


Life Cycle Assessment and Future Scenario Analysis of Internal Combustion and Electric Road Vehicles in the Context of Türkiye

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ABSTRACT

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This study employs a comparative Life Cycle Assessment (LCA) methodology and finds the potential environmental impacts of daily road transport in Türkiye. It also assesses the changes in potential impacts from electric vehicle (EV) usage instead of internal combustion engine vehicle (ICEV). The life cycle system boundary is determined as 'well-to-wheel' and 'person.km' is used as the functional unit for comparing different vehicle capacities. The Global Warming Potential (GWP) of the diesel-powered car, gasoline-powered car, and diesel-powered minibus are calculated as 202, 250, and 20.3 gr CO₂-eq/person.km respectively. Electric cars reduce the GWP by 56% compared to diesel usage, with an additional 45.8% reduction for the electric minibus. However, the consumption of fossil fuels in electricity production increases the Terrestrial Acidification, Freshwater Eutrophication, and Freshwater Ecotoxicity impacts. Türkiye aims to increase its renewable energy sources by 2035. Changing electricity generation is assessed through a sensitivity analysis. The results show a 40% decrease in TAP and FWEP impacts if the target electricity production is achieved by 2035 compared to today's electricity mix. The study highlights the importance of considering various impact categories in environmental assessments.

1. Introduction

Road transportation is a critical sector in terms of energy consumption and environmental impacts on a global scale. It is evident that traditional transport systems, which are dependent on fossil fuels, play a substantial role in the emission of greenhouse gases (GHGs). Moreover, in addition to the carbon footprint (CF), the phenomenon is associated with air pollution, acidification, and adverse impacts on human health. The most recent scientific research has demonstrated that these harmful impacts are still crucial despite the continuous improvement of internal combustion engines (ICEs) powered by fossil fuels [1, 2]. The transportation sector is responsible for approximately 14% of global carbon dioxide (CO₂) emissions. Road transport substitutes 75% of these emissions [3].

In 2010, the generation of GHG emissions from road transportation in Türkiye amounted to 43,403 GgCO₂-eq. This quantity has increased by up to 61.97% compared with 2010 and reached 70,271 Gg CO₂-eq in 2019 [4]. Figures 1 and figure 2 illustrate the sectoral distribution of Türkiye's GHG emissions in 2021 and the contribution rates of energy subcategories as specified in the Climate Change Mitigation Strategy and Action Plan (2024-2030) [5].

Globally, if the current trends continue, it is predicted that carbon emissions caused by the rise of internal combustion engine vehicles (ICEVs) will increase by more than 40% in 2035 [6]. It is evident that the transport sector plays a fundamental role in achieving the objectives established by the Paris Climate Agreement (GreenDeal), which targets limiting global

temperature to 1.5°C. Research indicates that transport emissions should be limited to 2 Gt CO₂-eq by 2050 to adhere to the targets set out in the climate agreement [7]. Policies for the reduction of emissions from road transport have been in place all over the world. The European Union (EU) plans to prohibit the sale of ICEV by the year 2035. While China promotes EV and hydrogen-fueled vehicles, the USA offers subsidies and incentives to switch to electric vehicles (EVs). Similar to development all over the world, in Türkiye, policies such as domestic EV production and low tax rates for EVs are being pursued. Besides, public transport is encouraged to reduce emissions per capita, and efforts are being made to increase the number of public transport facilities. In 2035, EVs are projected to account for 15% of the total number of vehicles on Türkiye's roads [4, 5].

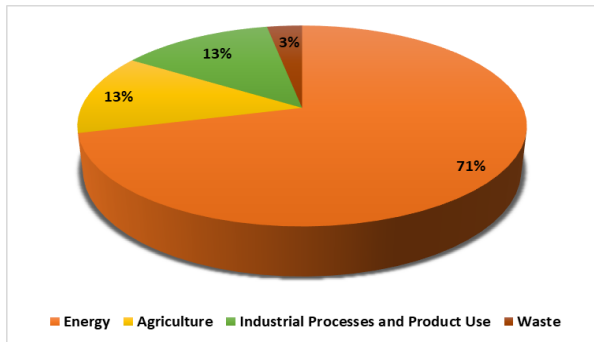


Figure 1. Sectoral distribution of GHG emissions in Türkiye in 2021 [5]

