

Article

Sustainable Mobility and Emissions: The Role of the Sale Structure in the Automotive Energy Transition

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Abstract

The aim of this article is to assess the sale structure impact of selected, popular brands of passenger vehicles on total CO₂ emissions in the context of the energy transition in the transport sector. A detailed analysis was conducted of the projected sales of gasoline-, diesel-, hybrid-, as well as electric-powered vehicles over the years 2021–2028. Based on the available empirical data, a mathematical model was developed to estimate emissions over the entire life cycle of vehicles, taking into account the unit carbon footprint of each type of drivetrain and the expected number of vehicles sold. The results indicate a gradual decline in total CO₂ emissions during the analyzed period, mainly due to the increasing share of alternative drivetrains. Despite the growth in electric vehicle sales, their impact on emission reductions remains limited due to the long lifespan of conventional vehicle fleets. The article concludes with a proposal to expand the LCA model to include regional, energy, and recycling components, which could help in formulating more effective climate policies.

Keywords: CO₂ emissions; sale forecast; life cycle analysis (LCA); energy transition; electric drivetrain; hybrid vehicle



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1. Introduction

In the face of the growing global problem of greenhouse gas emissions and their impacts on climate change, the transport sector plays a crucial role [1–3]. It is estimated that transport accounts for a significant portion of total greenhouse gas (GHG) emissions, with carbon dioxide being one of the main contributors. Therefore, a precise assessment and comparison of CO₂ emissions related to different types of passenger vehicles is fundamental for both consumers and policymakers to make informed decisions. One of the comprehensive methodologies for evaluating the environmental impacts of products and services is life cycle assessment (LCA), which covers all stages of a product's life, from raw material extraction to its disposal.

The environmental advantage of electric vehicles (EVs) is intrinsically linked to the carbon intensity of the electricity grid they utilize. In regions with a high proportion of fossil fuels in their energy mix, the well-to-wheel emissions of EVs might be comparable to or

even, in some specific analyses focusing on manufacturing, temporarily higher than those of efficient internal combustion engine vehicles (ICEVs), particularly when considering vehicle production. Conversely, as the energy sector decarbonizes through the increased adoption of renewable energy sources (solar, wind, and hydro), the life cycle emissions of EVs progressively decrease, solidifying their role as a key technology in mitigating transport-related CO₂ emissions [1,4].

Whereas dealing with CO₂ emissions generated by the transport sector is imperative, a comprehensive environmental assessment should also consider other pollutants and impacts. These include particulate matter (PM), nitrogen oxides (NO_x), and other volatile organic compounds emitted during vehicle operation and manufacturing, as well as the environmental burdens associated with battery production (resource depletion, water usage, and land use) and end-of-life management. A broader perspective might reveal trade-offs between different powertrain technologies across various environmental indicators, highlighting the need for multi-criteria decision-making [3,4].

The successful transition to a low-carbon transport sector is not solely dependent on technological advancements. Consumer acceptance, driven by factors such as purchase price, range anxiety, charging infrastructure availability, and individual environmental consciousness, plays a crucial role in shaping market trends. Policy interventions, including subsidies, tax incentives, and the development of a robust charging infrastructure, are essential to accelerate the adoption of cleaner vehicles and influence consumer preferences [1,2].

The energy transition in the transport sector is regarded a gradual process affected by technological innovation, infrastructure development, policy changes, and economic factors. Whilst the increasing market share of alternative drivetrains is a positive trend, the inertia of the existing vehicle fleet entails that the full benefits of this transition in terms of emission reductions will be realized over several years. Therefore, long-term policy frameworks and consistent signals are necessary to guide investment and innovation toward sustainable mobility solutions [1,3].

This article consists of two stages. The first is a comparison of the total CO₂ emissions in the life cycle of passenger vehicles powered by gasoline, diesel, and electricity, based on available studies and statistical data. The second stage focuses on the characterization and evaluation of the passenger vehicle market at the national level using a selected manufacturer as an example. Combining sales structure data with a discussion of the life cycle allows for a comprehensive analysis of the environmental impacts of dominant drivetrain (also known as powertrain or propulsion) technologies and an assessment of real market trends in terms of the energy transition in the transport sector.

This analysis will make it possible not only to determine which types of drivetrains have the lowest CO₂ emissions across their entire life cycle but also to indicate to what extent the current market offer and consumer preferences contribute to the reduction in greenhouse gas emissions. This analysis can also serve as a starting point for discussions on future directions for transport policy development and strategies for automotive manufacturers.

2. Literature Review

The issues of emissions and their environmental impacts in the context of market dynamics of sales across various energy technologies and the overarching global energy transformation are deemed critical areas of contemporary research and policy. Understanding the connections among these subjects is crucial for navigating the transition toward a sustainable energy future and mitigating the adverse effects of climate change and pollution [4]. Future research should yet focus on further elucidating the complex interconnections and addressing the identified gaps in the existing body of knowledge.

The topic of emissions and environmental impact of energy systems, particularly when quantifying the produced emissions associated with different energy sources and their resulting environmental consequences, has been addressed in a wide range of works, for instance [5–12]. Specifically, extensive research [5] details the greenhouse gas emissions (e.g., CO₂, CH₄, and N₂O) from the combustion of coal, oil, and natural gas, whilst [6] highlights air pollutants (e.g., SO_x, NO_x, and particulate matter) and their impacts on air quality, human health, and ecosystems. On the other hand, Sovacool focuses on low direct GHG emissions of nuclear power during operation but addresses concerns regarding radioactive waste disposal, potential accidents [7], and the nuclear fuel cycle, and in [8], research on solar, wind, hydro, geothermal, and biomass energy is discussed when emphasizing their potential for significantly lower GHG emissions compared to fossil fuels. However, several studies also investigate the life-cycle emissions associated with the manufacturing, deployment, and disposal of renewable energy technologies, e.g., Pehnt et al. focused on biomass [9] and Schleisner focused on wind [10]. In addition, environmental impacts beyond emissions, such as land use changes, habitat disruption, and water consumption, have been explored as well, e.g., by Godfray et al. on hydropower [11] and by Rykała et al. when using logistic regression [12].

