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Discussion Paper

Climate and Cost Analysis of SUVs in Saudi Arabia

A Life Cycle Analysis Approach

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Abstract

This study is conducted within the framework of the Saudi Vision 2030 agenda to diversify its economy and promote sustainable technologies, specifically examining the life-cycle performance of hybrid and conventional sport utility vehicles (SUVs) in the Kingdom (KSA). It employed the Life Cycle Assessment (LCA) and Total Cost of Ownership (TCO) methods to comprehensively evaluate the environmental and cost performance of these vehicles from a life-cycle perspective. The findings indicate that hybrid SUVs' global warming potential is approximately 19.5% less than that of conventional SUVs in KSA despite the extra carbon emissions from producing their electric powertrain components. However, despite their superior fuel efficiency, hybrid SUVs exhibit a slightly higher TCO – around 6% more than their conventional counterparts. Notably, depreciation costs emerge as a significant factor influencing the TCO of these vehicles, underscoring the necessity for cost-competitive financing options and measures to reduce the initial purchase cost of hybrid electric vehicles (HEV). Considering these findings, we recommend that policymakers consider promoting HEVs as a near-term decarbonization strategy in line with the Saudi Vision 2030 agenda. However, we also suggest intensifying efforts to achieve purchase cost parity with conventional vehicles to accelerate market uptake.

Keywords: Life Cycle Assessment (LCA), Total Cost of Ownership (TCO), electric vehicles, Saudi Arabia, passenger vehicles

1. Introduction

The transportation sector is significant in Saudi Arabia's environmental landscape, accounting for approximately 20% of the country's total greenhouse gas (GHG) emissions. This figure is projected to increase in the coming decades due to population and economic growth (Alajmi 2021). Besides, climate change challenges Saudi Arabia's economy, affecting both the oil and non-oil sectors. In response, the Kingdom of Saudi Arabia (KSA) intends to take action and plan accordingly, thus aligning its economic diversification efforts with the decarbonization goal (Al-Sarihi 2019; KSA 2016).

In that light, it is crucial to comprehensively understand the sector and its sustainability performance to effectively map deep decarbonization pathways for transportation in KSA. Decarbonization efforts include promoting low-carbon vehicles, renewable energy sources, and clean technology initiatives, among others. While low-carbon vehicles currently represent only a small fraction of the KSA passenger car market, a strategic plan exists to expand the infrastructure across the nation for these types of vehicles. This plan encompasses nationwide infrastructure development and the rollout of incentives to accelerate their adoption in the coming years (Elshurafa and Peerbocus 2020; Alyamani, Pappelis, and Kamargianni 2024).

Private car ownership has grown rapidly in the past decade, with sedans and sport utility vehicles (SUVs) emerging as popular choices for private vehicle owners in KSA (Alyamani, Pappelis, and Kamargianni 2024). As one of the largest automobile markets in the Middle East, Saudi Arabia is witnessing a significant rise in SUV ownership (TechSciResearch 2021). In this analysis, we examined two types of vehicles: Internal Combustion Engine SUV (ICEV SUV) and Hybrid Electric SUV (HEV SUV). This technology selection was deliberate, driven by the dominance of the SUV segment, which accounts for over 43% of new vehicle sales in 2023, and the limited adoption of battery electric vehicle (BEV) SUVs in the region (Statista 2023). Additionally, SUVs are highly popular in Saudi Arabia due to their spaciousness, performance, and suitability for the country's terrain and driving conditions. While sedans, including BEV sedans, represent an important segment, SUVs serve a distinct consumer need that is not fully addressed by sedan-based vehicles. By concentrating on the SUV segment, the findings of this research can provide targeted insights for key stakeholders navigating sustainable transportation solutions in Saudi Arabia.

ICEV SUVs are conventional vehicles running on gasoline or diesel, and they have higher fuel consumption than their HEV SUV counterpart. HEV SUV combines an internal combustion engine (ICE) with an electric motor, offering better fuel efficiency than ICEV SUVs. Hybrid vehicles are considered a transitional technology because they still rely on fossil fuels and fall short in terms of mitigating climate impact regarding long-term decarbonization efforts. However, their market uptake is projected to increase in the coming years due to the introduction of the Fuel Efficiency Added Fees (KSA 2023) and the limited access to public charging infrastructure for BEVs in the KSA. Thus, it is crucial to assess their sustainability performance in the Saudi Arabian context, considering their global warming potential (GWP) and cost implications from a life-cycle perspective.

Life Cycle Assessment (LCA) provides a comprehensive framework to evaluate the environmental footprint of products throughout their entire life cycle, including raw material extraction, manufacturing, use, and end-of-life disposal (Guinée et al. 2011). By applying the LCA methodology to SUVs, we can gain insights into their GHG emissions and overall climate impact. Additionally, a total cost analysis will shed light on the economic viability of SUV ownership in Saudi Arabia. A Total Cost of

Ownership (TCO) analysis provides a more comprehensive understanding of long-term costs by considering purchase (including financing), operation, maintenance, and resale value expenses (Ferrin and Plank 2002).

1.1. Related Research Activity

Studies on the life-cycle cost and environmental impacts of vehicles in the KSA are limited, and the topic of sustainability has not been thoroughly analyzed. A notable work by Elshurafa and Peerbocus (2020) focused on comparing passenger vehicle emissions in KSA. Elshurafa and Peerbocus evaluated 18 different scenarios of powertrain technologies in KSA. Their findings indicated that replacing just 1% of ICEVs with BEVs could reduce transportation emissions by 0.5%. However, they also identified a worst-case scenario where low-efficiency BEVs could potentially increase total GHG emissions. This underscores the necessity of considering specific technologies and their efficiency levels when assessing vehicle impacts.

More recently, Ankathi et al. (2024) conducted a well-to-wheels (WTW) analysis of GHG emissions for passenger vehicles in the Middle East and North Africa (MENA) region. They employed both technology-normalized and fleet-representative modeling approaches. Their study reported WTW emissions of approximately 308.01 g CO_2eq/km for ICEV gasoline vehicles, based on a fleet-representative fuel economy of 10.46 km/L in KSA. The technology-normalized approach by Ankathi et al. showed emissions of 109 g CO_2eq/km and 117.5 g CO_2eq/km for small and midsize SUVs, respectively, assuming technology-specific fuel economies of 16.58 km/L and 15.39 km/L for small and midsize SUVs, respectively. The variation in results underscores the importance of accounting for regional differences in factors such as fuel economy when evaluating vehicle emissions performance. However, the WTW-only approach utilized by Ankathi et al. offers a limited perspective on the overall life-cycle impacts of vehicles.

1.2. Research Motivation

Given the lack of sufficient local studies on this issue and the need for a more comprehensive understanding of vehicle emissions in the KSA context, this paper presents findings on a robust life-cycle analysis of SUVs in Saudi Arabia. Our focus is on the climate impact, environmental profile, and cost of ownership implications associated with these vehicles. In general, as vehicles become more sophisticated with advanced technologies, their TCO tends to rise due to increased complexity and reliance on specialized repair and maintenance services. Moreover, with hybrid vehicles commanding a price premium over conventional cars in the initial purchase, it is important to examine if their TCO, considering their relatively low fuel consumption during usage, could make them a cost-effective choice for Saudi consumers. Therefore, our findings could help consumers make informed decisions and guide policymakers in designing interventions that promote more sustainable transportation choices with favorable lifecycle economics.

The paper is organized as follows: Section 1 provides an overview and context for the study. Section 2 describes the LCA and TCO methods and their application in this study. Section 3 presents the assessment's key findings, including a sensitivity analysis of selected parameters. Lastly, Section 4 summarizes the research conclusions and implications for policymakers.