In the context of ongoing efforts to reduce greenhouse gas emissions, environmental impact assessment studies are being conducted to ascertain the present situation and to analyze the potential consequences of implemented policies on the environment. A substantial number of studies have been carried out on the calculation of greenhouse gas emissions from road transport using the CF methodology [4, 8, 9]. The ISO 14040/44 Life Cycle Assessment (LCA) methodology is another widely used method for determining the potential environmental impacts of transport. The LCA methodology, a widely utilised approach on a global scale, facilitates the analysis of numerous categories, encompassing acidification, eutrophication, human health, resource consumption, and the assessment of the Global Warming Potential associated with transport activities.

In comparison to alternative methods, the LCA methodology's distinct advantage lies in its capacity to address multiple impact categories, rather than being confined to a single category. This capacity to encompass multiple impact categories enables the identification of burden-shiftings across different impact categories due to policy changes, facilitating the implementation of measures in an early stage. While LCA studies have been extensively utilized for transport globally, studies focusing on road transport in Türkiye predominantly center on carbon footprint determination [10 - 13].

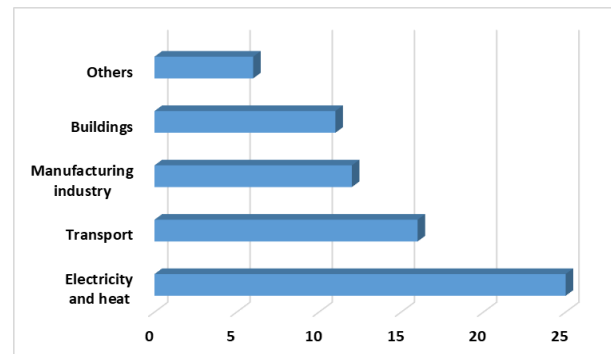


Figure 2. Sectoral contribution of energy-related GHG Emissions [5]

In a 2021 study, Dündar calculated the total greenhouse gas emissions from road transport in 30 metropolitan cities in Türkiye between 2010 and 2019 using the Tier 1 method developed by the IPCC [4]. In another study, Timuralp (2023) utilised the IPCC Tier 1 method to calculate CO₂ emissions from fuel consumption in road transport in Eskişehir province [9]. According to the 2020 Automotive Industry Association (OSD) sustainability report, approximately 70% of carbon emissions generated throughout the life cycle of vehicles occur during use, with 20% arising from production and a further 10% from disposal [14].

In a 2022 publication, Üçtuğ conducted a comparative LCA to evaluate the environmental impacts of EVs and ICEVs manufactured in Türkiye. The study reported the GWP of EVs and ICEVs as 120 g CO₂-eq/km and 210 g CO₂-eq/km, respectively, indicating that EVs have approximately 43% lower GWP than ICEVs. Regarding acidification potential, EVs exhibited a value of 3.21 g SO₂-eq/km, compared to 0.48 g SO₂-eq/km for ICEVs; this difference was

attributed to the use of low-quality fossil fuels, such as lignite, in Türkiye's electricity grid mix. The analysis further identified that the primary contributors to the environmental impacts during the use phase are energy/electricity consumption and tyre wear, which together account for 82% of the total CF and 94% of the total acidification potential of EVs [15]. Coşkun and Oktay calculated the CF of different modes of transport in Türkiye, analysing actual usage data for 2016 for 13 vehicle types, including cars, buses, trucks, minibuses, motorcycles, tractors, aeroplanes, trains, metros/trams, and maritime transport.