As for the subject of the sales dynamics and market penetration of energy technologies with a special consideration of factors affecting the sales and market adoption of different energy technologies, including both fossil fuels and cleaner alternatives, multiple studies have been published as well [13–20]. While Acemoglu et al. deal with price competitiveness, investment costs, operational expenses, government subsidies, carbon pricing mechanisms, and tax incentives as key drivers of energy technology sales [13], Jaffe et al. analyze the price elasticity of demand for different energy sources and the impact of policy interventions on the market share [14]. On the other hand, innovation, performance improvements, technological maturity, infrastructure availability, and grid integration capabilities that significantly affect the marketability of energy technologies are dealt with by Foster [15], and Grübler et al. explore the diffusion of innovations and the role of learning curves in reducing the cost of new technologies [16]. Social and behavioral factors have been analyzed as well. For instance, Stern evaluates consumer preferences, awareness of environmental issues, social norms, and trust in new technologies as aspects that play crucial roles in adoption decisions [17], and Rogers provides insights into behavioral economics and sociology in terms of various energy technologies [18]. Last but not least, government policies, including renewable energy mandates, feed-in tariffs, emissions standards, and regulations on fossil fuels, having a profound impact on the sales and deployment of different energy technologies are discussed by Helm [19], and Vieira et al. compare the effectiveness of various policy instruments [20].

Apart from the above aspects and literature sources, the topic of the ongoing global energy transformation and its drivers (such as climate change, energy security, and technological advancements) have also been examined. For instance, Smil explores the pathways and challenges related to shifting away from fossil fuel-dominated energy systems. This includes analyses of stranded assets, the role of incumbent industries, and the need for new infrastructure [21]. Furthermore, a study [22] focused on the rapid growth of renewable energy technologies and their integration into existing energy systems, and Jacobson et al. address issues such as grid stability, energy storage, and the intermittency of renewable sources [23]. The increasing electrification of various sectors (e.g., transportation and heating) and the integration of different energy systems (e.g., power-to-gas) as key indicators of the energy transformation are discussed in [24]. This literature explores the potential for reducing emissions and increasing energy efficiency through these trends. And last but not least, Falkner investigates the role of international agreements (e.g., Paris Agreement),

national energy strategies, and sub-national initiatives in driving the energy transition [25]. The effects of political economy, public opinion, and stakeholder engagement are analyzed as well.

While significant research exists in each area under investigation, a further in-depth and meticulous examination is needed to fully understand the comprehensive interconnections among emissions and environmental impacts, sales dynamics, and the broader energy transformation. For example, more research could explore

- The feedback loops between public awareness of environmental impacts and consumer demand for cleaner energy technologies;
- The influence of specific emission regulations on the market competitiveness of different energy sources;
- The roles of sales and market penetration in accelerating the learning curves and cost reductions of low-carbon technologies (so called “eco-friendly”), thus further driving down emissions;
- The social and economic consequences of different energy transition pathways, considering both environmental benefits and potential disruptions, and so forth.

The conducted research, in addition to scientific studies, was also based on available reports, analyses, and tests published by car manufacturers, specialist industry portals, and motoring enthusiasts. Such a wide range of sources allowed a more comprehensive and diverse picture of the subject matter to be obtained, taking into account both the theoretical foundations and practical aspects of use and the opinion of the automotive community.

3. Methodology

Life cycle assessment (LCA) is a well-established and standardized methodology for evaluating the environmental impacts of products, processes, and services, covering the full scope of their existence—from raw material extraction to final disposal [26]. The term “cradle to grave” means that LCA considers all stages of the life cycle: the extraction and processing of raw materials, component production and assembly, distribution of the finished product, its use by the consumer, as well as end-of-life waste management, including recycling and landfilling [27,28].

In the automotive sector, particularly for passenger vehicles, life cycle analysis enables a comprehensive assessment of the total environmental footprint of a given means of transport [29–31]. A particular emphasis is placed on estimating total greenhouse gas emissions, most commonly expressed in terms of the carbon dioxide equivalent (CO₂e), generated at each of the mentioned stages. This approach allows not only for a comparison of different drivetrain technologies—such as internal combustion engines (gasoline and diesel) and electric drivetrains—but also for the identification of life cycle stages with the highest contribution to emissions [32,33].

In practice, LCA takes into account numerous variables, such as the type and origin of raw materials, the source of energy used in the production process, the energy intensity of vehicle use (including the fuel type or energy mix), as well as end-of-life scenarios for vehicle disposal. As a result, the findings can serve as a basis for developing more sustainable strategies for technological development, climate policy, and consumer decision-making. Operational emissions include all energy-related emissions occurring during vehicle use, including fuel consumption during engine idling, warm-up, and stop-and-go conditions, as captured in the total lifetime fuel consumption estimates.

This study considers the following key stages of a vehicle’s life cycle:

- Raw material extraction and processing—This stage includes emissions associated with obtaining the raw materials needed for vehicle production, such as steel, alu-

minum, plastics, and—in the case of electric vehicles—the materials used in battery production (lithium, cobalt, nickel, and manganese) [33]. These processes are often energy-intensive and generate significant amounts of CO₂. For example, meta-analyses of lithium-ion battery production show a global warming potential ranging from 12 to 313 kg CO₂e per kWh of battery capacity, with a global average around 187 kg CO₂e/kWh [34,35]. Another study reports 110 g CO₂e (≈0.11 kg CO₂e) per Wh, i.e., 110 kg CO₂e/kWh [36]. Vehicle and component manufacturing—This stage relates to emissions from manufacturing the vehicle itself and its key components, including the engine, gearbox, and, in the case of electric vehicles, the battery. The production of lithium-ion batteries for electric vehicles is particularly energy-intensive and can significantly contribute to their initial carbon footprint, causing increases of 15% to 68% in vehicle manufacturing emissions and adding roughly 53–356 kg CO₂e per kWh of battery capacity (global average ~110–187 kg CO₂e/kWh) [33,37,38].