2. Data and Methods

2.1. The LCA Model

The LCA model developed for this study provides a comprehensive analysis of the environmental impacts associated with the production, use, and end-of-life phases of both hybrid and conventional SUVs in the Saudi Arabian context. The model follows the ISO 14040 and 14044 standards for LCA (ISO 2020; 2006), incorporating secondary data collected from reputable sources. The model utilizes the SimaPro modeling tool and ecoinvent database to ensure a robust and accurate representation of the studied vehicle technologies and the Saudi Arabian market conditions. The following sections provide a detailed overview of the LCA model's scope, data sources, methodology, and modeling techniques utilized.

2.1.1. Goal and Scope

The goal of this LCA is twofold: first, to assess the climate impact of hybrid and conventional SUVs operating in KSA, and second, to offer a concise overview of their broader environmental implications. A comparative attributional LCA modeling approach has been used. The powertrains assessed are gasoline (ICEV SUV) and hybrid (HEV SUV). The system boundary considers the entire life cycle of the vehicles, covering material extraction and production, transportation, manufacturing, use, maintenance, and end-of-life disposal.

The functional unit (FU) serves as a standardized measure of a product system performance, enabling comparisons between different systems based on a commonly provided service (the reference unit). For this study, the FU is defined as driving one vehicle kilometer in an SUV in the KSA over an average lifetime mileage of 250,000 km. The vehicle's lifetime mileage is assumed based on Sheldon and Dua (2020). However, this is considered a sensitive parameter since vehicle lifetime mileage can vary in real-life conditions (Weymar and Finkbeiner 2016).

2.1.2. Life-Cycle Inventory

Foreground data for each vehicle, including fuel type, fuel consumption, emission standard, and weight, is gathered from the literature (Cox et al. 2020) and the manufacturer's website (Toyota KSA 2022). Background data is derived from the ecoinvent v3.9.1 database using the SimaPro v9.5 modeling tool (PRé Sustainability 2022; Wernet et al. 2016).

2.1.3. Vehicle Production and End-of-Life Treatment

The inventory data of the Volkswagen Golf A4 vehicle has been utilized to model the vehicle production stage (Schweimer and Levin 2000), as implemented in the ecoinvent database. The adaptation of this data focuses on the specific weights of the vehicles, specifically for the scalable parts, primarily the glider. The vehicle production includes the glider, drivetrain, and traction battery. A large part of vehicle production is assumed to be common besides their technology-specific powertrain components such as electric drive (e-drive), ICE, and traction battery pack (LIB). The main difference considered in the model is their respective weights (see Table 1). The ecoinvent dataset for passenger cars is used for the SUVs considered. Likewise, the ICE, e-drive, and LIB production are modeled using their representative manufacturing processes in the ecoinvent database. A list of the production processes for these components is reported in Table A.1 in the Appendix.

The end-of-life stage is modeled considering only the treatment and disposal of the vehicles, using representative processes in the ecoinvent database. Recycling at the vehicles' end of life is excluded due to limited access to reliable data for the Saudi context. However, recycled materials are utilized burden-free during the vehicles' manufacturing stage following the cut-off system modeling approach implemented in the ecoinvent database (ecoinvent 2023).

2.1.4. Vehicle Operation

During the use phase, direct emissions from vehicle usage (tank-to-wheel) and indirect emissions from fuel production (well-to-tank) are considered. The well-to-tank (WTT) analysis includes emissions along the gasoline production stage as the fuel source for the vehicles. The production process for low-sulfur gasoline is based on the respective ecoinvent datasets for manufacturing low-sulfur gasoline for the rest of the world (RoW) production. However, the processes for key feedstocks such as petroleum and gas production, electricity, and heat used during the production stage have been changed to match the KSA context.

The fuel consumption figures provided for both the ICEV and hybrid SUVs are derived from the official data of the Toyota RAV4, as presented in Table 1. However, it is important to note that the official data is obtained through laboratory measurements, which have been shown to underestimate the actual fuel consumption performance of the vehicles in real-world conditions by approximately 25%-40% (Fontaras, Zacharof, and Ciuffo 2017). To address this discrepancy, we have considered a 25% increase in the official data to reflect the vehicles' real-life performance more accurately on the road. In addition, this is considered a sensitive parameter since the fuel efficiency of vehicles depends on several factors and can vary significantly in real-life conditions (Fontaras, Zacharof, and Ciuffo 2017).

The tank-to-wheel (TTW) emissions are calculated based on the Euro 5 emission standards, which are incorporated into the ecoinvent database. The Euro 5 standard has been adopted since the Kingdom officially introduced it as an ongoing effort to promote environmental sustainability and the Saudi Vision 2030 objectives (KSA 2024). Specifically, the emissions of a medium-sized gasoline passenger car belonging to the Euro 5 category and equipped with an engine size ranging from 1.4 to 2.0 liters are estimated. These specifications align with the vehicles analyzed in this study. The dataset used also considers the emissions resulting from fuel evaporation from the gasoline vehicle's fuel tank as modeled in the ecoinvent database. Emissions dependent on fuel consumption are matched to the fuel efficiency of vehicles in this study. The updated emission data are reported in Table A.2 in the Appendix. Impacts from non-exhaust originating from tire, brake, and road wear and those from road construction and maintenance and vehicle maintenance were also considered during the vehicle's operation stage (referred to as operation—others in the model and result section). To model these parameters, their production processes are obtained from the ecoinvent database, utilizing their global average dataset.

2.1.5. Life Cycle Impact Assessment

We employed the ReCiPe 2016 impact assessment method to evaluate the environmental impacts considered in this study. Our focus is primarily on specific indicators within the ReCiPe 2016 framework (Huijbregts et al. 2017). We specifically examined the midpoint indicator for climate change, as well as the endpoint indicators for human health, ecosystems, and resources, as outlined in Table 2. We have chosen these indicators as they are particularly relevant to our research objective. The global warming potential (GWP)

Table 1. Summary of key vehicle parameters.

Vehicle component/characteristic	ICEV SUV	HEV SUV
Curb mass (kg)	1,643	1,724
Glider (kg)	1,446	1,446
Electric drive (kg)	–	70.8
ICE drivetrain (kg)	197	191
LIB capacity (kWh)	–	1.9
LIB pack (kg)	–	16.2
Official fuel consumption (L/km)	0.0613	0.045
Adjustment for real-life fuel consumption (L/km)	0.0797	0.0586

Table 2. Impact categories and indicators used in this study.

Impact categories	Impact indicator	Unit	Impact assessment method
Climate change	GWP	gCO_2-eq	ReCiPe Midpoint
Human well-being	Human health	Points	ReCiPe Endpoint
Ecosystem quality	Ecosystem		
Natural resources	Resources		

midpoint indicator allows us to assess the climate impact of both hybrid and conventional SUVs from a more granular standpoint. GWP indicator quantifies the comparative effect of GHG emissions on global warming within a specific timeframe. In that context, the GHG emissions presented in this study are expressed as CO_2-equivalent (CO_2-eq) based on the 100-year time frame (IPCC 2022).

Additionally, we utilized the endpoint indicators to provide a concise overview of the broader environmental implications associated with these vehicles. The ReCiPe model classifies impacts into three endpoint categories: human health, ecosystems, and resources. These categories represent the areas of protection that society values. The human health endpoint encompasses factors such as climate change, ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation, and ionizing radiation. The ecosystems endpoint focuses on the effects of climate change, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, agricultural land occupation, urban land occupation, and natural land transformation on ecological systems. The resources endpoint examines the depletion of fossil fuels and metals. By utilizing these endpoint categories, the ReCiPe model offers a comprehensive framework for evaluating and understanding the environmental impacts associated with various areas of protection.

