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Remarkable results of energy consumption and CO_2 emissions for gasoline and electric powered vehicle

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Abstract

Increasing concerns about climate change and efforts on reducing reliance on fossil fuels have led to research on electric vehicles for sustainable solutions to increasing energy demands. This study comprehensively analyzes the impact of power plant emissions on the adoption of electric vehicles in relation to air pollution. The main pollutants emitted by power plants and the potential change in emissions with the deployment of electric vehicles are assessed. Energy consumption of the vehicles was calculated. A gasoline-powered and an electric vehicle are modelled in MATLAB Simulink software. The theoretical model results of the main pollutants are compared with the power plant emissions to analyze the effect on major pollutants. This investigation aims to identify the potential CO_2 emission and power requirement by transitioning to electric vehicles. Results show that energy consumption and CO_2 emissions can be 111% and 82% higher than GPVs depending on the electricity generation technologies.

Keywords

Electric vehicles, energy consumption, CO_2 emission, gasoline-powered vehicle, Simulink

Introduction

Powerplants are a major contributor to air pollution, releasing carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM).[1] For many power plants, data on emissions from electricity generation can be found in government reports and environmental organizations. These emissions are associated with many phenomena, such as climate change, acid rain formation, and respiratory diseases.[2–4]

The transportation sector is one of the largest contributors to greenhouse gas emissions.[5,6] Reducing emissions helps to decrease the amount of CO_2 in the atmosphere, a

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significant contributor to global warming, and simultaneously improves air quality, benefiting human health.[2,7] Lower concentrations of harmful pollutants will improve air quality and reduce the risk of illnesses such as cardiovascular and respiratory diseases caused by air pollution.[8] Consequently, transportation is one of the focal points of research into environmentally friendly alternatives. Among these, electric vehicles (EVs) are shown to have the potential to reduce emissions and promote the use of clean energy sources.[9]

Research into EVs is driven by the need to address environmental concerns, enhance energy efficiency, integrate renewable energy sources, manage resources responsibly, and adapt to shifting economic and technological landscapes. Carbon-neutral strategies aim to transition the transportation sector from relying on fossil fuel-powered vehicles to cleaner and more sustainable alternatives, such as EVs or fuel cell vehicles.[10] Unlike traditional internal combustion engine vehicles (ICEVs), which emit significant amounts of CO_2 and other pollutants, EVs have the potential to substantially lower emissions of NO_x and PM, particularly when charged with renewable energy. For instance, 1% increase in EV sales in one city can reduce CO_2 emissions by 0.096%.[11] However, the impact of EVs on air pollution heavily depends on the electricity sources used for charging the vehicles.[12]

As EV adoption expands, electricity demand will rise, potentially leading to higher emissions if the additional electricity comes from fossil fuel power plants. If this increased demand is met by renewable energy sources such as wind or solar, emissions from power generation could decrease, resulting in lower levels of CO_2, NO_x, SO_2, and PM. In regions where electricity generation predominantly relies on fossil fuels, such as coal or natural gas, the environmental benefit of EVs may be reduced compared to gasoline-powered vehicles (GPVs).[13,14] On the other hand, when the electricity is generated from renewable sources, EVs can significantly contribute to reducing air pollution and greenhouse gas emissions, resulting in even greater overall emissions reductions.[15] Thus, the net impact of EV adoption on power plant emissions is contingent upon the energy mix used to meet the increased electricity demand. A transition towards cleaner technologies and renewable energy could reduce emissions, while continued reliance on fossil fuels might offset some of the environmental benefits of EVs. Therefore, policies promoting renewable energy and energy efficiency are crucial in determining the net impact of EV adoption on power plant emissions.