- Fuel/energy production and distribution—For gasoline and diesel vehicles, this stage includes crude oil extraction, transport, and the energy-intensive refining process to produce gasoline and diesel fuel. For electric vehicles, this stage involves the generation of electricity from various sources (fossil fuels, nuclear power, and renewable energy) and its transmission and distribution to charging stations. It is important to emphasize that the energy mix of a given region plays a crucial role in determining the CO₂ emissions associated with the use of electric vehicles [39].
- Vehicle use and maintenance—For gasoline and diesel vehicles, this stage focuses on direct CO₂ emissions from fuel combustion in the engine. Electric vehicles do not emit CO₂ directly during operation, but their use is indirectly associated with emissions from electricity generation. Indirect emissions related to the production and use of consumables such as tires and lubricants should also be considered.

End-of-life/recycling—This stage includes emissions related to the disposal of the vehicle and its components, as well as the potential environmental benefits from recycling materials (steel, aluminum, and battery components), and the energy savings and avoided emissions made possible by using recycled materials [33].

In the vehicle life cycle analysis, the well-To-wheels (WTW) approach is often used. It focuses on the life cycle of the energy carrier used to power the vehicle (liquid fuel or electricity), considering environmental protection aspects from the energy source to its use in the vehicle [33,40,41].

The methodology for calculating the linear regression applied to the sale forecasts is that the sale forecast was conducted independently for each drivetrain type using linear regression [42]:

$$S_i(t) = a_i \cdot t + b_i$$

where

$S_i(t)$ is the number of vehicles of type i (gasoline, diesel, hybrid, electric) sold in year t ,
 a_i, b_i is the regression coefficients for the drivetrain,
 $t \in \{2021, \dots, 2025\}$ are the observation years, and
 predictions were made for the years $t = 2026, 2027, 2028$.

Based on the projected number of sold vehicles, CO₂ emissions over the full lifecycle of each vehicle were estimated using the following equation:

$$E_i(t) = S_i(t) \varepsilon_i$$

where

$E_i(t)$ is the CO₂ emissions for vehicle type i in year t , in tons, and
 ε_i is the unit CO₂ emission per vehicle of type i .

4. Results Obtained

4.1. CO₂ Emissions of Petrol-Powered Passenger Cars

The life cycle of a petrol-powered car begins with the extraction of crude oil, its transportation, and the energy-intensive refining process required to produce petrol. Each of these stages contributes to CO₂ emissions. Subsequently, during the production of the vehicle itself, additional emissions are generated due to the extraction and processing of raw materials such as steel and aluminum [33], the production of various components, and the final assembly of the car.

The largest share of CO₂ emissions in the life cycle of a petrol car occurs during the usage phase [43,44]. Direct CO₂ emissions result from burning petrol in the engine. Average CO₂ emissions during the use phase of petrol cars are estimated at 120–150 g/km [45,46]. Studies show that the total life cycle CO₂ emissions of a petrol car in Europe in 2021 were just under 250 g CO₂/km. Forecasts for 2031, assuming the implementation of the Paris Agreement, predict only a slight decrease to around 240 g CO₂/km [6]. Another study by VDI estimated that a petrol car emits 37.1 tons (≈ 186 gCO₂/km) of CO₂ over a lifetime distance of 200,000 km [47]. In comparison, the Renault Clio's average total life cycle CO₂ emissions in European use were estimated at approximately 47 tons (≈ 235 gCO₂/km) [48].

The end-of-life phase of a petrol vehicle also generates CO₂ emissions, related to its disposal, including potential emissions from landfills and the energy needed to recycle materials such as steel and aluminum [33].

Analyzing the life cycle of a petrol vehicle shows that fuel combustion is the dominant phase in terms of emissions, although fuel production and vehicle manufacturing also make significant contributions. The limited forecasted reductions in emissions for petrol cars by 2031 suggest that achieving a substantial environmental impact reduction may be difficult through internal combustion engine improvements alone [49].

4.2. CO₂ Emissions of Diesel-Powered Passenger Cars

Similar to petrol vehicles, the life cycle of a diesel car begins with the extraction, transport, and refining of crude oil to produce diesel fuel. These processes generate CO₂ emissions, which may differ slightly from those involved in petrol production. Manufacturing a diesel vehicle also results in CO₂ emissions from material processing and assembly.

During operation, diesel vehicles emit CO₂ directly. Average tailpipe emissions are estimated at 130–170 g/km [50]. WHO data for Europe in 2021 indicate total emissions for diesel cars comparable to petrol cars, around 250 g CO₂/km [6]. A VDI study estimated emissions at 33.0 tons of CO₂ over 200,000 km, slightly lower than petrol vehicles in this specific analysis [47]. A noteworthy result from the Green NCAP study showed that the Škoda Octavia Combi 2.0 TDI consumes 164 MWh of energy over its lifetime, which is comparable to, or even better than, some electric and hybrid vehicles [48].

The end-of-life stage for diesel vehicles is similar to that of petrol vehicles.

Although diesel cars are commonly thought to emit more CO₂ during operation than petrol cars, some life cycle analyses suggest that due to potentially better fuel efficiency, their total emissions may be slightly lower [46,47,50]. However, these outcomes can vary depending on the adopted methodology and study assumptions. The Green NCAP study highlights the complexity of comparing different drivetrains, suggesting that in certain scenarios, modern diesel vehicles may have comparable or even lower life cycle energy consumption than some electric and hybrid vehicles [48]. This underscores the importance of the assumptions and methodologies used in LCA (life cycle assessment) studies [51].

