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Discussion Paper

Life Cycle Assessment of Road Freight Decarbonization in Saudi Arabia

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December 2024 | Doi: 10.30573/KS--2024-DP63

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Key Insights

- Conducted LCA of truck powertrains in Saudi Arabia's freight sector.
- Compared ICEVs, HEVs, BEVs, and FCEVs under BAU and low-carbon energy scenarios.
- Hybrid trucks reduce the most GHG emissions under Saudi Arabia's current energy landscape.
- BEVs offer the greatest GHG emission reductions as renewable energy increases.
- Larger trucks reduce energy consumption and GHG emissions per ton-kilometer due to economies of scale.

Abstract

The Kingdom of Saudi Arabia (KSA) is committed to transitioning towards a diversified, low-carbon economy, necessitating the decarbonization of its road freight sector, which is a significant source of domestic energy consumption and greenhouse gas (GHG) emissions. This study addresses the critical need to evaluate and compare the life cycle climate impacts of current and alternative truck powertrain technologies within KSA. We conducted a comparative life cycle assessment (LCA) of various truck powertrains, including internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs).

The assessment considered two scenarios aligned with KSA's Vision 2030: a business-as-usual (BAU) scenario with a static energy mix and a low carbon (LC) scenario incorporating projected increases in renewable energy and shifts in hydrogen production methods. Our analysis revealed that under the BAU scenario, hybrid trucks offer the most significant GHG emission reductions compared to ICE trucks, without requiring substantial new infrastructure. However, as the energy mix incorporates more renewables in the LC scenario, zero-emission powertrains, particularly BEVs, demonstrate greater potential for reducing emissions across light-, medium-, and heavy-duty trucks. While FCEVs also contribute to emissions reductions, their effectiveness depends on the carbon intensity of hydrogen production pathways. The findings highlight the importance of decarbonizing the energy supply and developing appropriate infrastructure to maximize the benefits of alternative powertrains. Crucially, leveraging economies of scale, using larger trucks with greater payload capacity significantly reduces energy consumption and GHG emissions per ton-kilometer. Therefore, adopting larger, low- or zero-emission trucks where feasible can enhance the decarbonization of road freight.

Keywords: Alternative powertrains, Trucks, LCA, Road transport, Electric vehicles, Vision 2030.

1. Introduction

The road freight transportation sector is a significant contributor to greenhouse gas (GHG) emissions globally, accounting for approximately 7% of total energy-related emissions (IEA 2017). In 2018, exhaust emissions from heavy-duty vehicles (HDV) reached 1,770 Mt of CO_2 emissions, accounting for over 5% of total energy-related CO_2 emissions for that year (IEA 2019). Furthermore, global GHG emissions from HDVs have grown at an annual rate of 2.6% since 2000 (IEA 2023). This increase can be attributed to rising economic activity and demand for goods, which have offset the reductions achieved through the adoption of more efficient vehicle technologies.

In the Kingdom of Saudi Arabia (KSA), the need for sustainable transportation solutions is increasingly urgent. Being the world's top energy producer and the largest economy in the Middle East and North Africa (MENA) region, the Kingdom heavily relies on fossil fuels as an enabler for its domestic economic development (Al-Saidi 2022). Transportation represents a critical area for improvement, as it is the second-largest domestic carbon-emitting sector in KSA, with most of its emissions coming from road transport (26%) (Kamboj et al. 2024; Shannak, Mikayilov, and Dua 2022).

In 2021, Saudi Arabia pledged to achieve net-zero GHG emissions by 2060 (Al-Sinan, Bubshait, and Alamri 2023). In the meantime, the Kingdom's Vision 2030 strategy aims to transform KSA into a major logistics hub in the MENA region, while promoting diversified energy utilization and sustainable practices (KSA 2016; MOTLS 2024). To achieve its diverse policy objectives, Saudi Arabia needs to explore different technology options in road freight transportation. At present, trucking serves as the backbone of KSA's freight system and is dominated by internal combustion engine vehicles (ICEVs). However, alternative powertrains, such as hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs), are emerging as viable options for reducing GHG emissions and enhancing efficiency in freight transport.

To identify which vehicle technologies offer the best opportunity for Saudi Arabia to meet its policy targets, it is essential to evaluate their overall emission impact comprehensively. Hence, in this study, we employ the life cycle assessment (LCA) methodology, which has been widely used to compare the climate and environmental impacts of vehicle technologies (Sacchi, Bauer, and Cox 2021; Meyer 2020). The literature on LCA of transportation technologies has identified several key trends, particularly the increasing emphasis on low-carbon energy usage and the integration of alternative powertrains. Studies have shown that powering hybrid, electric, and hydrogen vehicles with low-carbon energy can significantly reduce GHG emissions compared to traditional ICEVs, highlighting their potential to contribute to a low-carbon future (Booto, Aamodt Espegren, and Hancke 2021; Sacchi, Bauer, and Cox 2021). However, several issues and gaps remain in the existing literature.

First, most LCA research tends to focus on passenger vehicles, while limited attention has been given to the road freight transport sector, despite its critical role in economic activities and significant contribution to GHG emissions. Second, while many studies have examined the environmental impacts of vehicle technologies in developed countries, there is a lack of comprehensive assessments in developing regions, particularly in the Middle East and North Africa – the world's major oil-exporting regions (IMF 2003). In the context of Saudi Arabia, although KSA is currently a leading producer and exporter of fossil fuels, it has also set ambitious targets to diversify its energy mix and develop renewable energy sources. Given the Kingdom's fast-changing energy landscape, it is essential to explore how alternative powertrain technologies can be effectively integrated

into Saudi Arabia's future transportation system, aligning with national goals for sustainability and GHG emissions reduction.

We aim to address these identified gaps by evaluating and comparing the life cycle climate impacts of current and alternative truck powertrain technologies in Saudi Arabia. The purpose is to conduct a comparative LCA of various truck powertrain technologies within the road freight transport sector in the KSA context. This assessment aims to provide empirical evidence regarding the global warming potential (GWP) of these technologies, facilitating informed decision-making for stakeholders and policymakers. The following objectives are addressed:

- To evaluate the life cycle GWP impacts of current and alternative truck powertrain technologies.
- To analyze the production, use, and end-of-life phases of each powertrain technology to identify key areas for improvement and potential climate benefits.
- To compare the relative environmental performance of these technologies against the backdrop of Saudi Arabia's current energy landscape.
- To provide recommendations for policymakers in KSA and globally, aimed at promoting the adoption of sustainable transportation technologies in the road freight sector.

By identifying the benefits and challenges of integrating alternative powertrains, this study will enhance the understanding of the climate performance of different powertrain technologies in KSA's road freight transport sector, and support the Kingdom's Vision 2030 goals for sustainability and economic diversification. Moreover, this research contributes to the broader field of LCA by underscoring the importance of localized studies that reflect unique regional energy contexts.

The remainder of the manuscript is organized as follows: Section 2 provides the methodological details and materials for the powertrain technologies and production pathways for fuel and energy, including data sources, system boundaries, and key assumptions. Section 3 presents and discusses the full life cycle results. The concluding section summarizes the key findings and offers insights to guide policymakers, industry leaders, and consumers toward more sustainable road freight practices, both in Saudi Arabia and globally.

2. Material and Methods

This study evaluated the life cycle GHG emissions of various truck powertrain technologies in accordance with the ISO 14040 LCA framework (ISO 2020b; ISO 2020a). We employed a process-based LCA using an attributional approach, structured around the four steps of conducting an LCA: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation. These steps are interrelated, and the assessment was conducted iteratively throughout the process.

