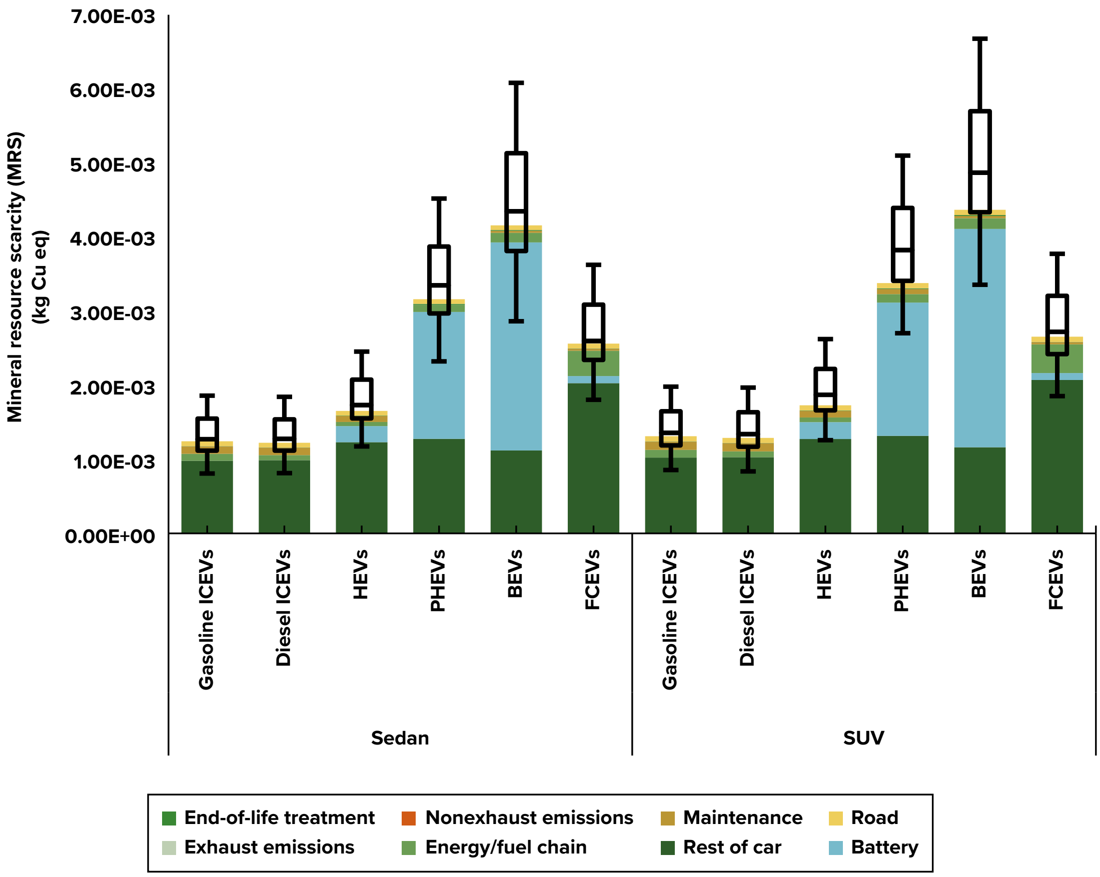
which accounts for 53%-68% of the overall impact. The extraction and refinement of metals such as lithium, cobalt, and nickel, which are essential for battery production, are the primary causes of this impact. In contrast, ICEVs and HEVs have weaker impacts, with other components of the car being the primary contributors. The production of ICEVs and HEVs utilizes primarily more common and readily available materials, in contrast to advanced powertrains, which depend on rare and specialized materials for batteries and fuel cells.

FCEVs fall between BEVs and ICEVs, with significant contributions from both the Rest of car and the Energy/fuel chain, reflecting the resource demands for H_2 production infrastructure. These findings emphasize the need for material efficiency improvements, the development of alternative materials, and increased recycling to reduce the MRS impacts of advanced vehicle technologies.