2.2. The TCO Model

The TCO analysis summarizes the SUVs' present and future costs under certain assumptions. Equation (1) shows a general TCO equation:

$$\begin{aligned}&Total\ cost\ of\ ownership = One\ time\\ &cost + Rercurring\ cost - Resale\ value\end{aligned} \tag{1}$$

Vehicle replacement rates are higher among private vehicle owners in KSA, with an average ownership period of 3.8 years for purchasers of new vehicles (Abdulkareem and Ellaboudy 2022). However, despite the relatively short ownership periods for new vehicle purchasers, the active second-hand market plays a pivotal role in extending the lifespan of vehicles within the KSA fleet (Pandey 2021). In that light, a 10-year vehicle-holding period is assumed. In addition, it is assumed that the SUVs are purchased on an automobile loan. The loan model assumed a 10% down payment of the manufacturer's suggested retail price (MSRP) for a specific vehicle. The MSRP is taken as the initial vehicle cost. The remainder of the vehicle cost (i.e., 90% of the MSRP) is financed by a 48-month loan and a balloon payment at the end of a loan term (based on the Riyad Bank online finance calculator at riyadbank.com). Table 3 summarizes the key TCO parameters used in this study, with the cost unit in Saudi Arabian Riyals (SAR).

Thus, the one-time cost of owning a SUV based on the conditions in this study can be expressed as in Equation (2):

$$\begin{aligned}&One\ time\ cost = Upfront\ cost\\ &\qquad + Balloon\ payment\end{aligned} \tag{2}$$

The main component of the upfront cost is the down payment, including the taxes and fees:

$$\begin{aligned}&Upfront\ cost = Down\ payment\\ &\qquad + Sale\ taxes + Admin\ fees\end{aligned} \tag{3}$$

The balloon payment and resale value are discounted to their present value considering the time value of money and the principles of financial analysis (ANL 2021).

Table 3. Summary of key TCO parameters.

Vehicle type	SUV ICEV	SUV HEV	Reference
MSRP (SAR)	103,270.00	118,840.00	toyota.com.sa
Down payment (SAR)	10,327.00	11,884.00	riyadbank.com
Loan amount (SAR)	92,943.00	106,956.00	
Monthly installment (SAR)	1,958.78	2,254.1	
Balloon payment (SAR)	25,818.00	29,710.00	
Admin fees (SAR)	929.43	1,069.56	
Loan period (months)	48	48	
Annual discount rate	0.065	0.065	Authors' assumption
Salvage value (SAR)	28,550.00	30,850.00	drivearabia.com
Fuel price (SAR/L)	2.18	2.18	

Thus, these parameters are expressed as in Equation (4) and (5):

$$Balloon\ payment_y = \frac{\begin{array}{c} Lump\ sum\ payment \\ at\ the\ end\ of\ a\ loan\ term_y \end{array}}{(1+r)^y} \quad (4)$$

$$Resale\ value_n = \frac{\begin{array}{c} Salvage\ value\ after\ 10\ years \\ ownership\ period_n \end{array}}{(1+r)^n} \quad (5)$$

Where, y is the future years of the loan period, n is the future years of the holding period, and r is the annual discount rate. TCO studies commonly assumed discount rates between 5% and 8% (Breetz and Salon 2018). A discount rate of 6.5% is assumed in this study.

The salvage values of the vehicles after 10 years of ownership are estimated based on the resale calculator from DriveArabia (2022). The input parameters include the vehicle brand and model, model year and trim level, resale year, and mileage in kilometers.

The recurring costs (RC) include the monthly installment for the financed vehicle, maintenance and repairs, insurance, fuel, and vehicle taxes. The recurring costs are also discounted through the vehicle holding period and can be expressed as in Equation (6):

$$RC = \sum_{y=1}^{Y}\left(\frac{(Financing_y)}{(1+r)^y}\right) + \sum_{n=1}^{N}\left(\frac{(MR_n + Insurance_n + Vehicle\ taxes_n + Fuel_n)}{(1+r)^n}\right) \quad (6)$$

Where, Y is the loan period, N is the vehicle holding period, and MR_n is maintenance and repair costs in future years. Maintenance and repair costs are estimated based on the Jameel maintenance program offer from toyota.com.sa/en/offers. Annual insurance prices are modeled following an analysis of the KSA No-Claim Discount System (Alyafie, Constantinescu, and Yslas 2023). This study assumed no claim was made during the vehicle holding periods. Costs for annual vehicle taxes are based on annual fees reported on www.moi.gov.sa for vehicle and vehicle plate registration. No extra fees related to fuel efficiency were added since the official fuel economy of the vehicles assessed is above 16km/L as the policy suggested (Saudi Standards 2023).

Average fuel consumption is assumed for each vehicle based on the official values reported by their manufacturers plus a 25% increase to account for real-life performance (see Table 1). Thus, the fuel cost is estimated as in Equation (7):

$$Fuel_n = \sum_{n=1}^{N} VMT_n * Fuel\ consumption_n * Fuel\ price_n \quad (7)$$

Where VMT_n is the annual vehicle miles traveled (km), fuel consumption (L/km) obtained from the manufacturer's official data, and fuel price[1] (SAR/L) in the KSA context. Inflation rate for future costs of fuel is not considered following the royal directive to establish a local price ceiling for gasoline (petrol) (KSA 2021). The vehicle miles traveled are assumed to be fixed throughout the vehicle ownership period and are modeled as 25,000 km per annum (Sheldon and Dua 2020).

2.3. Sensitivity Analysis

A sensitivity analysis was performed to assess different assumptions of key parameters on the results. Table 4 outlines the specific parameters selected for testing on the GWP midpoint indicator and the TCO results. This analysis aimed to assess the robustness of the findings and evaluate the impact of variations in these parameters on the overall outcomes.

Table 4. Selected parameters for sensitivity analysis.

Parameter	Variation in selected parameters	Application
Fuel consumption (L/km)	Changed by -10% and 10%	LCA & TCO
Lifetime mileage (km)	Changed by -10% and 10%	LCA & TCO
Down payment (SAR)	Changed by 50% and 100%	TCO
Discount rate (%)	Changed by -10% and 10%	TCO

[1] *Fuel prices assumed constant for this study, based on the royal directive issued on July 10, 2021, setting the ceiling prices for gasoline (Octane 91/SR2.18 per liter and Octane 95/SR2.33 per liter), effective July 10, 2021 (https://www.spa.gov.sa/en/807d08c73c).*