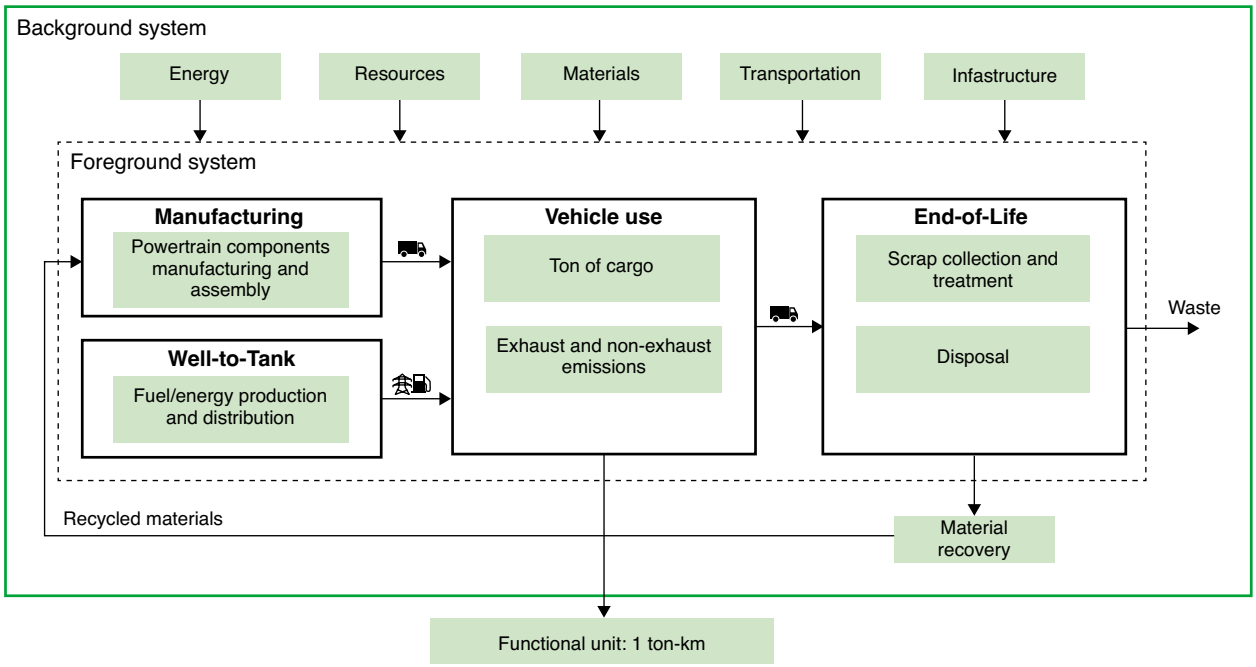
While the attributional approach has limitations – such as its static nature, which may not capture future changes or broader system impacts (these are largely outside the scope of this study) – the approach offers strengths, particularly in providing a comprehensive evaluation of emissions across a product's life cycle (Ekvall 2019). Additionally, it facilitates standardized comparisons, improving the reliability and transparency of results, which are seen as key factors for informed decision-making and policy development.

2.1 Goal, Scope, and General Considerations

The goal of this LCA is to conduct a comparative assessment of various truck powertrain technologies within the context of Saudi Arabia's current energy landscape. This assessment covers the global warming potential (GWP) impacts associated with the production, use, and end-of-life phases of the following powertrain technologies: diesel-powered internal combustion engine vehicles (ICEVs), diesel-powered hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs). For each of these technologies, we assessed light-duty trucks (<3.5 tons), medium-duty trucks (3.5-15 tons), and heavy-duty trucks (>15 tons).

Figure 1 illustrates the study's system boundary and simplified flow diagram of the product system. The background system includes external processes that support the primary activities analyzed, such as upstream processes for energy, materials, and services necessary for the production, use, and disposal of the powertrain options. In this study, the background system encompasses activities related to resources, energy, materials, transportation, infrastructure, and waste, modeled using average datasets from the ecoinvent v3.10 database. In contrast, the foreground system focuses on processes directly related to the product, which in this study includes manufacturing of powertrain components, operational fuel/energy, vehicle use, vehicle maintenance, emissions, and end-of-life (EoL) disposal of the powertrain options. Datasets for modeling the foreground system have been derived from scientific literature and the ecoinvent database.

Figure 1. Simplified flow diagram and system boundary of the powertrain options (product system).



Source: Authors' estimation.

Specifically, the assessment examines the following stages: production of key powertrain components, fuels and energy production, vehicle use, and EoL treatment and disposal. The production of key powertrain components includes the raw material extraction, processing, and manufacturing of components unique to each powertrain technology, such as engines, electric motors, battery packs, and fuel cells (see Table 1). The fuel/energy production and distribution (well-to-tank in Figure 1) includes the extraction processes for fuel and energy resources, along with their production and distribution to the point of use. The vehicle use phase evaluates the operational performance of the vehicles, focusing on the trucks' operational fuel consumption and emissions based on typical usage patterns in the Middle East region. The EoL phase assesses the treatment and disposal of powertrain components at the end of their operational life.

Table 1. Overview of key truck components.

Category	Components	Used by	System boundary*
Chassis system	Frame	All	X
	Suspension	All	X
	Braking system	All	X
	Wheels and tires	All	X
Cabin	Cabin	All	X
Powertrain	IC engine	ICEV-g, ICEV-d, HEV-d**	Y
	Gearbox	All	X
	Retarder	All	X
	Exhaust system	ICEV-g, ICEV-d, HEV-d	Y
	Transmission system	All	X
	Fuel cell system	FCEV	Y
	Electric motor	BEV, FCEV, HEV-d	Y
	Converter	BEV, FCEV	Y
	Inverter	BEV, FCEV, HEV-d	Y
	Charger	BEV, PHEV-d	Y
	Power distribution unit	BEV, FCEV, HEV-d	Y
	Fuel tank, compressed H_2, 700bar	FCEV	Y
	Fuel tank, diesel	ICEV-g, ICEV-d, HEV-d	Y
	Lithium-ion battery	BEV, FCEV, HEV-d	Y
	Power electronics	All	X

* *Where Y = considered and X = not considered.*

** *ICEV–g (internal combustion engine vehicle – gasoline), ICEV–d (internal combustion engine vehicle – diesel, HEV–d (hybrid electric vehicle – diesel).*

Table 1 categorizes the main components of the truck options, indicating which technologies utilize each component and whether they fall within the defined system boundary for the LCA. Components common to all truck options are excluded from the study, as their environmental impacts are assumed to be similar across the different vehicle technologies when produced using the same global average energy mix. The decision to exclude these components from the system boundary is considered a modeling choice, and the authors believe that it would not significantly affect the comparative analysis of the powertrain technologies under consideration.

The functional unit is defined as 1 ton-kilometer (tkm), representing the transport of 1 metric ton of cargo over 1 kilometer. This functional unit was selected to provide a consistent basis for comparing the environmental performance of different truck powertrain technologies across the truck categories. It enables an equitable assessment of each technology's efficiency in freight transport, aligning with the study's broader goal of identifying sustainable powertrain options in Saudi Arabia's trucking sector. By using tkm, the analysis allows for direct comparisons across vehicle types and informs stakeholders about their climate performance in real-world operational contexts.

2.2 Production Phase – Powertrain Manufacture and Assembly

As a modeling choice, we have excluded all components common to the trucks, focusing on their unique powertrain components, as shown in Table 1. We determined the weights and replacement schedules for the powertrain components using data from the scientific literature (Sacchi, Bauer, and Cox 2021).

For the material composition and background system data, we assumed they were identical to those for light-duty vehicles found in the ecoinvent v3.10 database and in the literature (Candelaresi et al. 2021; Notter et al. 2010). This approach ensures consistency and reliability in our assessment. In general, the internal combustion engine (ICE), exhaust system, and diesel fuel tank are assumed to have the same underlying design for the hybrid and ICEV trucks, with the differences in their weights reflecting the varied component sizes required for different truck categories. The analysis used the "internal combustion engine production, passenger car GLO [global]" process from the ecoinvent database as the starting point for modeling the assessed conventional powertrain components. Using supplementary data from Notter et al. (2010), the material composition for the ICE was derived, and the original inventory was adapted with respect to the engine power of the different trucks. Following a similar approach in Candelaresi et al. (2021), the exhaust system and fuel tank are scaled in accordance with the engine power and tank capacity, respectively.