Analyzing the environmental impact of EVs involves various methods, each focusing on different aspects of the vehicle lifecycle. Lifecycle assessment (LCA) evaluates the environmental impacts from raw material extraction through manufacturing, use, and disposal.[16] Carbon footprint analysis quantifies greenhouse gas emissions, considering both direct vehicle emissions and indirect emissions from electricity generation, manufacturing processes and supply chain activities.[17] Energy efficiency analysis assesses how effectively EVs use energy compared to internal combustion engine (ICE) vehicles.[18] This includes well-to-wheel efficiency, which evaluates the total energy consumed from fuel extraction or electricity generation to vehicle propulsion, and battery efficiency, which looks at energy losses during charging and discharging. Air quality impact assessment focuses on improvements in local air quality due to reduced tailpipe emissions while accounting for power plant emissions.[19] Policy and regulatory impact evaluation assesses the influence of emission and fuel economy standards on EV adoption. Lastly, consumer behavior analysis explores how consumer choices and driving habits affect the overall environmental benefits of EVs.[20] Together, these methods provide a comprehensive view of the environmental implications of EV technology, highlighting the wide range of factors—from manufacturers and consumers to policymakers—that affect the overall impact of EVs on the environment.

However, few studies in the literature have examined the impact of electricity generation technologies on the emissions associated with EVs. Woo et al. stated that the emissions from EVs are significantly influenced by the composition of a country's electricity generation mix. When a substantial reliance on fossil fuels exists in the electricity generation mix, the greenhouse gas emissions produced by EVs tend to be higher when compared to conventional ICEVs.[21] Michealides analyzed the energy needed for EV propulsion and the energy/exergy trade-offs between hydrocarbons and electricity through thermodynamic analysis. The findings indicate that substituting internal combustion vehicles with electric ones can lead to a decrease in CO2 emissions in national electricity grids with a high proportion of renewables and nuclear energy. Conversely, emissions are likely to increase in grids heavily reliant on coal.[22]

It is essential to note that the emissions associated with EVs are not only dependent on the technologies used for electricity generation but also on the vehicle lifecycle. Manufacturing processes, materials used, and end-of-life disposal contribute to the overall emissions of an EV.[23,24] This study will specifically examine the impact of EV adoption on CO_2 emissions.

Analyzing the impact of power plant emissions on air pollution in relation to the adoption of EVs involves understanding the interactions between different sources of emissions and their effects on overall air quality. Quantifying emissions will help to evaluate the overall environmental impact and provide clear insights about the EVs and their integration into the energy system. The study aims to assess CO_2 emissions and fuel consumption, as well as the fuel efficiency of the EV. The amount of harmful emissions released to the environment obtained as a result of the theoretical study was compared with the power plant emissions and gasoline powered vehicle. By analyzing power plant emissions alongside vehicle data, this study will provide insights into the electric transportation's efficacy in reducing air pollution and achieving sustainability goals based on power plant technology.

Materials and methods

In this study, the focus is on analyzing the emissions and power requirement of an EV during the FTP-75 (Federal Test Procedure for 75) driving cycle. A theoretical model

Table 1. Test vehicle data.

Weight	1100 kg
Projection area	2 m^2
C_d	0.37

was built for a 4-cylinder 4-stroke euro 5 engine and Table 1 Test vehicle data. shows the technical data of test vehicle.

The data utilized for the gasoline engine powered vehicle was collected through diagnostics test on a 4-cylinder sedan vehicle. CO_2 emissions were calculated taking into account fuel consumption and O_2 data. In the calculations carried out for the EV, an additional 200 kg was included in the weight of the GPV. Data on the electricity generation, fuel consumption and emissions were sourced from U.S. Energy Administration.[25]

Based on the analysis of power plant emissions and EV data, we can learn about the role of EVs in air pollution and their role in sustainable energy goals.

Theoretical model

Theoretical model of a commercial EV was designed in MATLAB Simulink (Figure 1). The model consists of vehicle data and engine maps. In the developed mathematical model, the energy consumption need was determined with Newtonian equations depending on the vehicle's driving resistances. Inverter efficiency and electric motor efficiency are taken into account. Also, charge-discharge efficiency maps for the battery have been added. A more advanced model based on battery temperature may provide higher accuracy. However, since we did not have battery temperatures, they could not be added to the model.