According to the results, total emissions from vehicle use in 2016 amounted to 217.77 Mt CO₂, which is higher than emissions from electricity production in the same year. Trucks account for 32.4% of emissions, followed by cars at 16.8%. The CO₂ emissions per km for cars were calculated as 214 g for gasoline vehicles, 183 g for diesel vehicles, and 181 g for LPG vehicles. The CF of diesel buses is 921 g CO₂-eq/km, and it is estimated that the use of EVs could reduce this emission to 95.65 g CO₂-eq/km, thereby reducing total emissions from cars by 48.9% [16]. In a fleet assessment study prepared by the International Council on Clean Transportation (ICCT) in 2016, the CO₂ emission performance of light-duty vehicles in Türkiye during their use phase was examined. As of 2014, the average CO₂ emission of passenger cars was 123 g/km, while that of light commercial vehicles was 170 g/km. The findings indicated that Türkiye's

emissions exceeded the 2020 targets established by the European Union. To address this discrepancy, the study recommended the implementation of a carbon-based tax system, incentives for alternative fuel vehicles, and the introduction of more stringent emission standards [17]. In their 2020 study, Güzel and Alp utilised the TIMES model for the Istanbul transportation sector to analyse GHG emissions up to 2050 based on different scenarios. In the event of widespread adoption of hybrid and EVs, a 49% reduction in emissions from cars and an 11% reduction in total transportation emissions are projected. The CO₂-eq values per km for different vehicle types are calculated as follows: 211 g for gasoline cars, 180 g for diesel cars, and 60 g for electric cars. In the context of public transport, the CO₂-eq values per person for electric systems such as metro, train, and metrobus are 45, 32, and 60 g CO₂-eq/person.km, respectively.

The findings indicate that individual car use results in significantly higher greenhouse gas emissions compared to public transport [18]. In their 2024 study, Şahin and Esen assessed GHG emissions associated with the use of EVs in Türkiye based on the Well-to-Wheel (WTW) approach. In consideration of Türkiye's electricity grid mix, the average emissions of electric passenger vehicles are determined to be 89.1 g CO₂-eq/km, whereas those of gasoline vehicles are established as 172.2 g CO₂-eq/km. This result indicates that EVs operate with 48.3% lower emissions [19].

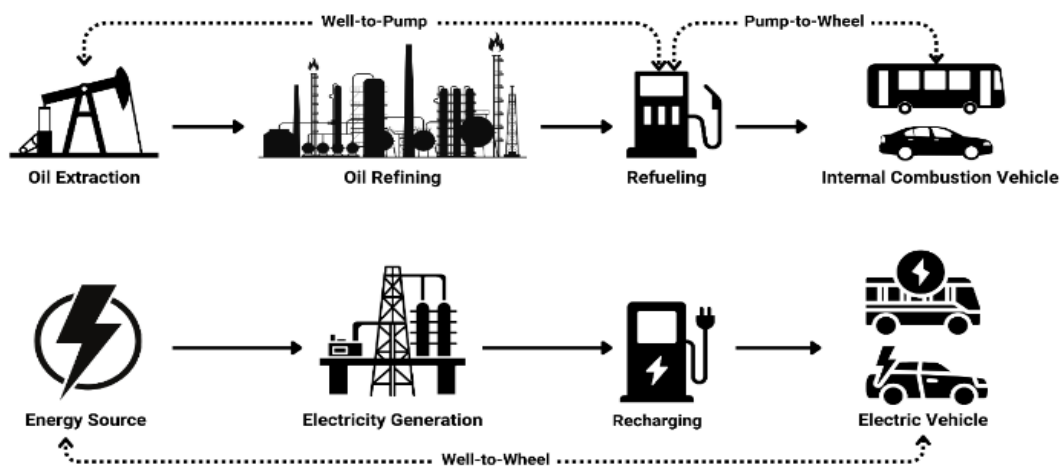


Figure 3. Well-to-wheel system boundaries

The present study has been conducted to address the potential environmental impacts arising from daily road transport choices using comparative LCA. The study aims to fill a gap in the literature by presenting a comprehensive LCA that assesses the environmental impacts of common road transport vehicles in Türkiye, with many impact categories beyond the carbon footprint. Furthermore, the study analyses the environmental impacts of the transition to EVs with current and 2035 electricity grid projections and provides recommendations for policymakers in line with future energy scenarios.

2. General Methods

In the context of the study, the potential environmental impacts of daily road transport were analyzed using ISO 14040/44 LCA methodology. The four principal stages of the LCA methodology, as specified in the ISO 14040/44 standard, were studied in detail. These stages are goal and scope definition, inventory analysis, impact assessment, and interpretation.