The electric powertrain components for BEV trucks consist of six components: an electric motor, onboard charger, inverter, converter, Li-ion battery (LIB), and power distribution unit. For HEV and FCEV trucks, we modeled a modified electric drivetrain. Specifically, the FCEV omitted the onboard charger, while the HEV lacked the onboard charger and converter. The production datasets for these components were modeled based on their corresponding processes in the ecoinvent database, ensuring accuracy and consistency in our analysis. In addition to the modified electric drivetrain, the FCEV features a hybrid powertrain that combines a polymer electrolyte membrane (PEM) fuel cell with a power-optimized LIB. The PEM fuel cell serves as the primary power source, providing continuous electricity for propulsion and auxiliary systems, while the LIB pack supplies additional power during peak demand. Material inventory data from Cox et al. (2020) were used to model the PEM fuel cell system, which has a most likely power output of 114 kW.

Similarly, the production datasets for the LIB packs used in BEVs, FCEVs, and HEVs are sourced from the ecoinvent v3.10 database, with material inventories derived from studies Dai et al. (2018), Dai et al. (2019), and Winjobi, Dai, and Kelly (2020). For BEVs and FCEVs, we assumed the installation of a lithium nickel manganese cobalt oxide (LiNi0.8Mn0.1Co0.1O2) LIB pack (NMC 811), with an energy density of 0.149 kWh/kg. In contrast, HEVs are assumed to utilize a lithium iron phosphate (LiFePO4) LIB pack (LFP), with an energy density of 0.089 kWh/kg. NMC batteries are selected for BEVs due to their high energy density, providing longer ranges and better performance. In contrast, LFP batteries are preferred for HEVs because of their lower cost, thermal stability, and durability, which suit the mixed driving conditions of HEVs.

Considering Saudi Arabia's unique conditions, such as the expected impact of extreme temperatures on battery performance, we modeled the potential for battery replacement using the ratio of vehicle lifetime kilometers to battery lifetime kilometers (see Table S1 in the supplementary material). Regarding temperature impacts, we assumed that the EVs employed state-of-the-art battery thermal management systems, resulting in minimal degradation in performance (Nyamathulla and Dhanamjayulu 2024; Neubauer and Wood 2014). Furthermore, research indicates that the energy consumption from air conditioning (AC) systems in vehicles operating in KSA does not significantly alter the overall LCA results (Zhao et al. 2024). This is likely because the total cooling load for AC systems in similar vehicle categories, operating under comparable conditions, is generally independent of the powertrain technology. However, this factor was implicitly accounted for by incorporating regional-specific fuel consumption based on the IEA Mobility Model (IEA 2018).

2.3 Use Phase – Well-to-Tank Fuel/ Energy Production

The diesel production process begins with the extraction of crude oil from both onshore and offshore wells in Saudi Arabia. According to the ecoinvent database for KSA, approximately 35.7% of crude oil is sourced from offshore operations, while 64.3% is extracted onshore. During extraction, associated natural gas is co-produced, of which 53% is combusted on-site for power generation, 15% is flared, and 32% is vented. The extraction also utilizes 31% grid electricity and 1% on-site diesel generators for energy needs requirements (Meili, Niels, and Wenzel 2023; ecoinvent 2023). After extraction, crude oil is transported via pipelines to local refineries, where it undergoes distillation and conversion processes to produce various petroleum products, including diesel. Specific inventories related to crude oil extraction, transportation, and conversion to diesel were sourced from the ecoinvent v3.10 database and the Archie Initiative (Meili, Niels, and Wenzel 2023; ecoinvent 2023; The Archie Initiative 2021).

The process for electricity generation is based on the KAPSARC Power Model (Elshurafa, Petitet, and Felder 2023). In 2022, the KSA electricity mix was modeled as approximately 80% natural gas, 18% oil, and the remaining from wind and solar energy sources. The carbon intensity of the mix was estimated as 735.2 gCO_2-eq/kWh (Figure 2) using the IPCC 2021 impact assessment method at the GWP100 timeframe (IPCC 2021).

In the current energy landscape of KSA, hydrogen (H_2) is primarily produced through steam methane reforming (SMR) of natural gas, with CO_2 venting. We modeled this production process based on the ecoinvent process for "hydrogen production, steam reforming RoW," with hydrogen being pressurized to 200 bar. In this process, natural gas serves as both the feedstock for the reaction and the fuel for the furnace, utilizing the ecoinvent process "market for natural gas, high pressure SA" to reflect the KSA context. Technical details of the SMR process employed in this assessment are outlined in Antonini et al. (2020). Additionally, the model incorporates a compression step for hydrogen to 700 bar, informed by the dataset presented in Cox et al. (2020).

2.4 Use Phase – Tank-to-Wheel Energy Consumption

Data on tank-to-wheel energy consumption are sourced from IEA's Mobility Model (MoMo) database. The IEA Mobility Model assesses transportation-related energy consumption and environmental impacts. The MoMo is integrated with the IEA's annual Energy Technology Perspectives optimization framework, which is based on the TIMES modeling system (IEA 2018). The version utilized in this study corresponds to the IEA's 2020 MoMo iteration, which contributes to the publication of the Energy Technology Perspectives 2020 (IEA 2020). As there is no publicly available detailed data on Saudi Arabia's road freight transportation sector, we used IEA's estimations for the Middle East region as an alternative. The Middle East region in MoMo consists of 12 countries: Bahrain, Iraq, the Islamic Republic of Iran, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, the Syrian Arab Republic, the United Arab Emirates, and Yemen. Since Saudi Arabia is the largest economy in the Middle East, accounting for around 35% of the region's total GDP in 2018 (World Bank 2024), we believe MoMo's Middle East estimates can reasonably reflect the conditions in Saudi Arabia. Furthermore, these countries share similar

climates and driving conditions that differ significantly from global averages.

We use IEA's categorization for light-, medium- and heavy-duty trucks consistent with data availability.

Detailed parameters considered include average energy consumption, lifetime vehicle kilometers, and average vehicle occupancy across vehicle categories. These values, reported in Table 2, are utilized to calculate the per-tkm fuel efficiency for the purpose of this study.

Table 2. Tank-to-wheel energy and truck utilization data used in this study.

Powertrain	Category	Consumption (MJ/km)	Lifetime vkm	Occupancy (average tons per vehicle)	Consumption (MJ/ton-km)
ICEV	Truck (0-3.5t)	3.2172	253126	0.6709	4.7953
	Truck (3.5-15t)	10.0528	373992	7.9692	1.2615
	Truck (15t+)	17.1159	728274	17.1320	0.9991
HEV	Truck (0-3.5t)	2.3152	253126	0.6709	3.4509
	Truck (3.5-15t)	7.1836	373992	7.9692	0.9014
	Truck (15t+)	12.2157	728274	17.1320	0.7130
BEV	Truck (0-3.5t)	2.5691	253126	0.6709	3.8293
	Truck (3.5-15t)	4.0829	373992	7.9692	0.5123
	Truck (15t+)	6.9280	728274	17.1320	0.4044
FCEV	Truck (0-3.5t)	2.1732	253126	0.6709	3.2392
	Truck (3.5-15t)	6.7486	373992	7.9692	0.8468
	Truck (15t+)	11.4906	728274	17.1320	0.6707

2.5 Use Phase-Exhaust and Non-Exhaust Emissions

Exhaust emissions are calculated using data from the ecoinvent dataset, which incorporates emission factors derived from the HBEFA model (HBEFA 2017). The analysis assumed compliance with Euro 5 emission standards, with emissions being fuel-dependent and influenced by the quantity of fuel consumed in Table 2. Non-exhaust emissions resulting from tire, brake, and road wear were treated as separate datasets in the ecoinvent database. These emissions are calculated based on average vehicle weights and load factors obtained from the International Energy Agency (IEA) report for the Middle East (IEA 2020). Specific quantities for non-exhaust emissions were quantified as follows: 8.13E-9 kg/kg GVW*km for brake wear, 7E-9 kg/kg GVW*km for road wear, and 8.055E-8 kg/kg GVW*km for tire wear (Dore, Montalvo, and Saarinen 2023; ecoinvent 2023).