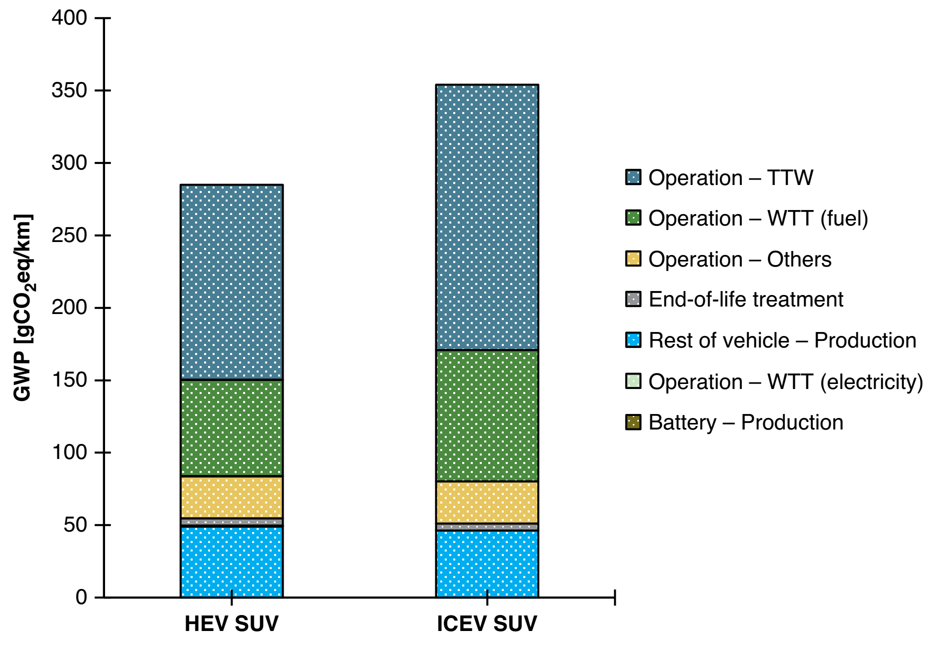
3. Result and Discussion

3.1. GWP Analysis

The life-cycle GWP impacts of the hybrid and conventional SUV are shown in Figure 1, expressed as CO_2-equivalents (accounting for emissions of the different greenhouse gases) per km driven. The HEV SUV shows the best potential to reduce GWP impacts between the two powertrains, contributing around 19.5% less GWP impact than the ICEV SUV. This reduction is driven by the better fuel efficiency of the hybrid SUV than its conventional counterpart. Moreover, it confirms the important role of energy-efficient powertrain components in reducing fuel or energy demand during vehicle operation, which in turn affects the associated GHG emissions. Higher powertrain efficiency is achieved through technological advancements, such as more efficient combustion engines, hybrid systems, or fully electric powertrains (Balazadeh Meresht et al. 2023; Damiani, Repetto, and Prato 2014). These technologies can optimize energy conversion and minimize energy losses during the vehicle operation phase, thereby reducing the overall GWP of the vehicle. Additionally, improving powertrain efficiency indirectly contributes to reducing GWP by reducing the demand for fossil fuels. As the transportation sector transitions to low-carbon energy sources, the GWP impact of vehicle operation further decreases.

The operation stage of the vehicles is the most significant contributor to GWP impacts, accounting for 201.14 gCO_2eq/km (81%) in hybrid SUVs and 273.74 g CO_2eq/km (86%) in conventional SUVs. The contribution analysis

Figure 1. Global warming potential of SUVs in this study. Legend: WTT = well-to-tank; TTW = tank-to-wheel.



Source: *Authors' estimation.*

shows that around 23%-26% of total GWP impacts are linked to the fuel production phase (Operation—WTT) and 47%-52% during the fuel combustion phase (Operation—TTW) of the SUVs.

Our GWP impact results are comparable to the recent WTW analysis by Ankathi et al. (2024), which reported WTW GHG emissions of approximately 308.01 gCO_2eq/km for ICEV gasoline vehicles in the KSA. The discrepancy in WTW emissions between our study and that of Ankathi et al. is primarily due to differences in the assumed fuel economy values. Ankathi et al. utilized a fleet-representative fuel economy of 10.46 km/L for ICEV gasoline vehicles. In contrast, our study employed a higher fuel economy of 12.547 km/L, derived from the manufacturer's data, with an additional 25% adjustment to account for real-life driving conditions (Fontaras, Zacharof, and Ciuffo 2017).

Ankathi et al. (2024) also presented a technology-normalized approach, reporting emissions of 109 g CO_2eq/km and 117.5 g CO_2eq/km for small and midsize SUVs, respectively. These figures were based on technology-specific fuel economies of 16.58 km/L for small SUVs (which is similar to the manufacturer's official fuel consumption data reported in Table 1) and 15.39 km/L for midsize SUVs. The variation in emissions results from technology-normalized and fleet-representative modeling approaches in Ankathi et al. underscore the importance of considering country-specific representative data for fuel economy assumptions when evaluating the environmental impacts of vehicle operation.

In addition, operation GWP impacts due to infrastructure requirements for road construction and maintenance, as well as vehicle repairs and maintenance, were also evident, accounting for approximately 8%-10% of total GWP impacts (Operation—Others). The vehicle production stage GWP impacts contributed around 17% and 13% in the hybrid and conventional SUV, respectively. The relatively higher GWP impact of hybrid SUV production is driven by the added burden of producing its electric powertrain components. The contribution analysis reveals that the production of precious metals and electronics for manufacturing electric powertrain components is energy-intensive, resulting in relatively higher embodied carbon emissions (Koroma et al. 2022).

However, this study used global averages for material and vehicle production and end-of-life disposal. It is important to consider the influence of manufacturing and production in different countries with varying conditions. For instance, the energy mix used during manufacturing affects environmental impact, with countries/energy scenarios relying on fossil-based energy potentially having higher emissions compared to those emphasizing low-carbon and renewable sources (Koroma et al. 2020; Zhang et al. 2023). Environmental regulations and emission standards also impact manufacturing, with stricter regulations driving the adoption of low-carbon practices. The supply chain's environmental impact, including transportation emissions and sustainability practices, can differ based on regional factors. Additionally, end-of-life impacts vary depending on disposal and recycling infrastructure. Therefore, focusing on reducing the GWP of material and vehicle production processes through efficiency improvements, cleaner energy sources, and materials advancements is crucial for improving the environmental profile of the vehicle production stage (IEA 2019).

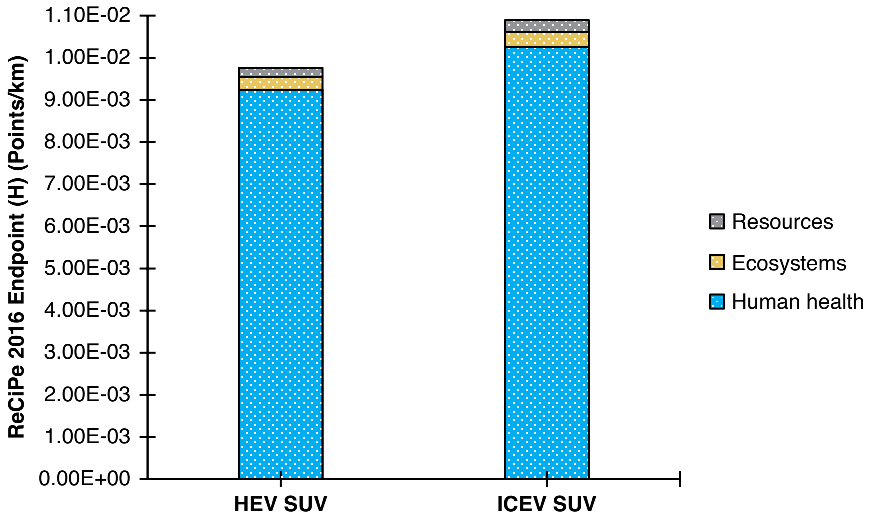
3.2. Endpoint Damage of the Vehicle Technologies

The results from the endpoint indicators provide valuable insights into the total environmental profiles of the vehicles analyzed. Figure 2 and Figure 3 offer a concise overview of these implications. By normalizing and weighting the three endpoint indicators (human health, ecosystems, and resources) using the ReCiPe 2016 hierarchical perspective, a single score is generated for each vehicle. The findings indicate that the hybrid SUV exhibits a more favorable environmental profile across all three endpoint indicators compared to the conventional SUV, with approximately 10% improvements in terms of points.

Figure 2 reveals that a significant portion (around 95%) of the endpoint impacts for both vehicles stem from their contribution to damage to human health. This highlights the importance of considering the health implications associated with vehicle emissions and pollution.