2.1. Goal and scope definition

The objective of this study is to assess the potential environmental impacts associated with current daily road transport practices and examine the implications of a transition to electric transport options. To this end, data from three ICEVs commonly utilized in Türkiye was collated and analyzed. Furthermore, scenarios involving the replacement of these vehicles with two different EVs were investigated. Hybrid and electric buses are recognized as significant components of sustainable transport systems. However, these vehicles were excluded from the system boundaries to maintain methodological consistency in terms of the data availability, and comparability between the selected vehicle categories. Public transport modes such as buses exhibit distinct service patterns and occupancy rates. Incorporating them into the model would require separate assumptions and datasets, which would reduce the direct comparability of results within the defined scope.

The system boundaries have been defined as “well-to-wheel”, as illustrated in Figure 3. The well-to-wheel system boundary for fossil fuel

vehicles covers the extraction, transportation, refining, distribution and storage of petrol, as well as the emissions resulting from the combustion of fuel in vehicles. Vehicle production, vehicle life, and end-of-life scenarios are not included in the system boundaries. For electric vehicles, the system boundaries include the extraction of the energy source (coal, natural gas, nuclear, renewable, etc.), electricity generation, transmission, distribution, and the use of electricity in the vehicle. Battery and vehicle production, recycling, and maintenance activities are not included in the system boundaries.

A review of the relevant literature reveals a preference for the use of “environmental impact per km” or “environmental impact per person.km” as functional units to normalize the environmental impacts of transport [20 – 22]. In this study, given the investigation of potential environmental impacts caused by vehicles with different transport capacities, the functional unit is determined as “environmental impact per person.km”.

The LCA was conducted utilising the SimaPro 9.5.0.0 software, with the necessary inventory selected from the Ecoinvent 3.9.1 database. The impact assessment was performed employing the “ReCiPe 2016 v1.1 midpoint (H) method”, a widely adopted approach on a global scale. Notably, the environmental implications associated with EV utilization can exhibit significant variations depending on the electricity source employed. In light of Türkiye's stated commitment to augment the utilization of nuclear and renewable energy sources in the future, a sensitivity analysis was conducted to ascertain the impact of a potential alteration in electricity source on the outcomes of the potential environmental impact.

2.2. Inventory analysis

To evaluate the potential environmental impacts associated with daily transportation preferences, a comprehensive LCA was performed. Three commonly used transport modes in Türkiye were selected as benchmarks: a diesel-powered car (D-Car), a gasoline-powered car (G-Car), and a diesel-powered minibus (D-Minibus). The

baseline analysis was conducted based on these three vehicle types.

Actual fuel consumption data for each vehicle were obtained directly from the onboard vehicle display. The fuel consumption inventory of fossil-fueled vehicles is given in Table 1.

The utilization of EVs in Türkiye is on the rise, with the aim of reducing dependence on fossil-fueled transport and mitigating potential environmental impacts. To determine the potential environmental impacts of electrifying transport, an inventory analysis of the use of electric cars and minibuses was carried out. For the E-Car, the official declarations of the vehicle companies were taken into account, and the electricity consumption of an E-Car was calculated as 17.6 kWh/100 km by averaging the electricity consumption of 10 E-Cars of different volumes [23 – 27]. As official declarations for electric minibuses are limited, analyses were conducted on the assumption of minibus electricity consumption of 30 kWh/100 km [28].

Table 1. Fuel consumption values of the selected vehicles

Vehicle Type	Fuel Consumption (L/100km)	Fuel Consumption (kg/km)
D-Car	7.2	0.06
G-Car	6.6	0.049
D-Minibus	10.7	0.09

Following the determination of fuel consumption, the exhaust emissions of ICEVs were calculated. As electric vehicles do not produce exhaust emissions, the analysis focused exclusively on the exhaust emission values of ICEVs. Initially, emission factors from the Intergovernmental Panel on Climate Change (IPCC) were utilized to estimate CO₂ emissions resulting from the combustion of 1 kg of diesel and gasoline. The IPCC CO₂ emission factors (EF) for diesel and gasoline are 74,100 kg CO₂/TJ and 69,300 kg CO₂/TJ, respectively, with lower heating values of 43 MJ/kg for diesel and 44.3 MJ/kg for gasoline [8, 29]. Accordingly;

$$\text{CO}_2 \text{ (kg/kg diesel)} = 74100 \text{ kg CO}_2/\text{TJ} \times 43 \text{ MJ/kg} \times 10^{-6} = 3.187 \text{ kg CO}_2/\text{kg diesel}$$

$$\text{CO}_2 \text{ (kg/kg gasoline)} = 69300 \text{ kg CO}_2/\text{TJ} \times 44.3 \text{ MJ/kg} \times 10^{-6} = 3.069 \text{ kg CO}_2/\text{kg gasoline}$$