4.3. CO₂ Emissions of Electric Passenger Cars

The life cycle of electric passenger cars differs significantly from combustion engine vehicles, particularly in the usage phase. However, they generate CO₂ emissions at other stages. The extraction and processing of raw materials necessary for battery production—such as lithium, cobalt, nickel, and manganese—are associated with significant CO₂ emissions [33]. These processes are energy-intensive and have notable environmental impacts. The production of lithium-ion batteries itself is highly energy-consuming and represents a major contribution to the initial carbon footprint of electric vehicles [1,33]. This stage is estimated to account for 50% to 90% of the total CO₂ emissions in the life cycle of an electric vehicle [38,52]. Nevertheless, due to technological advancements and the use of cleaner energy sources in manufacturing, CO₂ emissions per kWh of battery production show a decreasing trend [38,52].

The production of the electric vehicle itself, excluding the battery, involves emissions from material processing and assembly similar to those in combustion vehicles [33].

CO₂ emissions during the use phase of electric vehicles depend entirely on the source of electricity used for charging [53,54]. Assuming the average European energy mix in 2021, total CO₂ emissions for electric vehicles were about 80 g CO₂/km, with projections for 2030 indicating a decrease to around 65 g CO₂/km [55]. When powered entirely by renewable energy, emissions drop below 50 g CO₂/km [55]. In countries with a high share of fossil fuels in the energy mix, such as Poland, per-kilometer emissions during use can be higher compared to countries with cleaner energy sources [56].

The end-of-life stage of batteries and their recycling is critical for assessing the environmental impacts of electric vehicles. Battery recycling can help reduce CO₂ emissions and recover valuable raw materials [33]. Developing an efficient and sustainable battery recycling infrastructure is therefore crucial.

A VDI study found that the electric Volkswagen ID.3 emits 24.2 tons of CO₂ over 200,000 km [47]. For comparison, the Renault Zoe emits 32 tons of CO₂ over its entire life cycle in Europe [48]. The potential reduction in life cycle emissions for electric vehicles ranges from 17–30% when using non-renewable electricity to 60–80% when powered entirely by renewables compared to a petrol vehicle [57]. A WHO study suggests that electric vehicles in Europe generate 66–69% fewer greenhouse gas emissions than comparable petrol vehicles [6]. A study by Volvo indicates that manufacturing an electric vehicle may produce 70% more CO₂ than a combustion vehicle, but the total life cycle carbon footprint becomes lower over time and mileage [57].

The initial carbon footprint of electric vehicles is usually higher than that of petrol or diesel vehicles due to energy-intensive battery production [58]. However, operational emissions are significantly lower, especially when the electricity comes from renewable sources [59]. This leads to a lower overall life cycle emission level in many scenarios [58]. The point at which an electric vehicle's total emissions become lower than those of a comparable petrol or diesel car depends largely on the carbon intensity of the power grid. In regions with a high share of fossil fuels in the energy mix, this point may be reached after a longer period of use [56]. Studies such as those by WHO [6] suggest that even with the current European energy mix, electric vehicles already offer a significant reduction in life cycle greenhouse gas emissions compared to conventional vehicles. This advantage is expected to grow as the energy sector becomes more decarbonized [59].

4.4. Emission Comparisons and Statistics

Table 1 presents a comparison of the vehicle whole-life carbon emissions analysis of estimated lifecycle emissions (tons CO_{2e}) based on a 2015 vehicle in use for 150k KM using a 10% ethanol blend and 500 g/KWH grid electricity [60,61].

Table 1. Life cycle CO₂ emissions comparison: standard gasoline, hybrid, plug-in hybrid, and battery electric vehicles.

	Estimated Lifecycle Emissions (tons of CO ₂ e)	Proportion of Emissions in Production	Estimated Emissions in Production (tons of CO ₂ e)
Standard gasoline vehicle	24	23%	5.6
Hybrid vehicle	21	31%	6.5
Plug-in hybrid vehicle	19	35%	6.7
Battery electric vehicle	19	46%	8.8

Table 2 presents the life-cycle greenhouse gas (GHG) emissions (100-year global warming potential, in g CO₂e/MJ) for average fossil and biogenic blends of gasoline, diesel, and natural gas, as well as for grid electricity and hydrogen mixes in China, Europe (EU27+UK), India, and the United States. The data cover the 15–18 year lifetime of cars registered in 2021 and 2030, along with a sales-weighted global average across these regions. Emission values for gasoline, diesel, and natural gas are presented as (production emissions) + (consumption emissions) [60–62].

Table 2. Life-cycle greenhouse gas (GHG) emissions for average fossil and biogenic blends of gasoline, diesel, and natural gas, as well as for grid electricity and hydrogen mixes in China, Europe (EU27+UK), India, and the United States.

g CO ₂ e/MJ	Data	Gasoline (Including Biofuels)	Diesel (Including Biofuels)	Natural Gas (Including Biogas)	Average Grid Electricity	Hydrogen Mix
China	2021–2035	21.8 + 70.9	-	-	141.4	107.8
Europe	2021–2038	21.5 + 70.9	27.4 + 68.4	16.5 + 58.6	45.6	50.4
India	2021–2038	20.5 + 69.2	21.8 + 71.8	19.2 + 57.7	155.9	84.4
United States	2021–2035	22.2 + 69.7	-	-	66.5	64.3
Global average	2021 car	21.8 + 70.5	26.6 + 68.9	16.9 + 58.5	93.2	77.8

From the presented data, it is evident that CO₂ emissions over the vehicle life cycle vary depending on the type of vehicle and the study methodology. Gasoline (petrol) and diesel vehicles show similar levels of total CO₂ emissions per kilometer in many studies, especially when life-cycle emissions (including fuel production, vehicle manufacturing, and usage) are taken into account. For example, a comprehensive life cycle assessment by the International Council on Clean Transportation found that the total life cycle CO₂ emissions of diesel cars are only marginally lower (by about 3–5%) than those of gasoline cars, primarily due to slightly better fuel economy, which is largely offset by higher emissions during fuel production and vehicle manufacturing [61,63–65].

The energy mix has a significant impact on the life cycle emissions of electric vehicles. In countries where fossil fuels constitute a large share of the energy mix, the emission benefits of using electric vehicles may be reduced. However, as energy production shifts toward cleaner sources, the advantage of electric vehicles in terms of emissions will increase [66]. There is a trade-off between the higher initial emissions associated with the production of electric vehicles (especially batteries) and their lower operational emissions compared to gasoline and diesel vehicles.