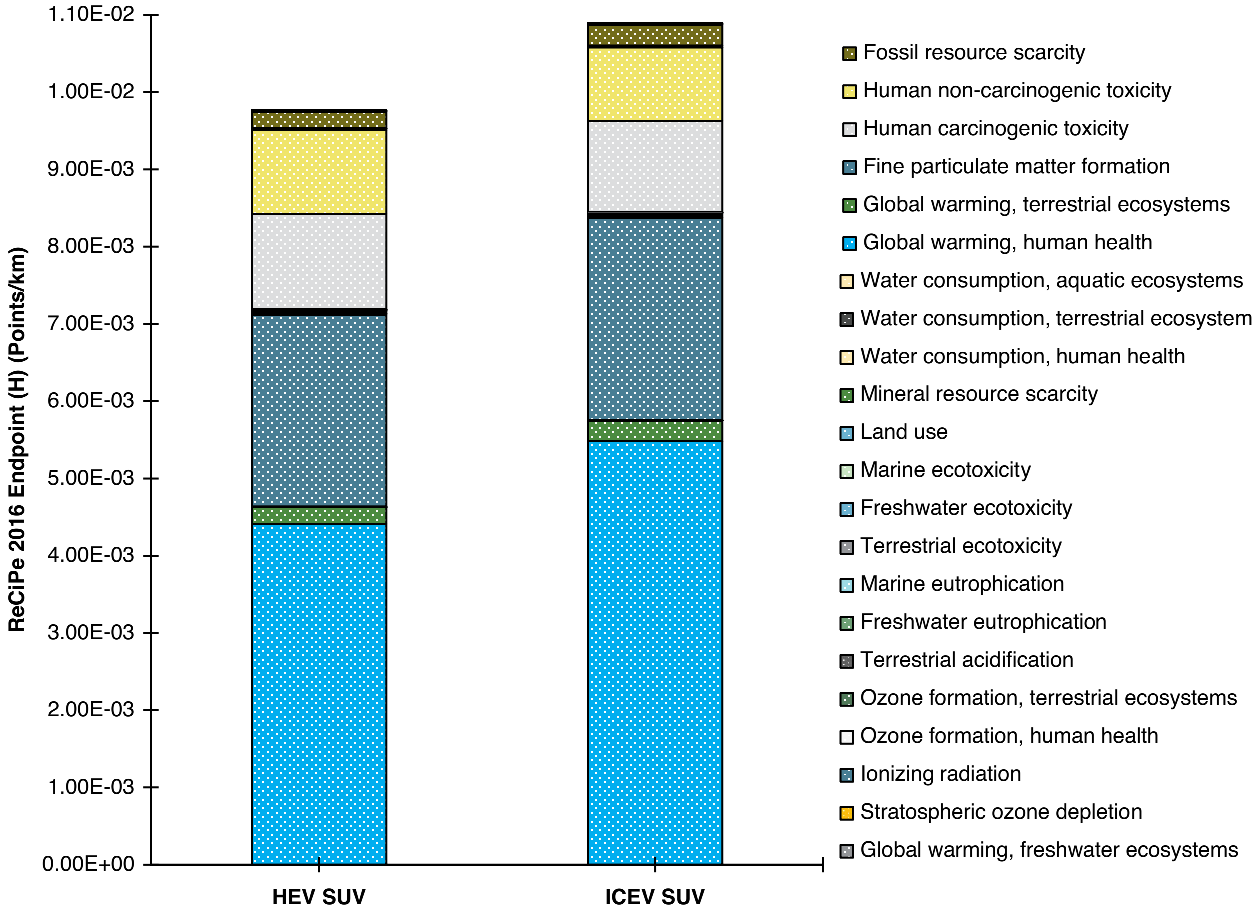
Further analysis in Figure 3 demonstrates that climate change indicators contribute the most to the overall damages, accounting for 46% of the total. Air pollutants resulting in the formation of fine particulate matter contribute 25% of the damages, followed by human toxicity-related categories at 23%. The remaining impact categories contribute to around 5%-6% of the total damages.

Figure 2. Life-cycle share of environmental damage to the single score of the vehicles in this study.



Source: *Authors' estimation.*

Figure 3. Life-cycle share of the environmental impact to the single score of the vehicles in this study.



Source: *Authors' estimation.*

In terms of ecosystem and resource damage, the average contributions are relatively lower, comprising approximately 3% and 2% of the total damages, respectively. This suggests that while these vehicles have some impact on ecosystems and resources, the majority of their environmental impacts are concentrated in the human health domain. These implications highlight the importance of prioritizing measures to reduce emissions and mitigate climate change impacts, as well as address air pollution and human toxicity concerns associated with vehicle life cycle. Additionally, efforts to minimize ecosystem and resource damage should be considered alongside these priorities to achieve a more sustainable transportation sector.

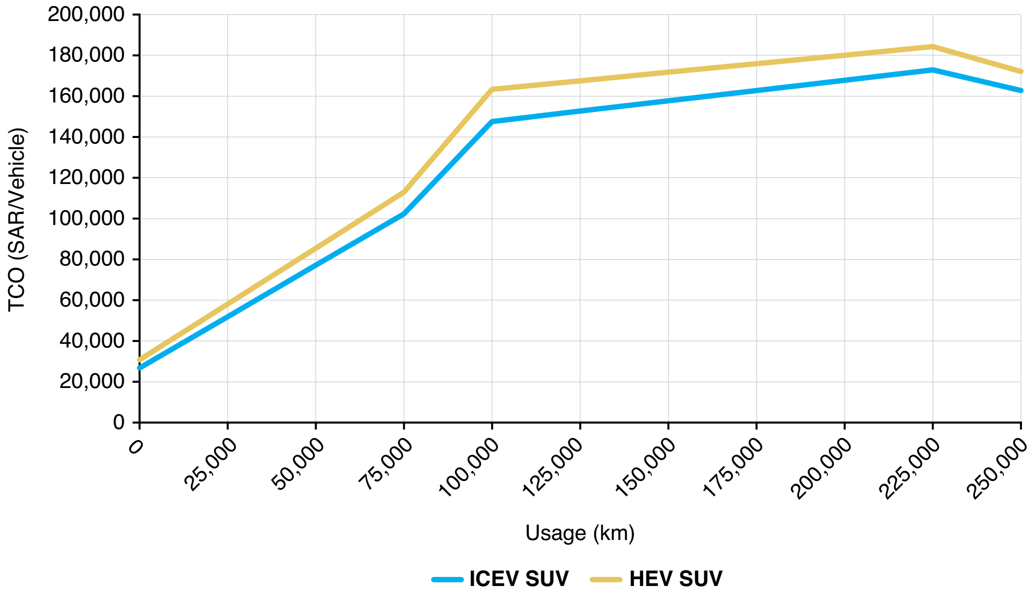
3.3. TCO Analysis

Figure 4 illustrates the TCO comparison between the hybrid and conventional SUV in this study over a 10-year (250,000 km) holding period in KSA. The findings indicate that the conventional SUV exhibits a slightly more favorable TCO (around 6% cost advantage) than the hybrid SUV in the KSA context. The higher TCO of the HEV SUV compared to its conventional counterpart is linked to its relatively higher purchase cost and depreciation.

In Figure 4, the sharp increase in TCO during the first 100,000 km is linked to auto loan repayment. Likewise, the widening gap between the hybrid and conventional SUV TCO is due to the different monthly and balloon payments based on the vehicles' purchase/retail cost. After the loan repayment (at 100,000 km onwards), the gap between the vehicles' TCO started to decrease in favor of the hybrid SUV due to its lower operating cost (specifically its lower fuel consumption) than the ICEV SUV. Similarly, between 225,000 km and 250,000 km, the TCO for both vehicles decreases due to their estimated resale value at the end of the holding period. Table A.3 and Table A.4 in the Appendix show the evolution of the cost components during the 10-year assessment period.