Subsequently, the CO₂ emissions per km were analyzed with the formula (1), based on the density of the fuel and CO₂ emissions per kg.

$$\text{CO}_2 \text{ emission (g/km)} = \text{FC} \times \text{FD (kg/L)} \times \text{CO}_2 \text{ EF} \quad (1)$$

FC: Fuel consumption (L/km),

FD: Fuel density (kg/L)

EF: Emission Factor (g/kg)

The density of diesel is 835 kg/m³, whereas that of gasoline is 740 kg/m³. Consequently, the CO₂ emissions of a D-Car are calculated to be 194.40 g CO₂/km, 149.94 g CO₂/km for a G-Car, and 287.13 g CO₂/km for a D-Minibus.

In examining vehicle exhaust emissions, this study adopts an alternative approach by prioritizing the upper limits of EURO 6 standards over the more conventional IPCC emission factors for hydrocarbon and nitrogen compounds. The analysis explores the complexities of vehicle emissions, particularly in EURO 6-compliant vehicles, which are equipped with advanced emission control technologies such as Selective Catalytic Reduction (SCR) and AdBlue systems to reduce harmful emissions from fuel combustion. A key observation is that the IPCC emission factors do not account for these purification processes, leading to an overestimation of exhaust emissions. Therefore, to ensure a more realistic and consistent assessment of exhaust emission inventories, the EURO 6 emission standards, as detailed in Table 2, are utilized in this study [30, 31].

Table 2. Exhaust emissions of the selected ICEVs

Emission	D-Car g/km	G-Car g/km	D-Minibus g/km
CO	0.5	1	0.74
HC	0.09	0.1	0.045
NO _x	0.08	0.06	0.125
PM	0.005	0.005	0.005

The inventory for ICEVs and EVs is then normalized to the functional unit of per person.km. Although personal cars have a seating capacity of five, normalization is based on single-person travel.

Table 3. Input and output life cycle normalized inventory of the selected vehicles

Inventory	D – Car	G – Car	D – Minibus	E-Car	E-minibus
Fuel cons. (kg)	0.06	0.049	0.004	-	-
Electricity cons.(kWh)	-	-	-	0.176	0.017
CO ₂ (g)	194.40	149.94	15.11		
CO (g)	0.09	1	0.74		
HC (g)	0.09	0.1	0.045	-	-
NO _x (g)	0.08	0.06	0.125		
PM (g)	0.005	0.005	0.005		

This approach reflects real-world conditions, as the majority of individuals commute alone in their personal vehicles. To ensure a realistic representation of usage patterns, the analysis considers single-occupancy vehicle travel. In contrast, the ICE and E-Minibuses examined in this study have seating capacities of 19 and 17 passengers, respectively, and are typically operated at full capacity. Therefore, fuel consumption and emission outputs are adjusted accordingly. The inventory normalized by the functional unit for all vehicle types is summarized in Table 3.

In the absence of a distinct unit process for diesel and gasoline specific to Türkiye in the Ecoinvent database, unit processes based on the European average have been considered. For electricity consumption, the national electricity mix of Türkiye is utilized. In this study, the low-voltage unit process from Ecoinvent 3.9.1 has been employed.

A sensitivity analysis has been conducted for the year 2035 when it is anticipated that the use of electric vehicles will increase and that TR

electricity generation sources will be more environmentally friendly than they are at present. According to the National Energy Plan of Türkiye, TR electricity generation is estimated to be 510 TWh in 2035, with the aim of meeting 54.7% of this production from renewable energy sources and 11.1% from nuclear energy. The probable electricity mix for 2035 has been re-modeled by considering official statements [32].