2.6 End-of-Life Treatment and Disposal

Following the ecoinvent cut-off modeling approach, we considered only the efforts to dismantle, treat, and dispose of waste flows at the end of the life of the powertrain components. This implies that material recovery was not considered at this stage of the model due to limited access to reliable data for the Saudi context. However, the use of recycling materials was considered burden-free in the production stage of the powertrain components, as implemented in the ecoinvent cut-off modeling database (Ekvall et al. 2020; ecoinvent 2023).

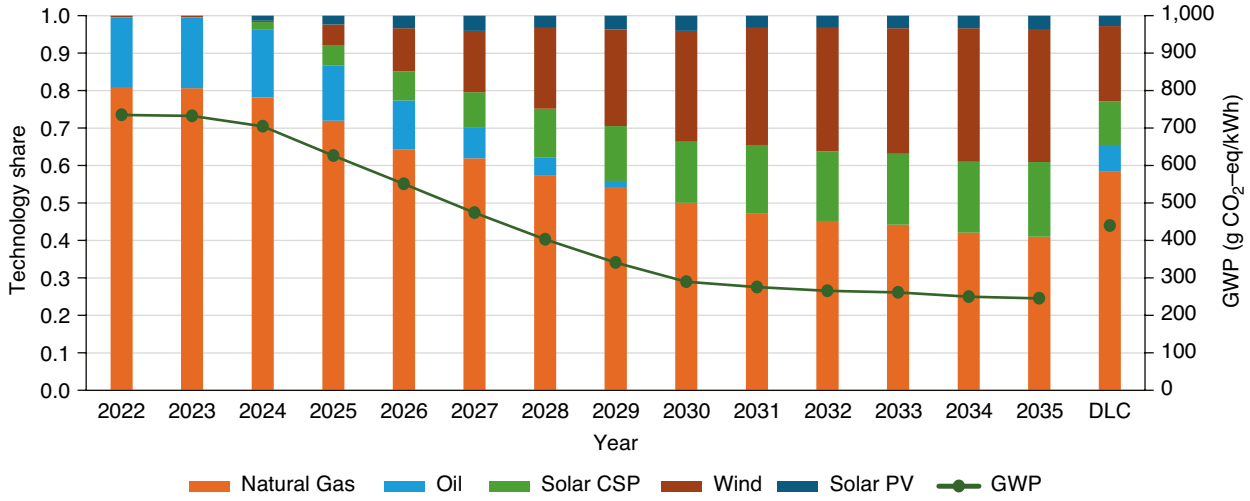
We recognize that recycling, especially for materials like those in lithium-ion batteries (used in BEVs and FCEVs), could offer significant climate and environmental benefits by reducing the need for virgin material extraction (Guzek et al. 2024). However, including these benefits at the end-of-life stage would risk double-counting, as recycled materials have already been treated as burden-free during production. Given the lack of reliable regional recycling data, this approach was necessary to avoid overstating the benefits. Future research could incorporate region-specific recycling data to more fully capture the life cycle impacts, particularly once recycling infrastructure for electric vehicle batteries is established in Saudi Arabia.

2.7 Impact Assessment

In the impact assessment phase, the IPCC (2021) impact assessment method is employed to evaluate climate change impacts, specifically using the global warming potential (GWP) over a 100-year timeframe (GWP100). This approach allows for a comprehensive understanding of GHG emissions associated with the life cycle of the powertrains.

The well-to-tank (WTT) fuel and energy production burden of different fuels and electricity will change during the lifespan of the trucks, influenced by changes in production pathways and stated regulations promoting low-carbon fuels. For example, as the Kingdom progresses towards its Vision 2030 goals, the production of hydrogen may shift from traditional steam methane reforming to greener methods, such as electrolysis powered by wind and solar energy (Shabaneh et al. 2024). Additionally, the increased integration of renewable energy sources, such as solar and wind, into the electricity grid will likely reduce the carbon intensity of electricity used for BEV trucks. Regulations mandating lower carbon emissions could further incentivize the adoption of carbon capture and storage for oil refineries, leading to a gradual decrease in the WTT emissions associated with both conventional and alternative powertrains throughout the trucks' operational life.

Figure 2. Saudia Arabia's current and future electricity mix at medium voltage level and global warming potential (GWP) per kilowatt hour.

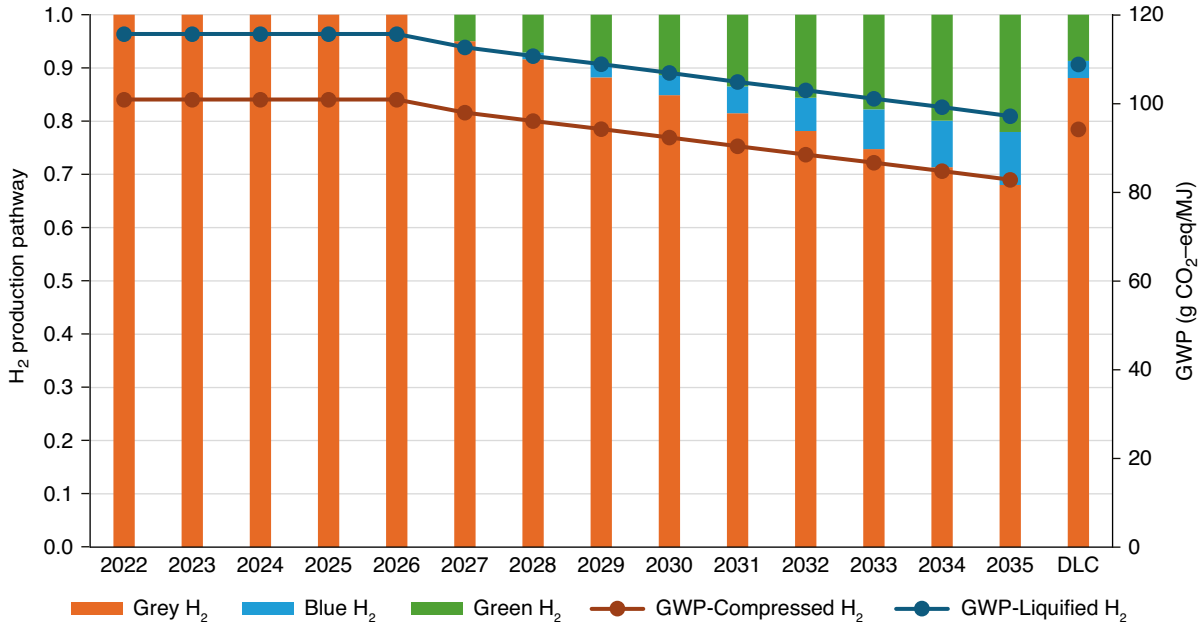


Legend: DLC = dynamic low carbon scenario, GWP = global warming potential.

Source: Authors' estimation.

In assessing the temporal variation in upstream impacts of fuel and energy production during the truck usage period from 2022 to 2035 (see Figure 2), we introduced two scenarios to evaluate future changes in the energy system of KSA, which are aligned with Vision 2030. The first scenario – business-as-usual (BAU) – assumes a static fuel and energy system with no changes in carbon intensity for operational fuel/electricity over the truck's lifespan. The carbon intensity for the year 2022 is utilized for the BAU and is assumed to be the baseline condition for all powertrain components in this study. The second scenario – low carbon (LC) – models the vehicle use stage by considering projected annual changes in the share of low-carbon and renewable energy sources in the future fuel and energy system of KSA based on stated initiatives (e.g., see Al-Sinan, Bubshait, and Alamri 2023; Hassan et al. 2024; Shehri et al. 2022).

Figure 3. Saudia Arabia's current and future market mix for hydrogen production with global warming potential (GWP) per megajoule (MJ).