FTP-75 cycle was performed for the pollution analysis and determine power requirement. FTP-75 procedure is used to measure emissions and fuel economy for vehicles in United States. The driving cycle encompasses city and highway tests, which comprise a range of conditions, such as idling, low-speed driving, and high-speed driving. These tests cover a broad spectrum of scenarios to ensure comprehensive evaluation. The selection of the FTP-75 cycle was guided by its widespread use and alignment with established emissions data and regulatory standards provided by U.S. power plants. Although real-world driving conditions may vary, employing this standardized cycle ensures consistency and comparability with existing emission factors and regulatory frameworks. Consequently, the FTP-75 cycle serves as a representative model for urban driving

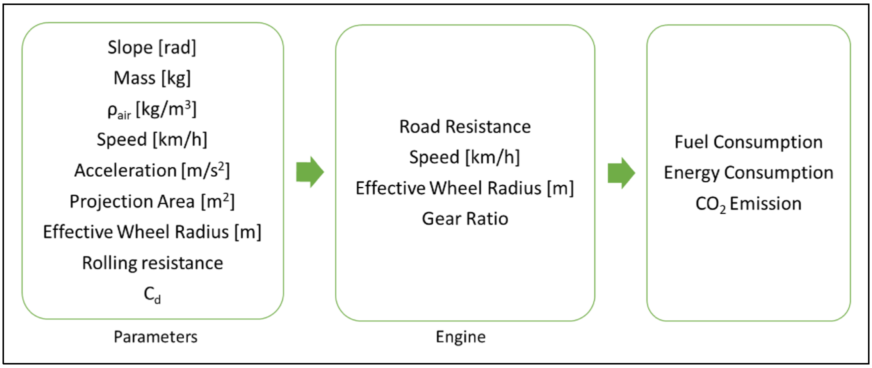

Figure 1. Simplified Simulink vehicle model.

conditions prevalent in many American cities, thus ensuring that our analysis adheres to recognized testing procedures.

Figure 2 shows the speed profile for FTP 5 cycle. Its key properties include a duration of approximately 31 minutes, an average speed of 34.12 km/h, a maximum speed of 91.25 km/h, and total distance of 17.77 km.

CO_2 emission data for different engine loads were obtained by MATLAB Simulink model. Results were compared with powerplant emission data.

The structure of the ANN model with parameters is presented in Figure 3.

Simulation results were compared with the gasoline fuel powered engine results to validate the performance of the electric engine.

Data reduction

The braking and drive torque balance due to the movement of the ICE or electric motor is given in Equation (1).