3. Life Cycle Impact Assessment Results

Potential environmental impacts per person.km from selected vehicles with internal combustion engines are given in Table 4 for 8 impact categories. The characterization results indicate that the GWP values for gasoline cars, diesel cars, and diesel minibuses are 202, 250, and 20.3 g CO₂-eq/person.km, respectively. Based on an average annual mileage of 15,000 km per individual, the corresponding annual GWP impacts per person are 30,300, 37,500, and 3,040 kg CO₂-eq/person-year, respectively.

Public transport offers a 99% reduction in annual GWP impact compared to a diesel car.

Table 4. Characterization results of life cycle impact assessment per person.km

Impact category	Unit	G-Car	D-Car	D-Minibus
Global warming (GWP)	kg CO ₂ eq	2.02E-01	2.50E-01	2.03E-02
Terrestrial acidification (TAP)	kg SO ₂ eq	1.96E-04	1.83E-04	1.65E-05
Freshwater eutrophication (FWEP)	kg P eq	3.00E-06	3.51E-06	2.88E-07
Freshwater ecotoxicity (FWETP)	kg 1,4-DCB	4.41E-04	4.82E-04	3.99E-05
Human carcinogenic toxicity (HTPcancer)	kg 1,4-DCB	1.69E-03	1.99E-03	1.66E-04
Mineral resource scarcity (MRSP)	kg Cu eq	9.43E-05	1.01E-04	8.36E-06
Fossil resource scarcity (FRSP)	kg oil eq	5.95E-02	7.23E-02	6.02E-03
Water consumption (WCP)	m ³	1.35E-04	1.58E-04	1.40E-05

An analysis of fuel consumption values per kilometer, as presented in Table 1, reveals that while the minibus has the highest fuel consumption, it exhibits the lowest GWP impact when normalized per person.km. This highlights the effectiveness of public transport in reducing

the environmental footprint of road transportation. When private cars are operated at full capacity, their GWP impacts are 40.4 and 50.1 g CO₂-eq/person.km for gasoline and diesel cars, respectively. Even under maximum occupancy conditions, private cars still exhibit

50% and 60% higher GWP impacts compared to the selected minibus. Similar trends are observed across other impact categories, aligning with the findings in the GWP assessment.

In 2035, with the increased use of EVs in Türkiye being a key factor, the potential environmental impact of electric cars and minibuses in road transport was investigated. As shown in Figure 4, the potential environmental impact of EVs and fossil fuel vehicles is compared. The GWP effect for EV is 109 g CO₂-eq/person.km and 11 g CO₂-eq/person.km for electric minibuses. It has been determined that GWP effects can be reduced by approximately 50% if electric vehicles are used and that FRSP effects are also observed in parallel to the GWP effect results, depending on the decrease in petrol use. However, the use of electric vehicles showed an increase in TAP, FWEP, FWETP, and MRSP impacts. When the process contributions are analyzed, it is seen that the increase in these impact categories is due to

the use of lignite coal in electricity generation and lignite mining.

This emphasizes the importance of decarbonizing the electricity grid, reducing the use of internal combustion engines, and expanding the use of electric vehicles. In 2035, a sensitivity analysis of potential environmental impacts was conducted, considering the projected grid electricity mix. Figure 5 compares the anticipated electricity grid in 2035 and the Ecoinvent 3.9.1 Türkiye electricity mix. The sensitivity analysis revealed that the GWP impact of electric cars (109 g CO₂-eq/person.km) leads to an impact of 75 g CO₂-eq/person.km in the probable electricity grid of 2035. In the minibus, the GWP effect decreased from 11 g CO₂-eq/person.km to 7.48 g CO₂-eq/person.km for 2035. TAP, FWEP, FWETP, and MRSP values, which show higher values in electricity use compared to fossil fuel, are also analyzed according to the electricity grid of 2035.