Legend: DLC = dynamic low carbon scenario, GWP = global warming potential.

Source: Authors' estimation.

Similarly, in forecasting the market mix for hydrogen production in the low-carbon scenario, informed by the report "Hydrogen Forecast to 2050" (DNV 2022), it was projected that by 2035, electricity-based green hydrogen would account for 22% of total production, driven by increased renewable energy capacity and decreasing costs (Shabaneh et al. 2024). Initially, blue hydrogen – produced from natural gas with carbon capture – was projected to play a substantial role, comprising about 10% of production by 2035. However, its competitiveness is predicted to decline as renewable energy becomes more prevalent and affordable. The remaining production was anticipated to be grey hydrogen, though its share is expected to decrease as cleaner alternatives become more viable and widespread. Figure 3 shows the projected annual market mix for H_2 production from 2022 to 2035 with global warming impacts per megajoule (MJ).

We performed a sensitivity analysis on the following parameters: (1) the vehicle lifetime vkm (+/-20%), (2) energy consumption (+/-20%), and (3) a deep decarbonization pathway considering 100% renewable electricity, utilizing 70% solar and 30% wind energy, for the BEV trucks and green hydrogen production via water electrolysis. All other background data for energy production remains consistent with the BAU scenario.

3. Results and Discussion

In this section, we present the results of the LCA and the subsequent sensitivity analysis, which evaluate the GHG emissions associated with the different powertrains assessed across different truck sizes and energy scenarios. We focus on BEVs, FCEVs, HEVs, and ICEVs for light, medium, and heavy-duty trucks. The findings include a detailed comparison of decarbonization potential, with emphasis on how factors such as size, energy source, energy consumption, and vehicle utilization (such as loading factor and lifetime vkm) influence overall emissions. The sensitivity analysis further illustrates the robustness of these results by assessing the impact of varying key parameters, providing a comprehensive understanding of how each powertrain technology performs under different conditions for the impact category global warming potential (GWP).

3.1 Decarbonization Potential of Alternative Truck Powertrains in KSA

Table 3 shows the potential for reducing GHG emissions from the powertrains assessed, expressed in kg of CO_2 equivalent per ton-km. The results reveal significant insights into the GHG emissions associated with various powertrains under the two scenarios: business-as-usual (BAU) and low carbon (LC). The main difference between these scenarios lies in the static nature of the BAU energy mix compared to the dynamic nature regarding the share of renewables in the LC mix, which accounts for anticipated yearly changes in the KSA energy landscape until 2035.

Table 3. Decarbonization potential of alternative powertrains for road freight considering KSA's current and near-future (2035) energy landscape.

		Business-as-usual scenario			Low carbon scenario		
Truck sizes	**Powertrains**	**GWP (kg CO_2-eq / ton-km**	**Rank**	**GHG reduction potential**	**GWP (kg CO_2-eq / ton-km**	**Rank**	**GHG reduction potential**
LDT (0-3.5t)	BEVs	0.886	4	111%	0.551	4	31%
	FCEVs	0.359	2	−14%	0.353	2	−16%
	HEVs	0.312	1	−26%	0.31	1	−26%
	ICEVs	0.42	3	0%	0.418	3	−1%
MDT (3.5-15t)	BEVs	0.117	4	7%	0.0724	1	−34%
	FCEVs	0.0892	2	−19%	0.0874	3	−20%
	HEVs	0.08	1	−27%	0.0796	2	−28%
	ICEVs	0.11	3	0%	0.109	4	−1%
HDT (15t+)	BEVs	0.0934	4	9%	0.058	1	−32%
	FCEVs	0.07	2	−18%	0.0686	3	−20%
	HEVs	0.0617	1	−28%	0.0614	2	−28%
	ICEVs	0.0856	3	0%	0.0851	4	−1%

Table 3 considers the ICEV vehicle in the BAU scenario for each truck category as the baseline for comparison. Hence, negative and positive percentage values indicate emission reductions and increases compared to the baseline, respectively. The top two performing powertrains are highlighted for each truck category across the evaluated energy scenarios.

For light duty trucks (LDTs), HEVs ranked first in both scenarios, with a GWP of 0.312 kg CO_2-eq/ton-km in the BAU scenario and 0.310 kg CO_2-eq/ton-km in the DLC scenario, resulting in a GHG reduction potential of -26% compared to ICEVs baseline. FCEVs rank second with a GWP of 0.359 kg CO_2-eq/ton-km in the BAU scenario and a slight decrease to 0.353 kg CO_2-eq/ton-km in the DLC scenario, reflecting GHG reduction potentials of −16%. ICEVs maintain a GWP of 0.420 kg CO_2-eq/ton-km in the BAU scenario, with minimal change in the DLC scenario. In contrast, BEVs rank fourth with a GWP of 0.886 kg CO_2-eq/ton-km in the BAU scenario, decreasing to 0.551 kg CO_2-eq/ton-km in the DLC scenario, indicating the largest relative GHG reduction potential compared to the other powertrains. However, the emission intensity of BEVs for LDTs remains higher compared to other powertrains, even in the DLC scenario.

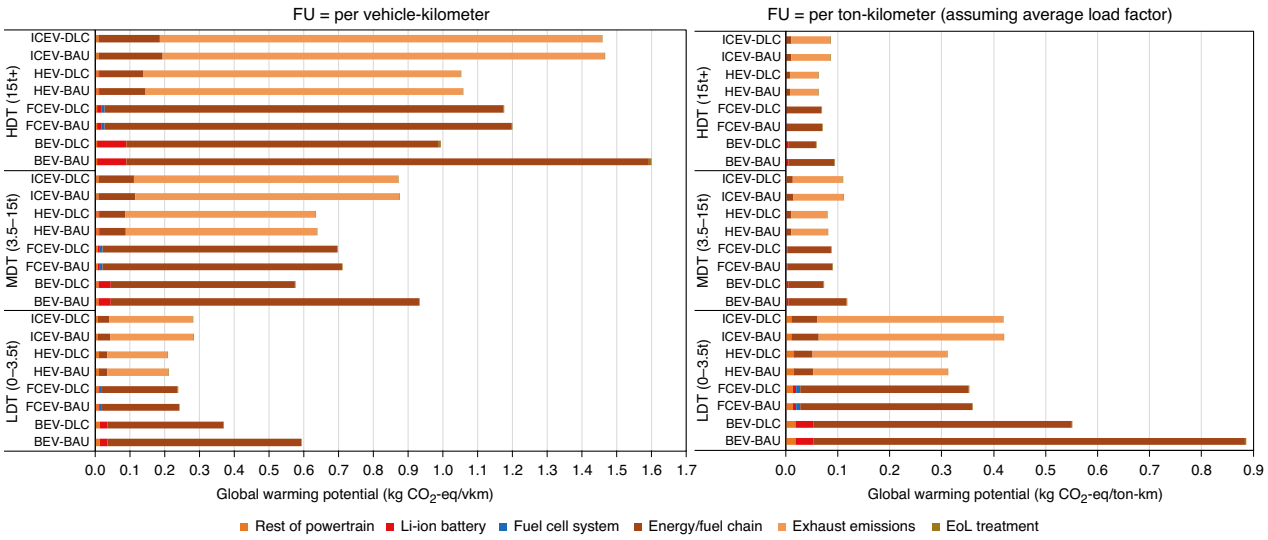
In the medium-duty trucks (MDT) category, the BEV improved its rank from fourth to first in the DLC scenario. It exhibits a GWP of 0.117 kg CO_2-eq/ton-km in the BAU scenario, dropping to 0.072 kg CO_2-eq/ton-km in the DLC scenario, with a GHG reduction potential of −34% compared to ICEVs baseline. FCEVs show a GWP of 0.0892 kg CO_2-eq/ton-km in the BAU scenario, decreasing slightly to 0.0874 kg CO_2-eq/ton-km in the DLC scenario, with decarbonization potentials of −20%. HEVs dropped a rank from first to second in the DLC scenario. It maintains a GWP of 0.0800 kg CO_2-eq/ton-km in the BAU scenario, decreasing to 0.0796 kg CO_2-eq/ton-km in the DLC scenario, reflecting a GHG reduction potential of −28%.