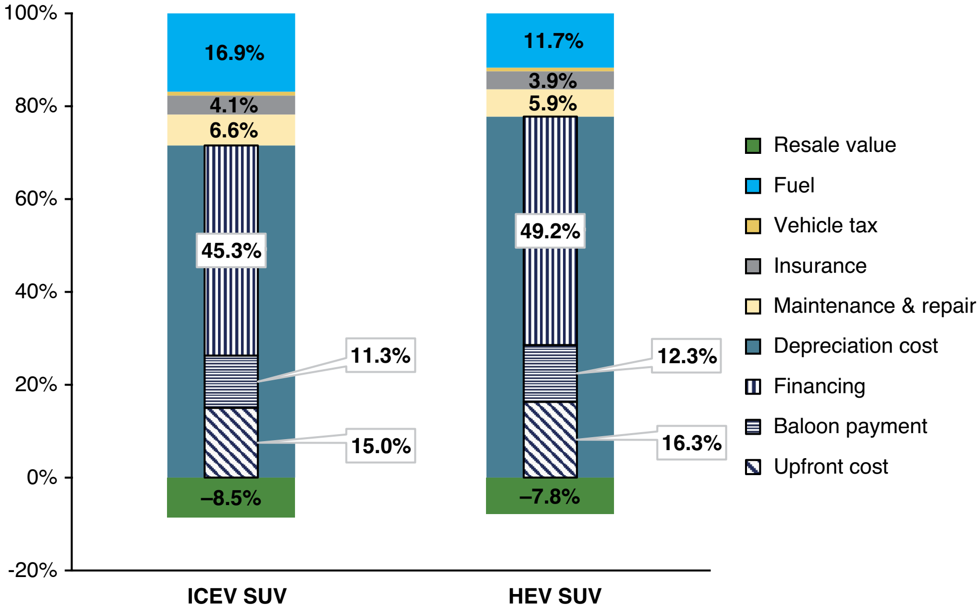
Overall, the study's findings are consistent with the TCO literature, which acknowledges that mid-sized hybrid vehicles generally have slightly higher TCO than conventional vehicles when government subsidies/incentives are not considered (Letmathe and Suares 2017; Guo, Kelly, and Clinch 2022). The results indicate that while hybrids offer better fuel efficiency and slightly lower maintenance costs due to regenerative braking, their retail costs need to be at parity with conventional vehicles for consumers in KSA to consider them cost-competitive.

Figure 4. Cumulative total cost of ownership of hybrid and conventional SUVs. SAR is Saudi Arabian Riyals; ICEV is an internal combustion engine vehicle, and HEV is a hybrid electric vehicle.



Source: *Authors' estimation.*

Figure 5. TCO contribution analysis of relevant cost parameters as a percentage of the total cost, excluding the SUV resale value.



Source: *Authors' estimation.*

Therefore, it is crucial to focus on achieving purchase cost parity (at minimum) between hybrid vehicles and conventional vehicles in KSA. Efforts should be directed towards reducing the purchase costs of hybrids, which would increase their adoption in the country. By making HEVs cost-competitive, KSA can encourage wider adoption of these vehicles, leading to reduced GHG emissions and a more sustainable transportation sector.

The contribution analysis of key cost parameters shows that the depreciation costs across the SUVs contributed a large share of the TCO, as shown in Figure 5. After a 10-year holding period, the share of the depreciation cost for the hybrid SUV (~77.7%) is higher than the conventional SUV (~71.6%). This difference in depreciation rates can be attributed to the current challenges of adopting electric vehicles in KSA, considering the uncertainties surrounding EV battery aging and performance in the hot climate of the Kingdom (Almatrafi et al. 2023; Alotaibi, Omer, and Su 2022). The cumulative financing and balloon payments are important factors influencing the depreciation cost, contributing around 45%-49% and 11%-12%, respectively, as shown in Figure 5. Additionally, the resale value at the end of the vehicle holding period significantly impacts the TCO, providing around 8.5% and 7.8% reductions in ownership costs for conventional and hybrid SUVs, respectively.

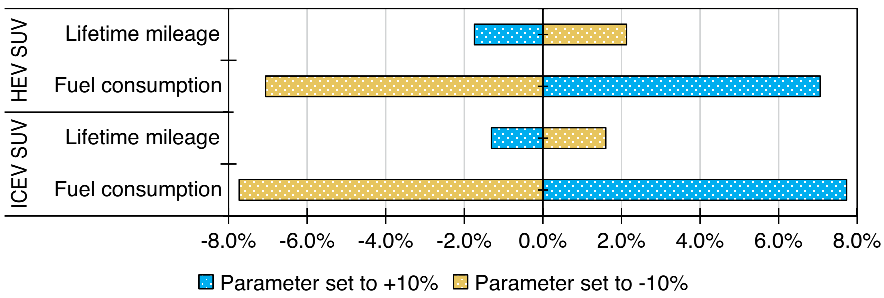
These findings suggest the importance of using quality data and informed assumptions for these parameters in TCO assessment. As a result, future research can extend the scope to cover the different auto finance methods and passenger vehicle classes in KSA. This will provide a more comprehensive understanding of the factors influencing TCO in the context of the Kingdom. For policymakers, it is crucial to focus on ensuring cost-competitive financing models for automobile loans in KSA. Since cumulative financing directly affects the potential savings after resale, efforts to reduce the net capital cost would make the TCO more competitive for hybrid vehicle owners in the country. By addressing financing challenges and creating favorable conditions for affordable ownership, policymakers can facilitate the adoption of hybrid and low-carbon vehicles, contributing to sustainable and low-carbon transportation in KSA.

3.4. Sensitivity of Results

The sensitivity assessment (SA) results are presented in Figure 6 and Figure 7 for selected parameters on the GWP midpoint indicator and TCO, respectively. Specifically, the focus was on examining the influence of assumptions related to fuel consumption and lifetime mileage on the GWP midpoint results. The analysis shows that the GWP indicator is more affected by assumptions relating to fuel consumption, compared to variations in lifetime mileage. When the fuel consumption parameter was subjected to a +/-10% variation, it resulted in an approximate change of over +/-7% in the GWP outcome for both vehicles. This emphasizes the importance of accurate considerations regarding fuel consumption assumptions in assessing the environmental impact of the vehicles under study.

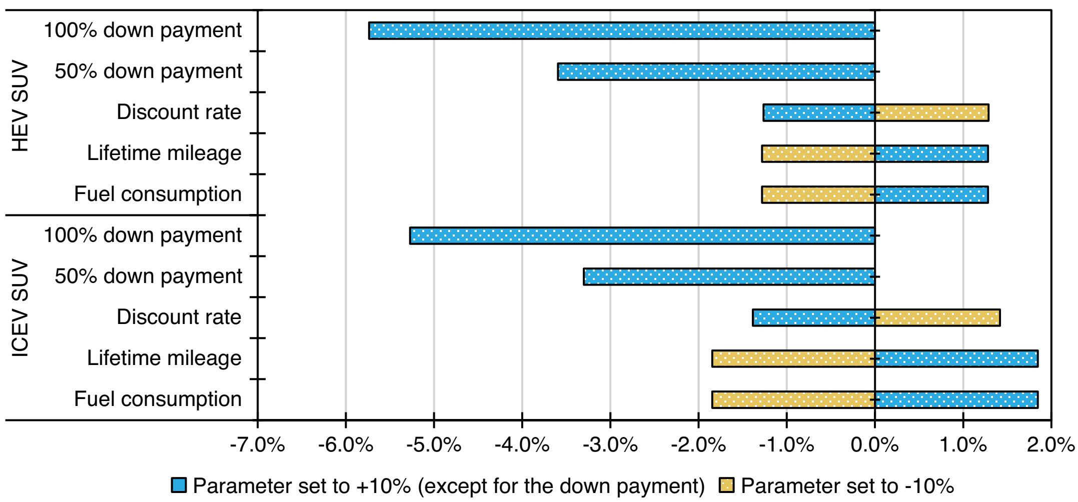
The SA also examined the impact of various assumptions on the TCO results. Specifically, the study analyzed the effects of assumptions related to fuel consumption, lifetime mileage, discount rate, and down payment. The SA findings reveal that the TCO outcomes are most

Figure 6. Sensitivity analysis results for selected parameters on the GWP midpoint indicator.



Source: *Authors' estimation.*

Figure 7. Sensitivity analysis results for selected parameters on the TCO.