This study is based on the assumption that renewable energy is low-emission in terms of CO₂, without considering the full life cycle of its production, which would require separate analyses. Nevertheless, many studies question the zero-emission status of renewable

energy production and point out its potential environmental harm—which should also be highlighted in the context of the studies presented in this paper. It is commonly assumed that renewable energy production is climate-friendly and essentially free of CO₂ emissions, especially during the energy generation phase [67]. This argument is frequently raised, for example, regarding the direct operation of renewable energy installations, where solar panels convert sunlight and wind turbines convert wind energy into electricity without emitting CO₂ [67]. However, such a simplified perspective ignores the complexity of processes involved throughout the entire life cycle of renewable technologies. CO₂ emissions should be assessed at all stages of a renewable energy technology's life cycle, including raw material extraction, component production, transportation, installation, operation, and end-of-life disposal or recycling. Relying on an incomplete picture of the environmental impacts of renewable energy development may lead to misguided strategies and ultimately hinder the achievement of a truly sustainable energy system [68].

Nevertheless, this aspect will be analyzed in future studies by the authors as the next stage of the analyses presented in the paper. For now, it has only been signaled.

4.5. CO₂ Emissions Forecast Based on the Sales Structure of Selected Brands of Vehicles (2021–2028)

To expand the assessment of greenhouse gas emissions over the vehicle life cycle, an annual CO₂ emissions forecast was conducted based on the sales structure of vehicles from 2021 to 2025 and extrapolated to 2028. The analysis included passenger cars, classified by drivetrain type: gasoline, diesel, hybrid, and electric.

The collected sales data were used not only to determine direct emissions associated with vehicle operation but also as a foundation for further modeling of future development trends in electromobility and their potential environmental impacts. The assessment covered not only the magnitude of emissions but also the dynamics of change, including the gradual decline in the share of internal combustion engine (ICE) vehicles and the growing significance of alternative drivetrains.

Additionally, based on the sales data, the following charts were created [61]:

- A radar chart of selected cars' parameters (2020–2024), see Figure 1;
- A three-dimensional histogram of the number of vehicles sold by type from 2020 to 2025 (no. of obs), see Figure 2;
- An annual CO₂ emissions forecast by drivetrain type (2021–2028), see Figure 3.

For a comparative analysis, we selected five investigated vehicle models, each representing a different drivetrain type: x (electric drive), y (petrol engine), z (plug-in hybrid drive), k (petrol engine), and l (diesel engine).

Figure 1 above displays a radar chart that compares four key technical parameters: maximum power (kW), torque (Nm), 0–100 km/h acceleration (s), and range (km). To allow for a direct comparison despite varying units, these parameters were normalized within the (0, 1) range.

The values in the chart are sourced from Table 3 below and reflect actual technical data, consistent with official manufacturer specifications. The chart's calibration sets the circle thresholds at normalized levels of 0.2, 0.4, 0.6, 0.8, and 1.0, thereby maintaining proper proportions between the models. Table 3 presents the actual values for each parameter.

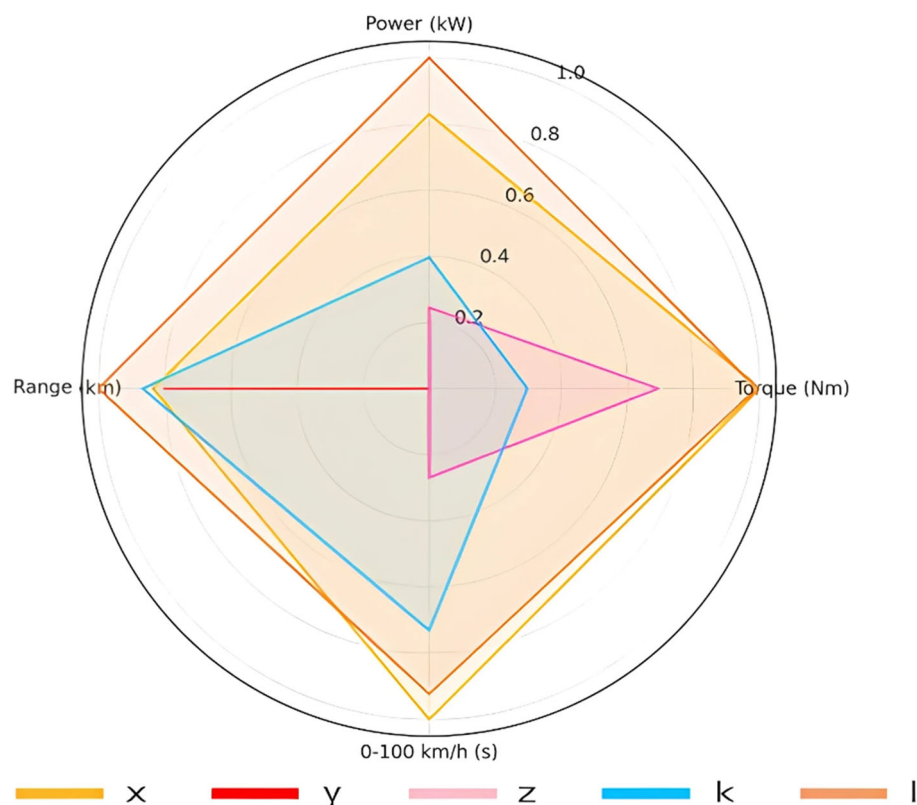


Figure 1. Comparison of the technical parameters of vehicles (2020–2024).

Table 3. Actual, catalog values of selected car parameters.

Symbol	Power (kW)	Torque (Nm)	Range (km)	Acceleration 0–100 km/h (s)	Powertrain Type
x	385	855	679	4.3	Electric
y	430	850	500	4.5	Petrol
z	230	550	117	6.7	Hybrid
k	270	500	590	5	Petrol
l	110	320	600	8.6	Diesel

An analysis of the chart reveals that model x an electric vehicle, excels in range and torque. In contrast, model y demonstrates the highest power output. Model z, a plug-in hybrid, shows significantly lower power and range values, but it offers a good compromise between performance and efficiency.