Heavy-duty trucks (HDTs) exhibit similar trends as the MDTs. BEVs have a GWP of 0.0934 kg CO_2-eq/ton-km in the BAU scenario, reducing to 0.0580 kg CO_2-eq/ton-km in the DLC scenario, indicating a decarbonization potential of -32%. FCEVs show a GWP of 0.0700 kg CO_2-eq/ton-km in the BAU scenario, decreasing to 0.0686 kg CO_2 eq/ton-km in the DLC scenario, with GHG reduction potentials of -20%. HEVs led with the lowest GWP of 0.0617 kg CO_2-eq/ton-km in the BAU scenario but ranked second in the DLC scenario with a GWP of 0.0614 kg CO_2-eq/ton-km – indicating a -28% GHG reduction potential compared to ICEVs.

Overall, the analysis highlights the potential of alternative powertrains to reduce GHG emissions across truck categories. In the BAU scenario, HEVs serve as an ideal powertrain option to decarbonize road freight, thanks to the higher efficiency of its electric motor compared to the ICE powertrain (Zhuang et al. 2020). Without resorting to additional investment while utilizing existing fueling infrastructure, switching to HEVs could potentially reduce emission intensity by more than a quarter compared to baseline. On the other hand, as the grid gradually switches to renewable sources, zero-emission powertrain technologies will exhibit increasing decarbonization potential. While FCEVs offer some emission reduction promises, their effectiveness is limited compared to BEVs, especially for MDTs and HDTs, due to their relatively inefficient energy chain (Figure 4) and lower efficiency of their powertrain as reported in the literature (Sacchi, Bauer, and Cox 2021). In contrast, BEVs show higher emission intensity only for LDTs, which could be due to the relatively small load factor in this vehicle class.

Figure 4 decomposes the emission contributions across the powertrains and scenarios on a per tkm basis. From the contribution analysis, it is clear that different powertrains' GHG emissions depend on various components, processes, and stages of the vehicle life cycle. For BEVs and FCEVs, the production phase of their operational energy (referred to as the energy/fuel chain in Figure 2) is the most critical, contributing over 85% of their total GWP impacts. In contrast, the combustion phase (referred to as the exhaust emissions in Figure 2) is the most critical for the HEVs and ICEVs, accounting for 80% of their total GWP impact. Therefore, the future decarbonization potential of zero-emission powertrains in the road freight sector will heavily depend on the paces of adoption of renewables and low-carbon energy sources in the Kingdom's energy mix.

Figure 4. Contribution analysis of GHG emissions across powertrains assessed.



Source: Authors' estimation.

3.2 Impact of Truck Size on Decarbonizing Road Freight

Figure 4 compares per vehicle-km (left panel) and per ton-km (right panel) GHG emissions for all vehicle sizes in the two scenarios. The results suggest that although larger vehicles such as HDTs have greater emissions per km, once the payload is factored in, their global warming potential is much lower compared to smaller vehicles. For LDT BEVs, it shows a GWP of 0.551 kg CO_2-eq/ton-km in the DLC scenario, while MDTs and HDTs demonstrate much lower emissions at 0.072 kg and 0.0580 kg CO_2-eq/ton-km, respectively. Similar trends are observed with FCEVs and HEVs, where GWP decreases as the truck size increases.

The substantial reduction in GWP as vehicle sizes increase suggests that utilizing economy of scale could be a potential strategy to decarbonize road freight in Saudi Arabia. Given that the Kingdom heavily depends on road trucking for domestic transportation of goods (Xu and Dua 2023), logistics and fleet operators may contribute to climate change mitigation by transitioning to larger vehicles (e.g. replacing MDTs with HDTs in regional and long-haul applications). This shift would allow them to capitalize on the greater payload capacity, resulting in lower energy use and emissions on a tkm basis. The mitigation potential can be further improved if the powertrains of the large vehicles have low or zero emissions. This underscores the importance of policies to drive the adoption of low- and zero-carbon powertrains while investing in the required infrastructure and renewable energy sources to support the operation of these vehicles. Policymakers may consider regulatory measures, such as tax incentives or weight allowances, to promote the adoption of electric and FCEV trucks. In the meantime, transitioning to larger vehicles with alternative powertrains may generate further transportation benefits, such as less traffic and less congestion, as a smaller vehicle stock will be required if the average vehicle load factor is increased. However, policymakers also need to take caution and consider any potential challenges that may arise with the adoption of alternative powertrain heavy-duty trucks.

3.3 Implications for Sustainability and Efficiency

This section presents the findings from the sensitivity analysis, focusing on the GHG emissions associated with the various powertrains when selected parameters are varied. Special attention is given to the decarbonization potential of each powertrain type, highlighting how different factors – such as energy source, energy consumption, and vehicle utilization – impact GHG emissions. Table 4 reveals the impact of selected parameters on the decarbonization potential of different powertrain types. The baseline here is the total GWP impact of each powertrain in the BAU scenario. Negative values and positive values indicate a reduction and an increase in GHG emissions, respectively, compared to the baseline case (BAU).

Table 4. Sensitivity analysis results for decarbonization potential across powertrain types and scenarios.

Truck sizes	Powertrains	Total (BAU) (kg CO_2-eq / ton-km)	100% renewable electricity/H_2	+20% energy consumption	−20% energy consumption	+20% lifetime vkm	−20% lifetime vkm
LDT (0-3.5t)	BEV	0.886	−85.5%	18.8%	−18.8%	−1.0%	1.5%
	FCEV	0.359	−53.9%	18.4%	−18.4%	−1.3%	2.0%
	HEV	0.312	0.0%	18.6%	−18.6%	−0.9%	1.3%
	ICEV-d	0.420	0.0%	19.2%	−19.2%	−0.5%	0.7%
MDT(3.5-15t)	BEV	0.117	−86.5%	19.0%	−19.0%	−0.9%	1.3%
	FCEV	0.0892	−56.8%	19.4%	−19.4%	−0.5%	0.8%
	HEV	0.08	0.0%	18.9%	−18.9%	−0.3%	0.5%
	ICEV-d	0.11	0.0%	19.3%	−19.3%	−0.2%	0.3%
HDT (15t+)	BEV	0.0934	−85.7%	18.8%	−18.8%	−0.1%	0.1%
	FCEV	0.07	−57.3%	19.6%	−19.6%	−0.2%	0.3%
	HEV	0.0617	0.0%	19.4%	−19.4%	−0.2%	0.2%
	ICEV-d	0.0856	0.0%	19.6%	−19.6%	−0.1%	0.2%

The sensitivity analysis highlights several interesting insights. First, maximizing the use of clean energy sources as the grid switches to 100% renewables could significantly enhance the decarbonization potential of zero-emission vehicles, such as BEVs and FCEVs. With an 86% relative emissions reduction compared to the baseline, BEVs become the most preferred powertrain when the energy source is fully renewable. Second, energy consumption efficiency in the use phase is directly proportional to GHG emissions and remains a fundamental determinant of GWP for all powertrain options. Therefore, policymakers need to continue to push for the improvement of vehicle fuel efficiencies via measures such as establishing and updating fuel economy standards for the trucking sector, which currently do not existent in the Kingdom. Third, vehicle utilization, represented by changes in lifetime vehicle-km, exhibits a marginal impact on GHG emissions. However, from a fleet perspective, this indicates that optimizing vehicle utilization can lead to significant GHG emissions reductions, making effective fleet management a critical strategy for logistics companies. Overall, these findings suggest that transitioning to renewable energy sources, improving energy efficiency, and boosting vehicle utilization are key strategies for enhancing sustainability in the trucking sectors, aligning with global efforts to mitigate climate change.