3.6 Fossil Resource Scarcity

The life cycle impacts of fossil resource scarcity are illustrated in Figure 10, expressed in kg oil equivalent per vehicle kilometer (kg oil eq/vkm). This impact category evaluates the depletion of fossil fuels due to vehicle production and operation.

Figure 9. Life cycle MSR impacts of sedan and SUV passenger vehicles.



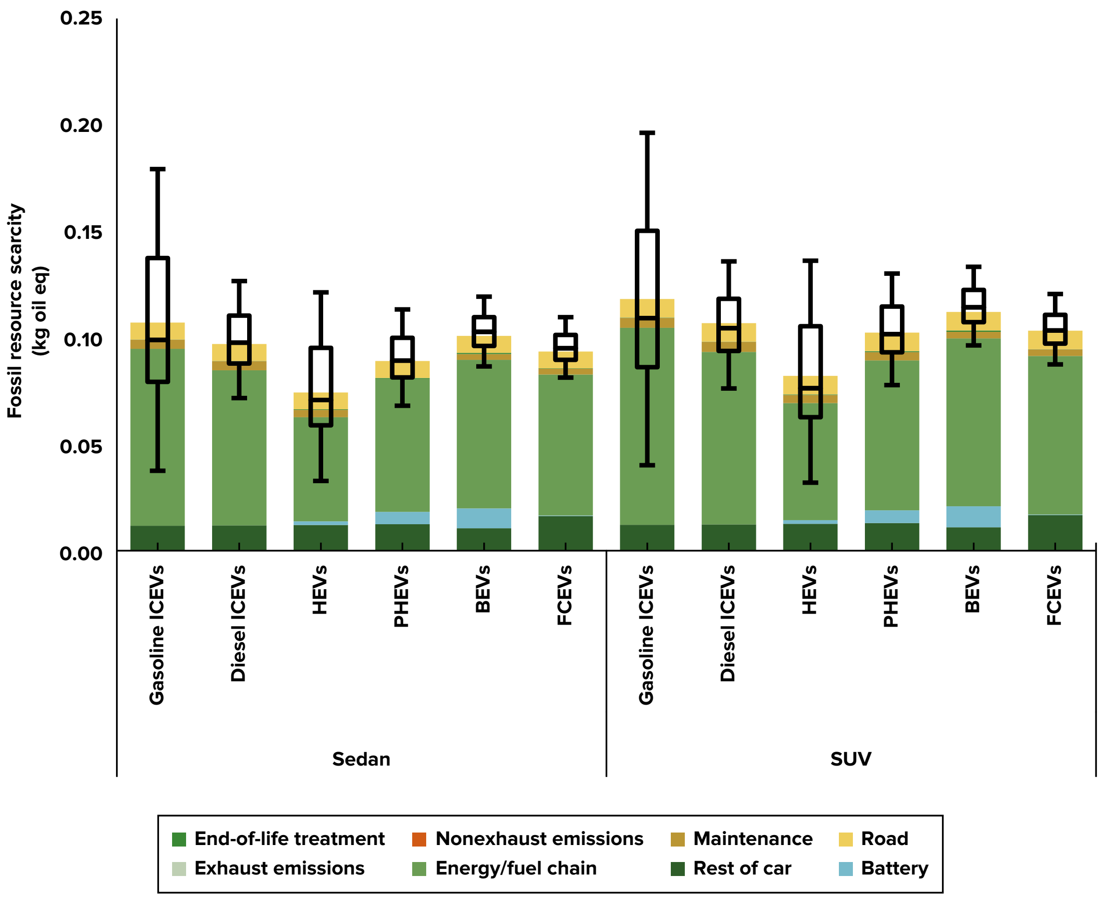
Note: The stacked bars indicate the most likely vehicle performance. The boxplots show the uncertainty of the results, with the whiskers showing the 5th and 95th percentiles, the box representing the interquartile range, and the line marking the median performance. Legend: Rest of car + Battery sums up the production stage of the vehicles, and Energy/fuel chain + Exhaust emissions + Maintenance + Road sums up the use phase contribution.