Source: *Authors' estimation.*

sensitive to assumptions regarding the down payment, followed by fuel consumption (Figure 7). When the down payment parameter varied from 10% (as used in the main study) to 50%, the TCO outcome showed a reduction of approximately 3.6% for the hybrid SUV and 3.3% for the conventional SUV. Alternatively, in the scenario where the consumer paid the entire vehicle cost upfront (i.e., 100% down payment), the TCO outcome showed a reduction of around 5.7% for the hybrid SUV and 5.3% for the conventional SUV.

These findings highlight the sensitivity of the GWP midpoint indicator to variations in fuel consumption assumptions, underscoring the need for careful evaluation and precise data in modeling the GWP indicator. Likewise, these results underscore the significance of accurate and reliable data for sensitive parameters when assessing the TCO of vehicles. It highlights the substantial impact that assumptions about the down payment can have on the overall cost evaluation. Additionally, the sensitivity of TCO outcomes to fuel consumption assumptions reinforces the necessity of accurate estimations to obtain robust and reliable results. Therefore, practitioners should prioritize obtaining high-quality data for these sensitive parameters to enhance the accuracy and reliability of TCO and LCA assessments.

4. Conclusions and Policy Implications

This study could serve as a baseline to inform sustainable pathways for decarbonizing the KSA passenger car fleet. The study has provided insights into the climate impact of hybrid and conventional SUVs operating in KSA. It offers a concise overview of their broader environmental implications on human health, ecosystems, and resources. The GWP results suggest that HEVs can be promoted for near-term decarbonization efforts in KSA. It emphasizes the global warming reduction potential of HEVs (around 19.5% in this study) compared to conventional vehicles, despite their added embodied carbon emissions from powertrain component production. However, hybrid SUVs show a higher TCO than conventional SUVs due to their relatively premium purchase cost. These findings underscore efforts to reduce their initial purchase cost, and TCO should be prioritized. Their depreciation costs comprised a significant portion of the TCO, with cost parameters linked to the auto financing model and resale value as key influencing factors.

Policymakers in KSA should consider promoting HEVs as a near-term decarbonization strategy while the infrastructure requirements for zero-carbon vehicles are being addressed. HEVs offer improved fuel efficiency and lower GHG emissions compared to conventional vehicles, making them a transitional solution for sustainable transportation. From a cost perspective, KSA policymakers should focus on ensuring cost-competitive financing models for automobile loans to make the TCO more favorable for hybrid vehicle owners. Addressing financing challenges, such as reducing net capital costs associated with vehicle ownership and promoting affordable ownership options, can facilitate the adoption of hybrid and low-carbon vehicles. This, in turn, will contribute to the transition for sustainable and low-carbon transportation in KSA while the unique climate and specific challenges associated with adopting zero-carbon vehicles in the region are addressed.

By supporting HEVs, KSA can reduce emissions in the near future and leverage existing refueling infrastructure, as they emit about 19.5% less GWP than ICEV SUVs. However, it is crucial to recognize that HEVs are not a long-term solution but a transitional one since they can play a valuable role in reducing fuel consumption and emissions in the short term while the infrastructure requirements for zero-carbon vehicles are developed. A comprehensive strategy to decarbonize the passenger transport sector should include several low-carbon fuels/energy vehicles, including the eventual transition to zero-carbon emission powertrains—such as battery and fuel-cell vehicles. Therefore, HEVs should be viewed as an important step in KSA's decarbonization journey, while simultaneously laying the groundwork for a sustainable transportation system in the future.

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Appendix

Table A1. Life cycle inventory (LCI) datasets used.

Component name	Name of LCI dataset	Location	Database
Glider	Market for glider, passenger car	GLO	ecoinvent 3.9
IC engine and rest of powertrain	Market for internal combustion engine, passenger car	GLO	ecoinvent 3.9
Battery production	Market for battery, Li-ion, LiMn2O4, rechargeable, prismatic	GLO	ecoinvent 3.9
Electric motor	Market for electric motor, electric passenger car	GLO	ecoinvent 3.9
Inverter	Market for inverter, for electric passenger car	GLO	ecoinvent 3.9
Cable	Market for cable, three-conductor cable	GLO	ecoinvent 3.9
Power distribution unit	Market for power distribution unit, for electric passenger car	GLO	ecoinvent 3.9
Car maintenance	Maintenance, passenger car	GLO	ecoinvent 3.9
Car end-of-life	Market for manual dismantling of used passenger car with internal combustion engine	GLO	ecoinvent 3.9
electric powertrain end of life	Market for used powertrain from electric passenger car, manual dismantling	GLO	ecoinvent 3.9
Petrol (gasoline)	Market for petrol, low-sulfur	RoW	ecoinvent 3.9
Electricity (to adapt petrol, low-sulfur production for Saudi)	Market for electricity, medium voltage SA		ecoinvent 3.9
Road maintenance	Market for road maintenance	RoW	ecoinvent 3.9
Road	Market for road	RoW	ecoinvent 3.9
Road wear	Market for road wear emissions, passenger car	GLO	ecoinvent 3.9
Tire wear	Market for tire wear emissions, passenger car	GLO	ecoinvent 3.9
Brake wear	Market for brake wear emissions, passenger car	GLO	ecoinvent 3.9

Table A2. Emission data datasets used.

Emissions	Value	Unit	Source
CO_2 per kg of petrol used	3.183340	kg / kg petrol	*EMEP/EEA (2016); ecoinvent 3.9
SO_2 per kg of petrol used	2.00E-05	kg / kg petrol	*EMEP/EEA (2016); ecoinvent 3.9
Benzene	9.99E-07	kg/km	**HBEFA (2017); ecoinvent 3.9; Assumed same for hybrid
Methane, fossil	0.00001587	kg/km	**HBEFA (2017); ecoinvent 3.9; Assumed same for hybrid
Carbon monoxide, fossil	3.87E-04	kg/km	**HBEFA (2017); ecoinvent 3.9; Assumed same for hybrid
NMVOC, non-methane volatile organic compounds	0.00006653	kg/km	**HBEFA (2017); ecoinvent 3.9; Assumed same for hybrid
Nitrogen oxides	0.00003101	kg/km	**HBEFA (2017); ecoinvent 3.9; Assumed same for hybrid
PM < 2.5 um	1.022E-06	kg/km	**HBEFA (2017); ecoinvent 3.9; Assumed same for hybrid
Zinc per kg of petrol used	1.00E-06	kg / kg petrol	*EMEP/EEA (2016); ecoinvent 3.9
Selenium per kg of petrol used	1.00E-08	kg / kg petrol	*EMEP/EEA (2016); ecoinvent 3.9
PAH, polycyclic aromatic hydrocarbons per kg of petrol used	3.48E-08	kg / kg petrol	*EMEP/EEA (2016); ecoinvent 3.9
Nickel per kg of petrol used	7.00E-08	kg / kg petrol	*EMEP/EEA (2016); ecoinvent 3.9
Mercury per kg of petrol used	7.00E-11	kg / kg petrol	*EMEP/EEA (2016); ecoinvent 3.9
Lead per kg of petrol used	1.50E-09	kg / kg petrol	*EMEP/EEA (2016); ecoinvent 3.9
Dinitrogen monoxide per kg of petrol used	1.30E-04	kg / kg petrol	*EMEP/EEA (2016); ecoinvent 3.9
Copper per kg of petrol used	1.70E-06	kg / kg petrol	*EMEP/EEA (2016); ecoinvent 3.9
Chromium IV per kg of petrol used	1.00E-10	kg / kg petrol	*EMEP/EEA (2016); ecoinvent 3.9
Chromium per kg of petrol used	5.00E-08	kg / kg petrol	*EMEP/EEA (2016); ecoinvent 3.9
Cadmium per kg of petrol used	1.00E-08	kg / kg petrol	*EMEP/EEA (2016); ecoinvent 3.9
Ammonia per kg of petrol used	3.00E-05	kg / kg petrol	*EMEP/EEA (2016); ecoinvent 3.9

**EMEP/EEA (2016).*

***HBEFA (2017).*

Table A3. Evolution of the cost components during the 10-year assessment period for the conventional SUV.