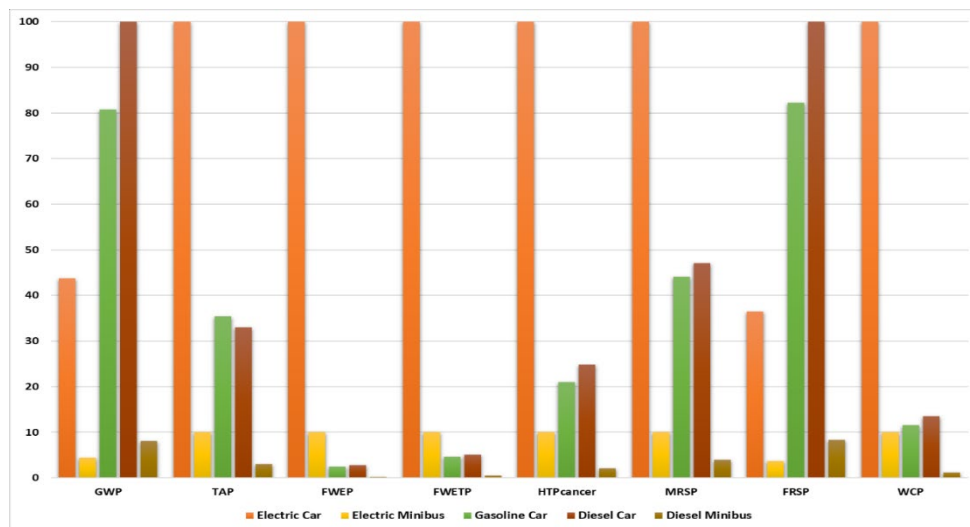


Figure 4. Comparative LCIA results of selected EV and ICEVs (per person.km)

Accordingly, except for the MRSP impact category, there is an improvement in other impact categories in 2035. The increase in the MRSP impact category is due to the copper used for the installation of renewable energy sources. According to the 2035 grid mix, the TAP and FWEP impact categories for electric cars decreased by 40 percent and FWEP by 12 percent, respectively. While the results indicate that public transport is more beneficial in all instances, the GWP impacts from personal use

will be reduced by 70% for an electric car in 2035 compared to today's diesel car.

According to the sensitivity analysis, while positive results are observed in most of the impact categories in 2035, there is an increase in the Ionised Radiation Potential (IRP) impact category. The IRP effect of 0.00087 kBq Co-60 eq for the electric car is determined as 0.0015 kBq Co-60 eq in 2035, with the increase in this category attributable to uranium mining for the purpose of nuclear energy production in 2035.

In their analysis of the environmental impacts of EV and ICEV in Hong Kong in 2022, Shafique et al. employed the LCA method to assess the environmental impacts of these vehicles. The results of this analysis revealed that the GWP impact of EVs in 2019 was 237 g CO₂-eq/km, while the impacts for ICEVs fueled by petrol and diesel were 282 and 242 g CO₂-eq/km, respectively. While the GWP impacts for ICEV are consistent with existing studies, a significant disparity emerges for EV. This discrepancy can be attributed to natural gas and coal being 73% of the Hong Kong electricity grid in 2019. The study also calculated that if the use of fossil resources in the electricity grid in 2050 is 15% and the use of renewable energy is 85%, the GWP effect due to EV use will be 110 g CO₂-eq/km [20]. The results of the present study are in accordance with those of another study published by Ternel et al. in 2021.

This study utilised the LCA method to analyse the GHG and environmental impacts of mid-segment passenger cars that were powered by biofuels and electricity. In 2019, the study calculated the GHG emissions of ICEV to be 192 g CO₂-eq/km, while EV was calculated as 71.3 g CO₂-eq/km with the French electricity grid. According to projections made for 2030, the study found that GHG emissions of biogas hybrid vehicles will decrease to 60.1 g CO₂-eq/km, while EV emissions will decrease to 54.7 g CO₂-eq/km. Plug-in hybrid electric vehicles (PHEVs) have been found to achieve the lowest emission levels of 54.7 g CO₂-eq/km when operated in electric-only mode [21].

The study published by Peng et al. in 2023 also supports the current findings. This study presents an analytical model developed to assess the life-cycle energy consumption and carbon footprint of passenger vehicles in China.