Source: Authors' estimation.

ICEVs have the greatest impact on fossil resource scarcity, driven primarily by Energy/fuel chain, which contributes 75%-78% of the total impact. This finding reflects the reliance on petroleum products for fuel production and the associated energy-intensive refining processes. BEVs and PHEVs have slightly weaker impacts, and Energy/fuel chain remains the primary contributor, accounting for 69%-70% of the total impact. The impacts of BEVs and PHEVs are associated mainly with the mix of electricity generation, which still largely depends on fossil fuels.

FCEVs and HEVs also have significant fossil resource impacts, although lower than those of ICEVs, with Energy/fuel chain and Rest of car as major contributors. For FCEVs, the manufacturing and delivery of H_2, which is frequently obtained from natural gas, adds to their impact on fossil resource scarcity.

Figure 10. Life cycle fossil resource impacts of sedan and SUV passenger vehicles.



Note: The stacked bars indicate the most likely vehicle performance. The boxplots show the uncertainty of the results, with the whiskers showing the 5th and 95th percentiles, the box representing the interquartile range, and the line marking the median performance. Legend: Rest of car + Battery sums up the production stage of the vehicles, and Energy/fuel chain + Exhaust emissions + Maintenance + Road sums up the use phase contribution.

Source: Authors' estimation.

4. Conclusions

This comprehensive LCA of various vehicle technologies in the context of the KSA provides valuable insights into their relative environmental performance. The findings emphasize the importance of addressing the environmental impacts associated with the manufacturing and energy supply processes for alternative powertrain technologies. Strategies to optimize production processes and transition to low-carbon energy sources can contribute to reducing the degree of environmental burden in the transportation sector.

The findings demonstrate that considering the KSA's current energy landscape, HEVs and FCEVs hold the greatest potential for reducing GHG emissions and mitigating climate change across both sedan and SUV categories. Compared with the baseline gasoline ICEVs, HEVs, and FCEVs exhibit GWP reductions of approximately 30% and 28%, respectively, followed by PHEVs and BEVs, at approximately 22% and 16%.

The consistent performance of these advanced powertrain technologies across vehicle classes underscores the significant environmental benefits that can be realized through their widespread adoption in the KSA transportation sector. In terms of deployment feasibility, PHEVs and HEVs have a distinct advantage over FCEVs, as they can leverage the existing electricity grid and fueling infrastructure, making them more practical and readily available solutions for reducing near-term emissions in the KSA. Policymakers and industry stakeholders should prioritize the development of targeted incentives, regulations, and support mechanisms to accelerate the market penetration of HEVs and PHEVs, capitalizing on their readily available and relatively more feasible deployment compared with the more infrastructure-intensive battery electric and fuel cell technology.

While BEVs also present lower GWPs than do conventional ICEVs, their relative advantages are less pronounced in the current KSA energy mix. The energy supply chain plays a crucial role for BEVs, including FCEVs and PHEVs. The significant influence of the energy and fuel supply chain on the climate impacts of these vehicles underscores the importance of decarbonizing electricity and H_2 production to realize the full environmental advantages of these technologies in the KSA.

Similar trends are observed across the sedan and SUV vehicle categories, indicating the scalability of these findings. The lower GWP of SUV FCEVs than of SUV gasoline ICEVs demonstrates the potential of fuel cell technology to provide a viable alternative for larger, more energy-intensive vehicle segments. Thus, these insights can inform policymakers, automakers, and consumers in selecting and adopting more environmentally sustainable vehicle technologies for mitigating climate change impacts.

The analysis of other environmental impact categories, such as HCT, FPM formation, TA, MRS, and fossil resource scarcity, reveals additional tradeoffs that must be carefully considered. Strategies to optimize manufacturing processes, improve fuel quality, and transition to RESs are crucial in addressing the multifaceted environmental implications of vehicle technologies and promoting more holistic sustainability in the KSA transportation landscape. Future research could build on this baseline through scenario analysis and life cycle costing (LCC) to explore alternative policy pathways.