Model k represents a premium car with high power and dynamic performance, making it suitable for fast highway driving, though it has moderate fuel efficiency.

Finally, model l is a more economical and practical choice that is well-suited for daily use, especially in urban and suburban conditions, with a focus on fuel efficiency and low emissions.

Figure 1 presents four key technical parameters of the selected models from the years 2020–2024: maximum power (in kW), maximum torque (Nm), acceleration from 0 to 100 km/h (s), and total driving range (km). The data for each parameter were normalized to standardize the scale and allow for direct comparison of values originally expressed in different units.

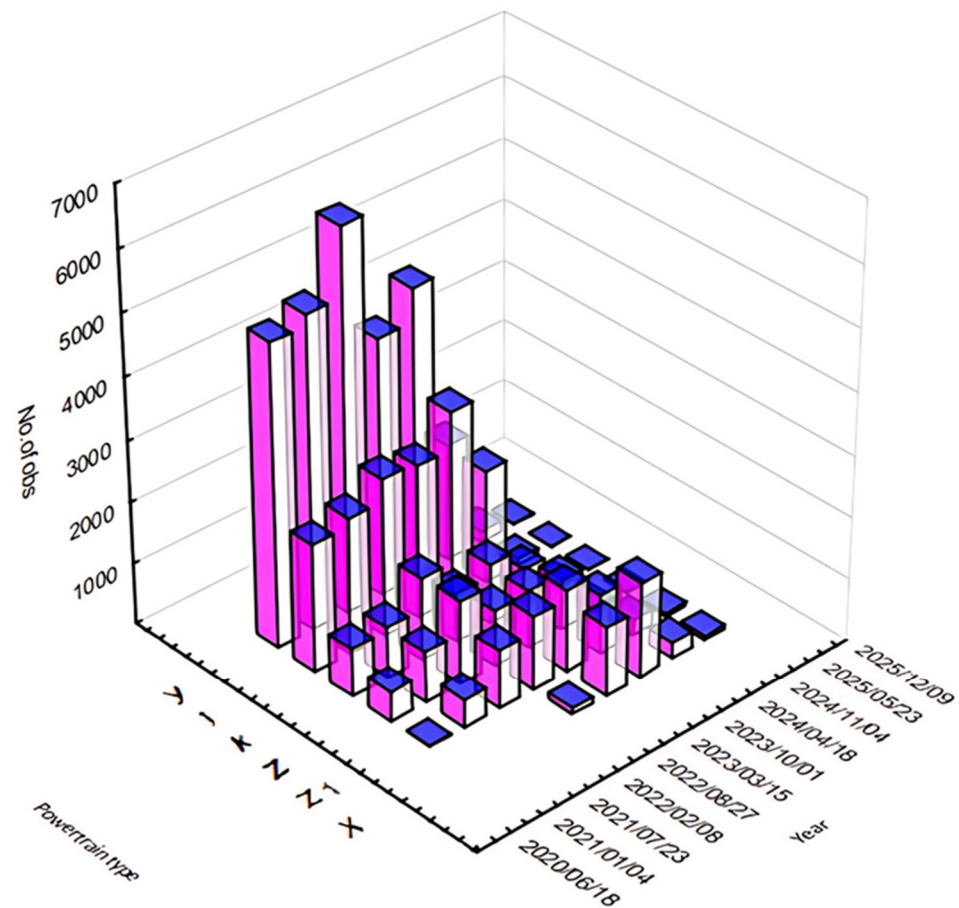


Figure 2. Histogram of the number of vehicles sold by type (2020–2025).

Figure 2 presents the number of vehicles sold, with the axes representing the following [62]:

The X-axis represents the sales date, which covers the period from June 2020 to December 2025. Dates are marked at aggregate points (e.g., every few months), allowing an analysis of sales seasonality and dynamics over time.

The Y-axis represents the vehicle drivetrain type, where x denotes electric vehicles, y and k correspond to petrol-powered vehicles (with k referring specifically to an exclusive convertible model), z and z_1 denote hybrid vehicles, and l represents diesel-powered vehicles.

The Z-axis represents the number of vehicles sold in a given period and for a given type/model (No. of obs = number of observations).

The results reveal that throughout the analyzed time frame, petrol-powered vehicles of type y consistently exhibited the highest sales volumes, with a pronounced peak observed between 2022 and early 2024. While a gradual decline is visible in the most recent data (2025), petrol engines still maintained a dominant market share.

The k variant, characterized as a premium convertible, showed significantly lower sales figures across the entire period, which aligns with its exclusive market positioning. Despite this, its relatively stable sales trajectory may suggest the presence of a steady, niche consumer base.

Electric vehicles, x, demonstrated a clear upward trend over time, with a noticeable acceleration in sales from 2023 onward. This pattern reflects the increasing adoption of electromobility, likely driven by broader regulatory, economic, and technological developments across the industry.

The hybrid category, z, experienced substantial sales during the mid-2021 to mid-2023 window, after which a modest decline occurred. In contrast, the alternative hybrid model z_1

maintained a steady yet comparatively lower sales volume, suggesting consistent interest within a targeted segment of the market.

Finally, diesel-powered vehicles, I, consistently recorded the lowest sales levels across all time points. Their marginal and declining trend further supports the broader observation of their decreasing relevance in light of global decarbonization policies and shifting consumer preferences.

In summary, the data presented in Figure 2 reveal a progressive transformation in the automotive market, characterized by a gradual shift away from traditional internal combustion engines—particularly diesel—toward electrified powertrains. While petrol engines remain prevalent, the growing uptake of electric and hybrid vehicles indicates a transition toward more sustainable mobility solutions.

Calculation Methodology (see Section 3)

Assumed Unit Emission Values

The values ε_i were adopted from the sources [61,69,70] (see Table 4).