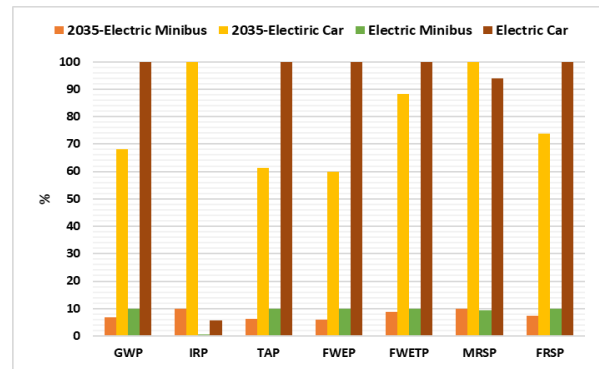


Figure 5. EV sensitivity analysis results according to the current and 2035 electricity grid

The study compares GHGs for ICEVs, EVs, and PHEVs. ICEVs are calculated to emit 281.6 g CO₂-eq/km over the life cycle, while BEVs emit 219.8-229.3 g CO₂-eq/km, depending on electricity from the grid. If the share of coal in electricity generation falls to 10% by 2030, the life cycle emissions of BEVs will be reduced by 70%, increasing the environmental benefits of EVs. The study highlights the need to develop low-carbon manufacturing processes alongside vehicle electrification [22].

The current study shows that, alongside the transition to electric vehicles, public transport options such as minibuses can reduce per capita impacts across all categories. A review of the literature reveals that using public transport vehicles, such as buses, trains and metros, significantly reduces GWP impacts. In their modelling for Istanbul Province in 2020, Güzel and Alp calculated emission values of 45 g CO₂-eq/person.km for the metro, 32 g CO₂-eq/person.km for trains, 60 g CO₂-eq/person.km for the metrobus, and 71 g CO₂-eq/person.km for buses [18].

In a different study carried out by Coşkun and Oktay, it was stated that the total CO₂ emissions from transportation in Türkiye in 2016 were 217.77 Mt, with passenger cars contributing 16.8% to this amount. Although the CO₂ emissions per km for buses are stated as 910 g, the impact per person decreases when high occupancy rates are achieved [16].

4. Conclusion

This study evaluates the potential environmental impacts of daily road transport choices using a comparative LCA methodology. In addition to

assessing the GWP, the study examines the broader environmental implications of transportation choices in Türkiye across multiple impact categories, providing a comprehensive contribution to the literature. The prevalent use of diesel and gasoline-powered cars and diesel minibuses in Türkiye is compared with the adoption of electric cars and minibuses. Furthermore, the projected increase in EV adoption by 2035, along with the decarbonization of the electricity grid, is incorporated into the analysis.

Sensitivity analysis is conducted to assess the potential environmental impacts of EV use under both present-day and future scenarios, with a particular focus on the influence of the electricity generation mix. Among fossil fuel-based vehicles, the D-Minibus demonstrates the lowest environmental impact per person-km across all impact categories. Even when operated at full capacity (five passengers), private cars exhibit a 50% higher GWP impact compared to the D-Minibus. Under current conditions in Türkiye, the adoption of electric vehicles is estimated to reduce GWP impacts by approximately 50%. However, increases are observed in other impact categories, including TAP, FWEP, and FWETP. An analysis of unit processes indicates that these increases are primarily attributed to the reliance on lignite coal for electricity generation, emphasizing the critical need for power grid decarbonization.

To account for this, the electricity grid mix is modeled based on Türkiye's 2035 energy transition targets. By comparing the current and projected electricity generation scenarios, the study evaluates the sensitivity of results to the energy mix. Decarbonizing the electricity grid is found to result in a 70% reduction in the GWP impact category. However, the continued presence of nuclear power in the 2035 energy mix leads to an increase in the IRP impact category.

The results emphasize the critical role of public transport in reducing the environmental impact of road transportation. The LCA findings also highlight that focusing solely on CF assessments may overlook burden shifting across different impact categories. While electricity use is often

considered a more sustainable option in terms of GWP, its environmental benefits depend significantly on the energy mix, as it may lead to undesirable increases in other impact categories. Similarly, the potential increase in radiation-related impacts due to nuclear energy use should not be disregarded. To ensure a holistic approach in policymaking and technological advancements, LCA methodology—capable of evaluating multiple environmental impact categories—should be integrated alongside traditional CF studies.

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