$$T_{eng} = I_{eng} \frac{d\omega_{eng}}{dt} \tag{1}$$

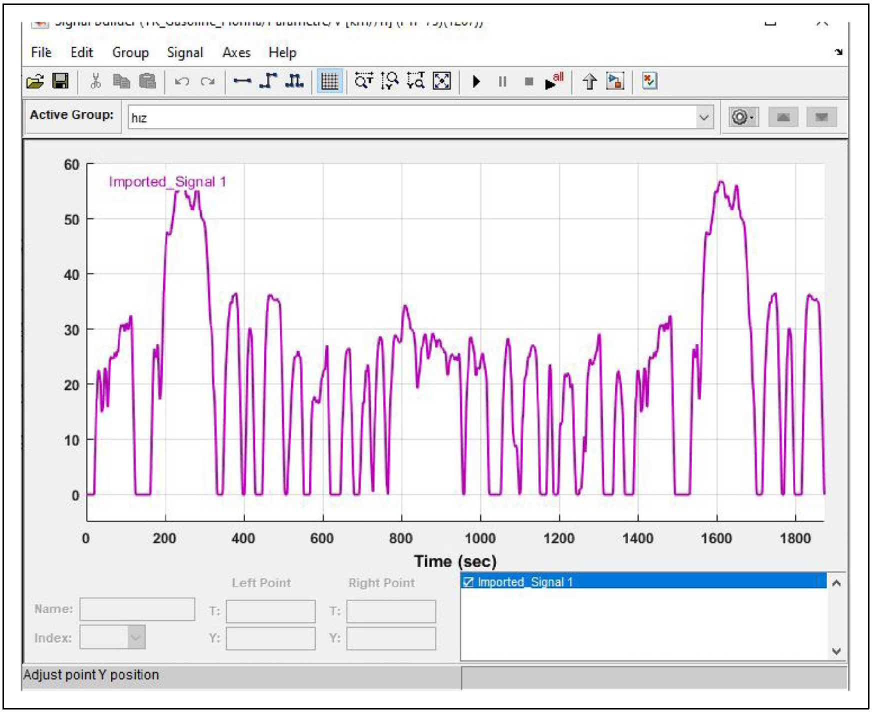

Figure 2. FTP speed profile.

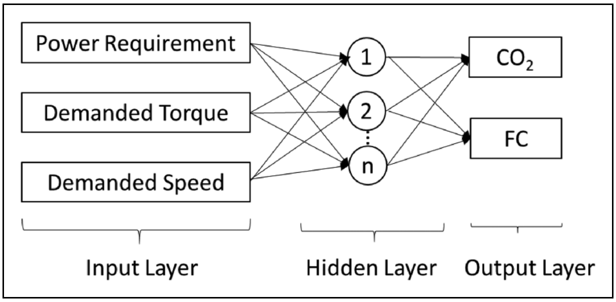

Figure 3. ANN model.

The driveline motion equation (equation (2)) describes how the ICE or electric motor generates output torque (T_{drv}) to balance the inertia of the entire drivetrain.

$$T_{\text{drv}} = \left[I_{\text{trans1}} + \frac{I_{\text{trans2}}}{R_t^2} + \frac{I_{\text{dsh}}}{R_t^2} + \frac{I_{\text{axl}}}{R_d^2 R_t^2} + \frac{M_{\text{veh}} r_{\text{whl}}^2}{R_d^2 R_t^2} \right] \frac{\mathrm{d}\omega_{\text{drv}}}{\mathrm{d}t} - \left[\frac{I_{\text{trans2}}}{R_t^3} + \frac{I_{\text{dsh}}}{R_t^3} + \frac{I_{\text{axl}}}{R_d^2 R_t^3} + \frac{M_{\text{veh}} r_{\text{whl}}^2}{R_d^2 R_t^3} \right] \omega_{\text{drv}} \frac{\mathrm{d}R_t}{\mathrm{d}t} + \left[\frac{F_{\text{aer}} + F_{\text{rol}} + F_{\text{grd}}}{R_d R_t} \right] r_{\text{whl}} \quad (2)$$

This balance also accounts for the inertia torque from the vehicle as well as the road resistances, such as aerodynamic drag, rolling resistance, and incline resistance.

Additionally, the calculations for forces resulting from vehicle travel resistances—such as aerodynamic resistance (F_{aer}), rolling resistance (F_{roll}), and incline resistance—are presented in equations (3)–(5).

$$F_{\text{aer}} = \frac{1}{2} \rho V^2 A_{\text{frontal}} \quad (3)$$

$$F_{\text{roll}} = d_{\text{road}} c_{\text{roll}} (M_{\text{veh}} + M_{\text{load}}) g \cos \alpha \quad (4)$$

$$F_{\text{grd}} = (M_{\text{veh}} + M_{\text{load}}) g \sin \alpha \quad (5)$$

In the vehicle model, ρ is the air density, d_{road} is the tyre resistance, c_{roll} is the rolling resistance factor, M_{veh} is the vehicle mass, M_{load} is the additional load on the vehicle, g is the gravitational acceleration, α is the slope value, V is velocity of air, A_{frontal} is the cross section area of the vehicle, T_{eng} is the engine or motor braking torque, I_{eng} is the engine or motor inertia, ω_{eng} is engine or motor speed, I_{trans1} is transmission moment of inertia input, I_{trans2} is transmission moment of inertia output, I_{dsh} is inertia of the driveline, I_{axl} is the inertia of the axle, r_{whl} is wheel radius, R_d is the ratio of power transmission, R_t is the ratio of the drivetrain, ω_{drv} is driveline speed.

$$N_{\text{e}} = F_{\text{v}} \times V \quad (6)$$

In this context, the term N_{e} represents the instantaneous power consumption of the vehicle, F_{v} denotes the sum of the instantaneous vehicle travelling resistances, and V

signifies the vehicle's travelling speed in meters per second.

$$L_e = N_{em} \times t_h \tag{7}$$

In this context, L_e represents the total energy demand attributable to the vehicle's cruise resistance, quantified in kWh. N_{em} denotes the average power consumption observed during the cruise cycle, while t_h denotes the duration of the cruise cycle in hours.