Table 4. The values ε_i adopted for individual vehicle types.

Vehicle Type	Unit Emissions ε_i [t CO ₂ /vehicle]
Gasoline	37.0
Diesel	33.0
Hybrid	28.0
Electric	22.0

To better illustrate the changes, the relative change in emissions compared to the base year (2021) was introduced:

$$\Delta E_i(t) = ((E_i(t) - E_i(2021)) / (E_i(2021))) \cdot 100\%$$

Assuming an average vehicle lifetime mileage of 200,000 km and average emissions per km, emissions can also be calculated with

$$\varepsilon_i = e_i \cdot d$$

where

e_i is the average emissions per 1 km,

$d = 200,000$ km and is the assumed mileage.

Results and Interpretation

For example, in 2026, the forecasted sales are

- 4527 gasoline vehicles;
- 3704 diesel vehicles;
- 100 hybrid vehicles;
- 893 electric vehicles.

This translates into

$$E_{benz}(2026) = 4527 \cdot 37.0 = 167,499 \text{ t CO}_2$$

$$E_{diesel}(2026) = 3704 \cdot 33.0 = 122,232 \text{ t CO}_2$$

$$E_{hyb}(2026) = 100 \cdot 28.0 = 2800 \text{ t CO}_2$$

$$E_{elek}(2026) = 893 \cdot 22.0 = 19,646 \text{ t CO}_2$$

$$E_{total}(2026) = 167,499 + 122,232 + 2800 + 19,646 = 312,177 \text{ t CO}_2$$

These calculations were repeated for each year, creating an annual emissions summary (see Table 5), which can serve as a basis for assessing the impacts of sales trends on emissions in the automotive sector.

Table 5. Results for 2021–2028.

Year	Gasoline	Diesel	Hybrid	Electric	Total Emissions (t)
2021	6300	4500	150	300	312,300
2022	5200	4200	130	450	282,170
2023	5000	4000	120	550	270,400
2024	4700	3800	110	675	256,350
2025	4600	3750	105	800	251,950
2026	4527	3704	100	893	248,177
2027	4450	3650	95	975	244,180
2028	4375	3600	90	1050	240,185

Figure 3 depicts a forecast of the vehicles under investigation according to the drive-train type and year (2021–2028).

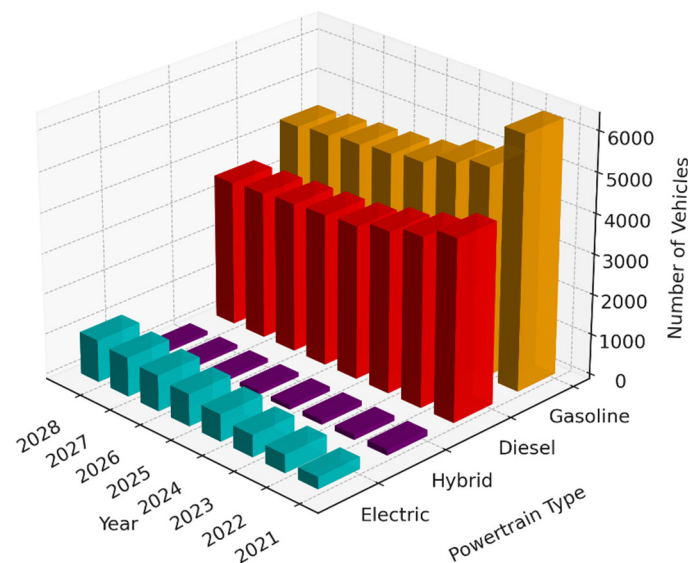


Figure 3. Forecast of vehicles by type and year (2021–2028).

Figure 3 above shows the number of vehicles sold between 2021 and 2028, broken down by drivetrain type: gasoline, diesel, hybrid, and electric. A clear reduction in the sales of internal combustion engine vehicles and an increase in the sales of electric vehicles are evident during the analyzed period.

5. Discussion

Based on the results obtained (see Section 4 above), the estimated CO₂ emissions (in tons) for four types of drivetrains: gasoline (orange line), diesel (red line), hybrid (dark pink line), and electric (light pink line) are depicted in Figure 4.

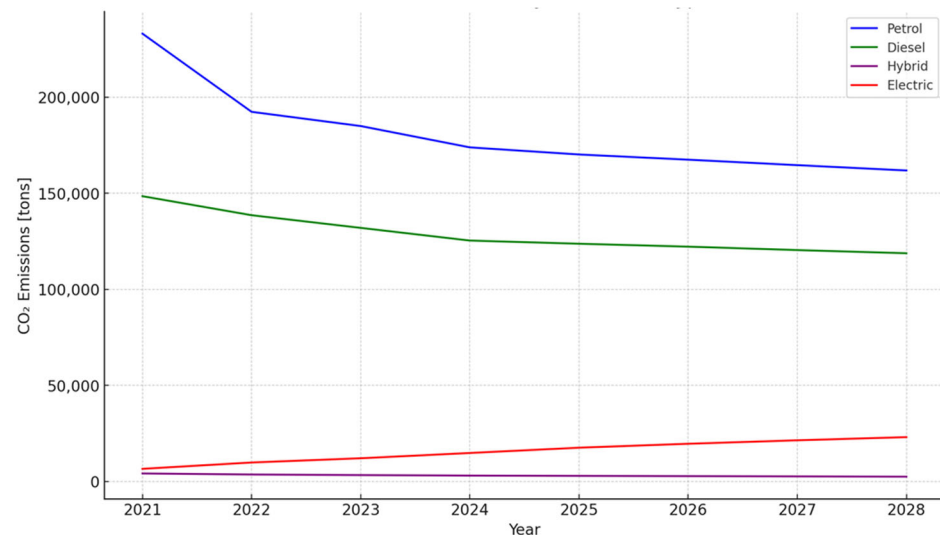


Figure 4. Annual CO₂ emissions forecast by drivetrain type (2021–2028).