4. Conclusion

Being traditionally a leading producer and exporter of fossil fuels, the Kingdom of Saudi Arabia has embarked on a journey in recent years to develop a more sustainable and low-carbon economy. To achieve this policy objective, it is imperative to decarbonize KSA's road freight sector, one of the primary sources of domestic energy consumption and GHG emissions. Within this context, we have conducted an LCA analysis of various truck powertrains and investigated their emission reduction potential under varying conditions of energy mix, vehicle size, and vehicle utilization.

The results of our analysis highlight the significant potential of alternative powertrains to reduce GHG emissions in the road freight transportation sector, although the decarbonization potential of alternative powertrain vehicles will also heavily depend on the carbon intensity of the energy mix. This is because, for ICEVs and HEVs, the majority of GHG emissions are from fuel combustions in the vehicle use phase. In comparison, for BEVs and FCEVs, most of the emissions arise from powertrain components, fuel production, and fuel distribution. Under the business-as-usual energy mix, which still relies on fossil fuels, we found that hybrid trucks could potentially contribute to the greatest reduction of GHG emissions compared to ICE trucks, without requiring significant investment in new infrastructure. However, as Saudi Arabia gradually incorporates renewables into its power supply, zero-emission powertrains demonstrate increasing potential for emission reduction in road freight transportation.

In the context of a greater proportion of renewables in the energy mix, we found that BEVs exhibit lower emissions than FCEVs across light-, medium- and heavy-duty trucks. Given this finding – and considering that Saudi Arabia is aiming to massively expand passenger EV production domestically (Astrolabs 2024) – the Kingdom may consider a similar strategy to launch the production of electric trucks simultaneously, thereby leveraging economies of scale in EV manufacturing. On the other hand, policymakers will also need to expedite the development of related charging stations, while considering the distinct charging needs of passenger EVs and electric trucks, to ensure a balanced infrastructure development for both passenger and freight applications.

In the meantime, although FCEVs do not achieve the lowest GHG emissions among the alternative powertrains, they are still very effective at lowering emissions compared to ICEVs and HEVs, especially as the feedstock supply increasingly comes from clean sources. Hydrogen fuel cells are a promising technology to decarbonize hard-to-abate sectors, especially in long-haul transportation (Shabaneh et al. 2024). With KSA's ambition to become a major producer and exporter of green hydrogen, some existing studies have reported that Saudi Arabia has one of the world's lowest green hydrogen production costs (Arab News 2022). Therefore, from the cost-competitiveness perspective, FCEVs remain a viable option for road freight decarbonization in the Kingdom. Future research may explore the cost aspects of the different powertrains accordingly so that policymakers can make more informed decisions about climate change mitigation in Saudi Arabia's road freight transportation.

References

Al-Saidi, Mohammad. 2022. "Energy Transition in Saudi Arabia: Giant Leap or Necessary Adjustment for a Large Carbon Economy?" *Energy Reports* 8: 312–18. https://doi.org/10.1016/j.egyr.2022.01.015.

Al-Sinan, Mazen A., Abdulaziz A. Bubshait, and Fatimah Alamri. 2023. "Saudi Arabia's Journey toward Net-Zero Emissions: Progress and Challenges." *Energies 2023*, Vol. 16, Page 978 16 (2): 978. https://doi.org/10.3390/EN16020978.

Antonini, Cristina, Karin Treyer, Anne Streb, Mijndert van der Spek, Christian Bauer, and Marco Mazzotti. 2020. "Hydrogen Production from Natural Gas and Biomethane with Carbon Capture and Storage – A Techno-Environmental Analysis." *Sustainable Energy & Fuels* 4 (6): 2967–86. https://doi.org/10.1039/d0se00222d.

Arab News. 2022. "Saudi Green Hydrogen Production Costs Could Be Lowest in the World: KAPSARC." September 29. https://www.arabnews.com/node/2171831/business-economy.

Archie Initiative. 2021. "Enhanced Transparency on Worldwide Energy Carbon Intensity." https://www.archieinitiative.org/publications.

Astrolabs. 2024. "How Saudi Arabia is Leading the EV Revolution Globally." Market Outlook. https://insight.astrolabs.com/how-saudi-arabia-is-leading-the-ev-revolution-globally/#:~:text=In%202023%2C%20Lucid%20Motors%20manufactured%2Cin%20Riyadh%20will%20be%20electric.

Booto, Gaylord Kabongo, Kari Aamodt Espegren, and Ragnhild Hancke. 2021. "Comparative Life Cycle Assessment of Heavy-Duty Drivetrains: A Norwegian Study Case." *Transportation Research Part D: Transport and Environment* 95 (June): 102836. https://doi.org/10.1016/j.trd.2021.102836.

Candelaresi, Daniele, Antonio Valente, Diego Iribarren, Javier Dufour, and Giuseppe Spazzafumo. 2021. "Comparative Life Cycle Assessment of Hydrogen-Fuelled Passenger Cars." *International Journal of Hydrogen Energy* 46, no. 72 (October 19): 35961–35973. https://doi.org/10.1016/j.ijhydene.2021.01.034.

Cox, Brian, Christian Bauer, Angelica Mendoza Beltran, Detlef P. van Vuuren, and Christopher L. Mutel. 2020. "Life Cycle Environmental and Cost Comparison of Current and Future Passenger Cars under Different Energy Scenarios." *Applied Energy* 269 (July 1): 115021. https://doi.org/10.1016/j.apenergy.2020.115021.

Dai, Qiang, C. Jarod Kelly, Jennifer Dunn, and Thathiana Pahola Benavides. 2018. "Update of Bill-of-Materials and Cathode Materials Production for Lithium-Ion Batteries in the GREET Model." U.S. Department of Energy, October 31. Chicago. https://greet.es.anl.gov/publication-update_bom_cm.

Dai, Qiang, Jarod C. Kelly, Linda Gaines, and Michael Wang. 2019. "Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications." *Batteries* 5 (2). https://doi.org/10.3390/batteries5020048.

Det Norske Veritas (DNV). 2022. "Hydrogen Forecast to 2050." *Energy Transition Outlook 2022*, 114. https://www.dnv.com/publications/hydrogen-forecast-226443.

ecoinvent. 2023. *The ecoinvent Database*. https://ecoinvent.org/the-ecoinvent-database.

Ekvall, Tomas. 2019. "Attributional and Consequential Life Cycle Assessment." In *Sustainability Assessment at the 21st Century*, edited by María José Bastante-Ceca, Jose Luis Fuentes-Bargues, Levente Hufnagel, Florin-Constantin Mihai, and Corneliu Iatu, 4. Rijeka: IntechOpen. https://doi.org/10.5772/intechopen.89202.

Ekvall, Tomas, Anna Björklund, Gustav Sandin, Kristian Jelse, Jenny Lagergren, and Maria Rydberg. 2020. "Modeling Recycling in Life Cycle Assessment." Gothenburg, Sweden: Stockholm Life Cycle Center. May. https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1549446&dswid=-9963.

Elshurafa, Amro M., Marie Petitet, and Frank A. Felder. 2023. "How Firm Capacity and Forced Outage Rate Assumptions of Renewables Impact Capacity Expansion Model Results." Riyadh: King Abdullah Petroleum Studies and Research Center (KAPSARC). https://doi.org/10.30573/KS--2023-DP01.

Guzek, Marek, Jerzy Jackowski, Rafał S. Jurecki, Emilia M. Szumska, Piotr Zdanowicz, and Marcin Żmuda. 2024. "Electric Vehicles—An Overview of Current Issues—Part 1—Environmental Impact, Source of Energy, Recycling, and Second Life of Battery." *Energies* 17 (1): 249. https://doi.org/10.3390/EN17010249.

Hassan, Qusay, Patrik Viktor, Tariq J. Al-Musawi, Bashar Mahmood Ali, Sameer Algburi, Haitham M. Alzoubi, Ali Khudhair Al-Jiboory, Aws Zuhair Sameen, Hayder M. Salman, and Marek Jaszczur. 2024. "The Renewable Energy Role in the Global Energy Transformations." *Renewable Energy Focus* 48 (March): 100545. https://doi.org/10.1016/j.ref.2024.100545.