Driving	Lifetime (years) Mileage (km)	Yr1 25,000	Yr2 50,000	Yr3 75,000	Yr4 100,000	Yr5 125,000	Yr6 150,000	Yr7 175,000	Yr8 200,000	Yr9 225,000	Yr10 250,000
Maintenance and repair model	Basic maintenance, including labor, parts fees & VAT (15%)	299	1,099	1,599	1,099	1,599	1,099	0	1,599	0	1,599
	12v battery (every four years in SAR)				299				299		
	Tires (every three years in SAR)			2,020.72			2,020.72			2,020.72	
	Total:	299.00	1,099.00	3,619.72	1,398.00	1,599.00	3,119.72	-	1,898.00	2,020.72	1,599.00
	Discounted total:	**280.75**	**968.94**	**2,996.58**	**1,086.70**	**1,167.08**	**2,138.05**	**-**	**1,146.83**	**1,146.46**	**851.83**
Vehicle tax model	Annual fees to vehicle driving licenses as per fuel efficiency (SAR)	0	0	0	0	0	0	0	0	0	0
	Private vehicle registration (SAR)	100	100	100	100	100	100	100	100	100	100
	Driving license (SAR)	0	0	0	0	0	0	0	0	0	0
	Registration plates (SAR)	100	100	100	100	100	100	100	100	100	100
	Total	200.00	200.00	200.00	200.00	200.00	200.00	200.00	200.00	200.00	200.00
	Discounted total:	**187.79**	**176.33**	**165.57**	**155.46**	**145.98**	**137.07**	**128.70**	**120.85**	**113.47**	**106.55**
Vehicle insurance model	Discount% (zero-claims) – Third-party	1,500	1,350	1,200	1,050	900	750	750	750	750	750
	Discounted total:	**1,408.45**	**1,190.24**	**993.42**	**816.19**	**656.89**	**514.00**	**482.63**	**453.17**	**425.51**	**399.54**
Fuel consumption model	Fuel consumption (L/km)	0.076687117	0.07668712	0.07668712	0.076687117	0.076687117	0.076687117	0.07668712	0.07668712	0.07668712	0.07668712
	Petrol price (SAR/litre)	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18
	Energy consumption cost (SAR/year)	4,179.45	4,179.45	4,179.45	4,179.45	4,179.45	4,179.45	4,179.45	4,179.45	4,179.45	4,179.45
	Discounted total:	**3,924.36**	**3,684.85**	**3,459.95**	**3,248.78**	**3,050.50**	**2,864.32**	**2,689.50**	**2,525.35**	**2,371.22**	**2,226.50**
Upfront cost	Down payment (10%)	10,327									
	Admin fees	929.43									
	Sales tax	15,490.5									
Bank interest loan model	Loan period (months)	12	12	12	12						
	Monthly installment	1,959	1,959	1,959	1,959						
	Annual payment	23,505.36	23,505.36	23,505.36	23,505.36						
	Baloon payment				25,818.00						
	Discounted annual payment:	**22,070.76**	**20,723.72**	**19,458.89**	**38,340.19**						
	Total	**48,817.69**	**20,723.72**	**19,458.89**	**38,340.19**						
Resale value											-15,209.33
	Yearly total (SAR):	**54,619.05**	**26,744.08**	**27,074.41**	**43,647.32**	**5,020.45**	**5,653.44**	**3,300.83**	**4,246.20**	**4,056.67**	**(11,624.91)**
	Total cost ownership (SAR):										**162,737.5**

Table A4. Evolution of the cost components during the 10-year assessment period for the hybrid SUV.

Driving	Lifetime (years) / Mileage (km)	Yr1 25,000	Yr2 50,000	Yr3 75,000	Yr4 100,000	Yr5 125,000	Yr6 150,000	Yr7 175,000	Yr8 200,000	Yr9 225,000	Yr10 250,000
Maintenance and repair model	Basic maintenance, including labor, parts fees & VAT (15%)	272.1	1,000.1	1,455.1	1,000.1	1,455.1	1,000.1	-	1,455.1	-	1,455.1
	12v battery (every four years)				299.0				299.0		
	Tires (every three years)			2,020.7			2,020.7			2,020.7	
	Total:	272.1	1,000.1	3,475.8	1,299.1	1,455.1	3,020.8	-	1,754.1	2,020.7	1,455.1
	Discounted total:	**255.5**	**881.7**	**2,877.4**	**1,009.8**	**1,062.0**	**2,070.3**	**-**	**1,059.9**	**1,146.5**	**775.2**
Vehicle tax model	Annual fees to vehicle driving licenses as per fuel efficiency (SAR)	-	-	-	-	-	-	-	-	-	-
	Private vehicle registration (SAR)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Driving License (SAR)	-	-	-	-	-	-	-	-	-	-
	Registration plates (SAR)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Total	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
	Discounted total:	**187.8**	**176.3**	**165.6**	**155.5**	**146.0**	**137.1**	**128.7**	**120.8**	**113.5**	**106.5**
Vehicle insurance model	Discount% (zero-claims) – Third-party	1,500.0	1,350.0	1,200.0	1,050.0	900.0	750.0	750.0	750.0	750.0	750.0
	Discounted total:	**1,408.5**	**1,190.2**	**993.4**	**816.2**	**656.9**	**514.0**	**482.6**	**453.2**	**425.5**	**399.5**
Fuel consumption model	Fuel consumption (L/km)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Petrol price (SAR/litre)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
	Energy consumption cost (SAR/year)	3,068.7	3,068.7	3,068.7	3,068.7	3,068.7	3,068.7	3,068.7	3,068.7	3,068.7	3,068.7
	Discounted total:	**2,881.4**	**2,705.5**	**2,540.4**	**2,385.4**	**2,239.8**	**2,103.1**	**1,974.7**	**1,854.2**	**1,741.0**	**1,634.8**
Upfront cost	Down payment (10%)	11,884.0									
	Admin fees	1,069.6									
	Sales tax	17,826.0									
Bank interest loan model	Loan period (months)	12.0	12.0	12.0	12.0						
	Monthly installment	2,254.1	2,254.1	2,254.1	2,254.1						
	Annual payment	27,049.2	27,049.2	27,049.2	27,049.2						
	Baloon payment				29,710.0						
	Discounted annual payment:	**25,398.3**	**23,848.2**	**22,392.7**	**44,120.2**						
	Total	**56,177.9**	**23,848.2**	**22,392.7**	**44,120.2**						
Resale value											(16,434.6)
	Yearly total (SAR):	**60,911.0**	**28,802.0**	**28,969.5**	**48,487.1**	**4,104.7**	**4,824.4**	**2,586.1**	**3,488.1**	**3,426.5**	**(13,518.6)**
	Total cost ownership (SAR):										172,080.8

About the Authors

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Michael is a Lead at KAPSARC, working on the life cycle sustainability assessment of transport and energy systems. His focus is on conventional and alternative powertrain systems, with a special interest in low-carbon fuels and energy pathways. He previously served as a Researcher at the Royal Institute of Technology (KTH) and Vrije Universiteit Brussel (VUB) on several Horizon 2020 transport research projects. Michael holds a Ph.D. in Engineering Sciences from VUB.

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Yagyavalk is an energy professional with more than seven years of experience in the transportation and electricity domain. Bhatt leads the project "The Role of Clean Energy Policies: Trends in India's Transport Sector," which aims to estimate India's transport energy demand and its potential impact on the crude oil supply chain. His expertise includes energy policy, energy economics, transport modeling, impact analysis of transport policies, energy transition in emerging economies, renewable energy, and cost-benefit analysis of the transport and electricity sectors. He has authored and contributed to numerous research papers and studies related to these fields.

About the Project

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

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