A downward trend in CO₂ emissions from gasoline vehicles is evident, from over 210,000 tons in 2021 to approximately 165,000 tons in 2028. Similarly, emissions from diesel vehicles declined from around 145,000 tons to just above 120,000 tons over the same period.

Hybrids generate significantly lower emissions than internal combustion engine (ICE) vehicles, on the order of several tens of thousands of tons annually, and show a stable, slow upward trend, which corresponds to an increasing number of hybrid vehicle sales.

Additionally, although CO₂ emissions associated with electric vehicles remain low (mainly due to electricity production and charging), the chart indicates a growing share of this group: emissions increased from approximately 6600 tons in 2021 to nearly 23,000 tons in 2028. It is worth noting that even though the emissions generated by electric vehicles are significantly lower, their growing number may, in the coming years, contribute to a shift in the emissions profile from the usage phase to the electricity production phase.

Figure 4 illustrates the evolution of emission structures in the premium private transport sector in the context of the energy transition. It also confirms that the continuous increase in the share of electric and hybrid drivetrains contributes to reducing total CO₂ emissions in the long term, although achieving this requires maintaining a high pace of technological transformation.

The results obtained confirm that, despite the growing share of electric vehicles, total CO₂ emissions remain significant due to the dominance of internal combustion engine vehicles in the sales structure. Only a substantial change in the sales structure (a mass transition to zero-emission drivetrains) will result in a real reduction in emissions in the post-2030 period [71]. The presented methodology can be applied to a scenario-based analysis of climate policies and the modeling of potential benefits from accelerating the energy transformation in the transport sector.

Although the sales of electric vehicles are growing dynamically, their impact on the overall reduction of CO₂ emissions by 2028 is still limited. A key factor that restricts the environmental effect is the high share of internal combustion vehicles from previous years, which remain in operation for many years [72,73].

The presented model also allows for the simulation of the impacts of decarbonization policies, changes in the energy mix, and tax regulations. In the next stages of the study, it is planned to introduce emission weights depending on the country of vehicle use and account for the effect of material recycling in the product's end-of-life phase [74].

In the context of further development of the proposed model, it will also be crucial to consider the differentiated emission intensity depending on the vehicle segment and its lifecycle mileage. Commercial vehicles, such as delivery and heavy trucks, have significantly higher unit emissions than passenger cars, meaning that their energy transformation could result in relatively larger environmental benefits. Expanding the model to include these aspects will allow for a more accurate assessment of the potential impacts of different policy scenarios. This will be part of the authors' further research [75,76].

It is also worth noting that the transport transformation is not limited to changes in the vehicle drivetrain itself. An important element will also be the development of the charging infrastructure, intelligent traffic management systems, and the promotion of alternative forms of mobility, such as public transport and micromobility. Only the synergistic actions of all these elements will provide a comprehensive and lasting reduction in emissions in the transport sector.

From the perspective of policymakers, it is therefore essential to develop integrated strategies that combine financial incentives, environmental regulations, and infrastructure investments. The presented model can support the decision-making process by identifying the most effective directions for action, considering both implementation costs and the expected effects in terms of emission reduction and economic impact.

In future research, it is also planned to include the social and economic aspects of the transformation, such as the availability of electric vehicles for different social groups, the impact on employment in the automotive sector, and changes in energy consumption patterns. Such an extension would enable a more comprehensive understanding of the consequences of transport decarbonization and assist in designing a just energy transition [77].

6. Conclusions

The conducted study aimed to evaluate the impact of the sales structure of the selected brands of passenger cars on total CO₂ emissions with regard to the ongoing global energy transformation in the transport sector. By analyzing sales forecasts for gasoline, diesel, hybrid, and electric vehicles over the years 2021–2028, and employing the LCA-based mathematical model when incorporating the carbon footprint of each powertrain type (called also as engine propulsion or drivetrain type) and projected sales figures, this research provides valuable insights into the emission trends of a major automotive manufacturer.

Following the outcomes of the analysis obtained, the findings indicate a gradual decline in total CO₂ emissions over the analyzed period. This reduction is primarily attributed to the increasing market share of alternative drivetrains, in particular hybrid and electric vehicles. However, this research highlights that despite the growth in electric vehicle sales, their immediate impact on overall emission reductions is somewhat constrained by the long lifespan of the existing fleet of conventionally powered vehicles. This suggests that a sustained and accelerated transition toward alternative drivetrains is inevitable to achieve significant emission reductions in the short to medium term.

Nevertheless, this study acknowledges several ensuing limitations that should be taken into consideration when interpreting the findings.

- First, this analysis is based on sales forecasts, which inherently carry a degree of uncertainty. Thus, deviations in actual sales figures could affect the projected emission reduction level.
- Second, the LCA model applied relies on mean emission factors for each drivetrain type. Variations in manufacturing processes, energy sources for electricity generation, and end-of-life treatment could affect the actual life cycle emissions.
- Third, this research focuses solely on the sales structure of passenger cars of one brand within a specific timeframe and does not account for the broader vehicle fleet or the

impact of external factors (such as evolving energy policies, consumer behavior beyond purchasing decisions, and so on). To enhance the understanding of the automotive sector's role in the energy transformation and to inform more effective climate policies, several avenues for further research are recommended, as follows:

- Expanding the LCA model to incorporate regional variations in energy grids, the environmental impacts of battery production and recycling, and the emissions associated with vehicle manufacturing would provide a more comprehensive evaluation.
- In addition, future research could explore the effects of government incentives, charging infrastructure development, and consumer adoption rates on the pace of electric vehicle penetration and its subsequent impact on emission reduction as well.
- Furthermore, analyzing the emission trends of other major automotive manufacturers and across different vehicle segments would offer a broader perspective on the sector's overall contribution to the energy transition.
- Last but not least, investigating the potential of other alternative fuels and drivetrain technologies beyond electrification, such as hydrogen fuel cells and sustainable biofuels, within the same analytical framework could provide a more holistic understanding of future mobility scenarios and their environmental implications

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