Handbook of Emission Factors for Road Transport (HBEFA). 2017. *Handbook of Emission Factors for Road Transport*. https://www.hbefa.net.

International Energy Agency (IEA). 2017. *The Future of Trucks*. https://www.iea.org/reports/the-future-of-trucks.

International Energy Agency (IEA). 2018. *The IEA Mobility Model*. https://iea.blob.core.windows.net/assets/imports/events/70/JacobTETERIEA.pdf.

International Energy Agency (IEA). 2019. *Global Energy & CO2 Status Report*. Paris: IEA Publications. https://www.iea.org/reports/global-energy-co2-status-report-2019.

International Energy Agency (IEA). 2020. *Energy Technology Perspectives 2020*. Paris: IEA Publications. https://iea.blob.core.windows.net/assets/7f8aed40-89af-4348-be19-c8a67df0b9ea/Energy_Technology_Perspectives_2020_PDF.pdf.

International Energy Agency (IEA). 2023. *Tracking Trucks and Buses*. 2023. https://www.iea.org/energy-system/transport/trucks-and-buses.

Intergovernmental Panel on Climate Change (IPCC). 2023. *Climate Change 2021: The Physical Science Basis*. Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK, and NY, USA: Cambridge University Press. https://doi.org/10.1017/9781009157896.

International Monetary Fund (IMF). 2003. "The Middle East and North Africa in a Changing Oil Market." https://www.imf.org/external/pubs/ft/med/2003/eng/okogu/okogu.htm#:~=Middle%20East%20Oil%20and%20Gas%20Resource%20Endowments&text=In%20contrast%2C%20the%20region%20accounted,market%20(see%20Figure%201).

International Organization for Standardization (ISO). 2020a. "ISO – ISO 14040:2006/Amd 1:2020 – Environmental Management — Life Cycle Assessment — Principles and Framework — Amendment 1." https://www.iso.org/standard/76121.html.

International Organization for Standardization (ISO). 2020b. "ISO – ISO 14044:2006/Amd 2:2020 – Environmental Management — Life Cycle Assessment — Requirements and Guidelines — Amendment 2." https://www.iso.org/standard/76122.html.

Kamboj, Puneet, Mohamad Hejazi, Yang Qiu, Page Kyle, and Gokul Iyer. 2024. "Saudi Arabia Net-Zero GHG Emissions by 2060 Transformation of the Transport Sector." Riyadh: King Abdullah Petroleum Studies and Research Center (KAPSARC). https://doi.org/10.30573/KS--2024-DP01.

Kingdom of Saudi Arabia (KSA). 2016. "'Saudi Vision 2030' – Saudi Arabia." 2016. https://www.vision2030.gov.sa/en.

Meili, Christoph, Niels Jungbluth, and Maresa Bussa. 2023. "Life Cycle Inventories of Long-Distance Transport of Crude Oil. ESU-Services Ltd. Commissioned by Ecoinvent & Carbon Minds." Schaffhausen, Switzerland. https://esu-services.ch/data/public-lci-reports.

Meyer, Tobias. 2020. "Decarbonizing Road Freight Transportation – A Bibliometric and Network Analysis." *Transportation Research Part D: Transport and Environment* 89 (December): 102619. https://doi.org/10.1016/j.trd.2020.102619.

Ministry of Transport and Logistic Services (MOTLS). 2024. "Saudi Arabia's Big Logistics Play." Available at: https://mot.gov.sa/en/help/Documents/KSALogisticsEN.pdf.

Neubauer, Jeremy, and Eric Wood. 2014. "Thru-Life Impacts of Driver Aggression, Climate, Cabin Thermal Management, and Battery Thermal Management on Battery Electric Vehicle Utility *Journal of Power Sources* 259 (August 1): 262–75. https://doi.org/10.1016/j.jpowsour.2014.02.083.

Notter, Dominic A., Marcel Gauch, Rolf Widmer, Patrick Wäger, Anna Stamp, Rainer Zah, and Hans Jörg Althaus. 2010. "Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles." *Environmental Science & Technology* 44 (17): 6550–56. https://doi.org/10.1021/es903729a.

Dore, Chris, Daniel Montalvo, Kristina Saarinen. 2023. "EMEP/EEA Air Pollutant Emission Inventory Guidebook 2023." https://www.eea.europa.eu//publications/emep-eea-guidebook-2023.

Nyamathulla, Shaik, and C. Dhanamjayulu. 2024. "A Review of Battery Energy Storage Systems and Advanced Battery Management System for Different Applications: Challenges and Recommendations." *Journal of Energy Storage* 86 (Part A, May 1): 111179. https://doi.org/10.1016/J.EST.2024.111179.

Sacchi, Romain, Christian Bauer, and Brian L. Cox. 2021. "Does Size Matter? The Influence of Size, Load Factor, Range Autonomy, and Application Type on the Life Cycle Assessment of Current and Future Medium- and Heavy-Duty Vehicles." *Environmental Science & Technology* 55 (8): 5224–35. https://doi.org/10.1021/acs.est.0c07773.

Shabaneh, Rami, Jitendra Roychoudhury, Jan Frederik Braun, and Saumitra Saxena, eds. 2024. *The Clean Hydrogen Economy and Saudi Arabia: Domestic Developments and International Opportunities*. 1st ed. London: Routledge. https://doi.org/https://doi.org/10.4324/9781003294290.

Shannak, Sa'd, Jeyhun Mikayilov, and Rubal Dua. 2022. "How to Mitigate Transportation Emissions in Saudi Arabia? The Role of Energy Price Governance." Riyadh: King Abdullah Petroleum Studies and Research Center (KAPSARC). https://doi.org/10.30573/KS--2022-DP04.

Shehri, Thamir Al, Jan Frederik Braun, Nicholas Howarth, Alessandro Lanza, and Mari Luomi. 2022. "Saudi Arabia's Climate Change Policy and the Circular Carbon Economy Approach." *Climate Policy* 23 (2): 151–67. https://doi.org/10.1080/14693062.2022.2070118.

Winjobi, O., Q. Dai, and J. C. Kelly. 2020. *Update of Bill-of-Materials and Cathode Chemistry Addition for Lithium-Ion Batteries in GREET® 2020*. Systems Assessment Group, Energy Systems Division, Argonne National Laboratory.

World Bank. 2024. World Development Indicators. https://databank.worldbank.org/source/world-development-indicators.

Xu, Xun, and Rubal Dua. 2023. "Cost-Effectiveness Analysis of Aerodynamic Improvement Technologies for Road Freight Transport in Saudi Arabia." Riyadh: King Abdullah Petroleum Studies and Research Center (KAPSARC). https://www.kapsarc.org/research/publications/cost-effectiveness-analysis-of-aerodynamic-improvement-technologies-for-road-freight-transport-in-saudi-arabia/.

Zhao, Chengcheng, Leiliang Zheng Kobayashi, Awad Bin Saud Alquaity, Jean-Christophe Monfort, Emre Cenker, Noliner Miralles, and S. Mani Sarathy. 2024. "Solutions for Decarbonising Urban Bus Transport: A Life Cycle Case Study in Saudi Arabia." *Communications Engineering* 3 (1): 95. https://doi.org/10.1038/s44172-024-00238-9.

Zhuang, Weichao, Shengbo Li (Eben), Xiaowu Zhang, Dongsuk Kum, Ziyou Song, Guodong Yin, and Fei Ju. 2020. "A Survey of Powertrain Configuration Studies on Hybrid Electric Vehicles." *Applied Energy* 262 (March 15): 114553. https://doi.org/10.1016/j.apenergy.2020.114553.

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About the Project

The “Evaluating Decarbonization Pathways in Passenger Vehicles in KSA Using an Integrated Lifecycle Analysis Approach” project aims to assess the sustainability aspects of current and future passenger road vehicles in KSA. The project seeks to understand and mitigate the environmental impact of transportation in the country. Using an integrated lifecycle analysis approach, the project examines decarbonization pathways, 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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