Future studies should explore dynamic low-carbon (DLC) scenarios, an evolving framework designed to model the transition to a low-carbon energy mix over time. This approach incorporates changes in energy generation technologies, the policy landscape, market conditions, and consumer behaviors, providing more dynamic insights into how the transportation sector in the KSA can maximize the potential advantages of emerging low-carbon technologies.

Supplementary Information (SI)

Table S1. List of input parameters and their distributions.

Powertrain type	Body style	Parameter	Uncertainty distribution	Mode	Minimum	Maximum	Unit	Source
BEV, PHEV, FCEV	All	Battery lifetime km	Triangular	200,000	100,000	250,000	km	Cox et al. (2020); authors' assumption
All	Sedan	Glider mass	Triangular	1,250	900	1,717	kg	Cox et al. (2020); authors' assumption
All	SUV	Glider mass	Triangular	1,317	950	1,800	kg	Cox et al. (2020)
BEV, PHEV, FCEV	All	Converter mass	Triangular	4.5	4	6	kg	Del Duce et al. (2013)
BEV, PHEV, FCEV, HEV	All	Inverter mass	Triangular	9	8	10	kg	Del Duce et al. (2013)
BEV, PHEV	All	Charger mass	Triangular	6	4	7	kg	Del Duce et al. (2013)
BEV, PHEV, FCEV, HEV	All	PDU mass	Triangular	4	3	5	kg	Del Duce et al. (2013)
BEV, PHEV, FCEV, HEV	All	Emotor mass	Triangular	60.6	49.7	79	kg	Brusa Electronic; authors' assumption
BEV, PHEV, FCEV	All	Cable	Triangular	2.27	1.86	2.95	m	ecoinvent; authors' assumption
HEV	All	Cable	Triangular	1.13	0.93	1.48	m	Authors' assumption
FCEV	All	Fuel cell stack efficiency	Triangular	0.535	0.5	0.57		Cox et al. (2020)
FCEV	All	Fuel cell power area density	Triangular	900	700	1100	mW/cm^2	Cox et al. (2020)
FCEV	All	Fuel cell ancillary balance of performance (BoP) mass per power	Triangular	0.4	0.3	0.45	kg/kW	Cox et al. (2020)
FCEV	All	Fuel cell essential BoP mass per power	Triangular	1	0.7	1.3	kg/kW	Cox et al. (2020)
FCEV	All	Fuel cell own consumption	Triangular	1.15	1.1	1.2		Cox et al. (2020)
ICEV-d, ICEV-g	All	Combustion power share	Triangular	1	1	1	%	
HEV	All	Combustion power share	Triangular	0.75	0.6	0.9	%	Authors' assumption

(Continued)

Powertrain type	Body style	Parameter	Uncertainty distribution	Mode	Minimum	Maximum	Unit	Source
PHEV	All	Combustion power share	Triangular	0.4	0.35	0.5	%	Authors' assumption
FCEV	All	PEM weight per kW	Triangular	1.39	1.14	1.78	kg/kW	Authors' assumption
ICEV	All	Engine power	Triangular	110	44	200	kW	Authors' assumption
Hybrid vehicle	All	Combined power	Triangular	100	66	220	kW	Authors' assumption
Hybrid vehicle	All	Engine power	Triangular	60	39.6	132	kW	Authors' assumption
Hybrid vehicle	All	Motor power	Triangular	40	26.4	88	kW	Authors' assumption

Table S2. Life cycle inventory datasets used.

Component name	LCI dataset name	Location	Database
Glider	Production for glider, passenger car	GLO	ecoinvent 3.10
Charger	Production for charger, electric passenger car	GLO	ecoinvent 3.10
Converter	Production for converter, electric passenger car	GLO	ecoinvent 3.10
Emotor	Production for emotor, electric passenger car	GLO	ecoinvent 3.10
Inverter	Production for inverter, electric passenger car	GLO	ecoinvent 3.10
PDU	Production for PDU, electric passenger car	GLO	ecoinvent 3.10
Cable	Market for cable, three-conductor cable	GLO	ecoinvent 3.10
Engine	Production for internal combustion engine, passenger car	GLO	ecoinvent 3.10
Battery	Production for LIBs, NMC811	RoW	ecoinvent 3.10
Battery	Production for LIBs, LFP	RoW	ecoinvent 3.10
Cooling system	Cooling system for ICE passenger car	GLO	Additional datasets
Exhaust system	Exhaust system for ICE passenger car	GLO	Additional datasets
Fuel system	Fuel system for ICE passenger car	GLO	Additional datasets
Starting system	Starting system for ICE passenger car	GLO	Additional datasets
IC engine	55-kW engine power for passenger car	GLO	Additional datasets
Fuel cell ancillary BoP	Essential BoP	GLO	Additional datasets
Fuel cell essential BoP	Ancillary BoP	GLO	Additional datasets
Fuel cell stack	Stack 2020	GLO	Additional datasets
H_2 tank	Fuel tank, compressed H_2 gas, 700 bar	GLO	Additional datasets
Electricity (for battery charging)	Market for electricity, medium voltage (KSA)	KSA	Additional datasets
Gasoline	Gasoline production, low sulfur	KSA	Additional datasets
Diesel	Diesel production, low sulfur	KSA	Additional datasets
Infrastructure construction	For regional distribution of oil product (RoW)	RoW	ecoinvent 3.10
WTW emissions	Passenger car, medium size, diesel, EURO 5	RoW	ecoinvent 3.10
WTW emissions	Passenger car, medium size, petrol, EURO 5	RoW	ecoinvent 3.10
Road	Market for road	GLO	ecoinvent 3.10
Road maintenance	Market for road maintenance	RoW	ecoinvent 3.10
Road wear	Market for road wear emissions, passenger car	GLO	ecoinvent 3.10

(*Continued*)

Component name	LCI dataset name	Location	Database
Brake wear	Market for brake wear emissions, passenger car	GLO	ecoinvent 3.10
Tire wear	Market for tire wear emissions, passenger car	GLO	ecoinvent 3.10
EV maintenance	Market for maintenance, passenger car, electric, without battery	GLO	ecoinvent 3.10
Passenger car maintenance	Market for passenger car maintenance	GLO	ecoinvent 3.10
Dismantling of electric car	Market for manual dismantling of used electric passenger car	GLO	ecoinvent 3.10
Dismantling of passenger car	Market for manual dismantling of used passenger car	GLO	ecoinvent 3.10

Endnotes

[1] Triangular distributions are used in modeling when a limited amount of data are available to estimate uncertainty via three values – minimum, most likely, and maximum – which form a simple probability distribution.

[2] Uncertain parameters are variables whose exact values are not known and can vary. They are often represented by a range of possible values or probability distributions to reflect this uncertainty.

[3] The system boundary defines the limits of an LCA by specifying which processes are included or excluded, such as raw material extraction, production, use, and disposal.

[4] The EURO 5 emission standard, introduced in 2009, sets limits on harmful vehicle emissions such as nitrogen oxide (NOx), carbon monoxide (CO), and particulate matter (PM) to reduce air pollution.

[5] The ecoinvent cutoff approach assigns environmental impacts only to new material production, whereas recycled materials carry no prior burdens, simplifying the corresponding LCAs.

[6] HCT measures the potential of a substance to cause cancer in humans.

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About the Project

This “Evaluating Decarbonization Pathways in Passenger Vehicles in the KSA via a Lifecycle Analysis Approach” project aims to assess the sustainability aspects of current and future passenger road vehicles in the KSA. This project seeks to understand and mitigate the environmental impact of transportation in the country. Using an integrated life cycle analysis approach, this project examines decarbonization pathways, considering factors such as energy generation sources, infrastructure development, and regional disparities, while also aiming to identify key sustainability hotspots and tradeoffs to inform policy decisions and drive the transition toward a more sustainable transportation sector in the KSA.

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