Results and discussion

The increase in vehicle weight was taken into account during the modeling studies related to the vehicle's conversion to electric power.

Energy consumption

The energy consumption and CO_2 emissions associated with EVs compared to GPVs can vary significantly based on several factors. These factors include power plant efficiency, power plant fuel source and EV technology. In the study, the energy consumption of EVs and GPVs have been calculated as an estimate of the potential energy savings.

EVs are generally more energy-efficient than GPVs, converting approximately 85% to 90% of the electrical energy from the grid into motion, compared to only 12% to 30% efficiency in ICEVs,[26,27] where much of the energy is lost as heat. Despite their superior efficiency in energy conversion, EVs may still result in higher total energy consumption if the electricity used for charging comes from sources with significant emissions or inefficiencies in the grid. Typically, the efficiency of the electricity grid, which includes transmission and distribution losses, ranges from 4% to 15%.[28] Additionally, the process of charging EVs incurs another 10% to 20% in losses.[29] When these factors are considered, the overall energy consumption of EVs may end up being higher than the direct energy consumption of gasoline vehicles.

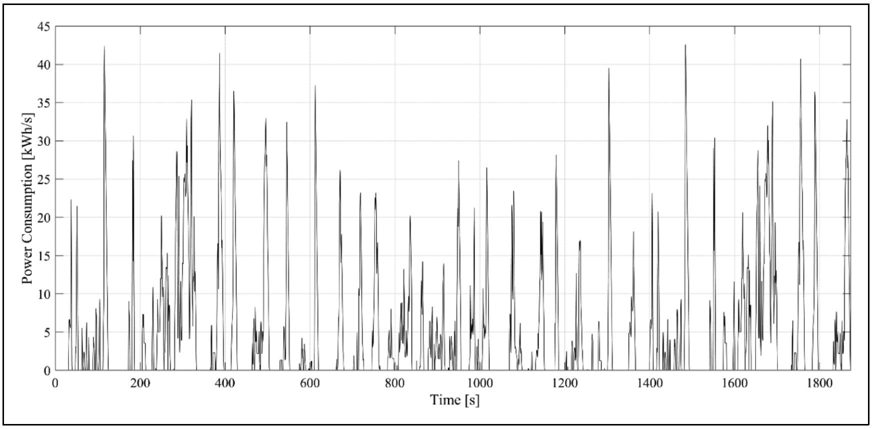

Figure 4. Power requirement of Gasoline powered vehicle.

The energy consumption of GPVs was calculated by determining the fuel consumption, converting it into the energy units, and taking into account the engine efficiency. Figure 4 shows instant power requirements of GPV. The instantaneous power requirement was calculated using Newtonian equations, taking into account the vehicle's travel resistances, rolling resistance, acceleration resistance and aerodynamic resistance. In GPV, the instantaneous energy consumption value, based on power consumption and the lower calorific value of gasoline, is represented graphically according to the FTP-75 cycle, using the developed MATLAB Simulink model.

Energy consumption from power plants was determined by considering state-level fuel consumption and energy production information from the power plant dataset. The energy consumption of EVs is calculated by determining the energy efficiency rating of the vehicle, calculating the total energy required based on the distance travelled and adjusting for charging efficiency. The calculations were performed for energy consumption to drive 100 km and data shown in Figure 5. In consideration of the additional weight of the EV resulting from the battery, the values were calculated with the assistance of a mathematical model. Total electric energy consumption from combustion power plants is presented without considering energy source type.

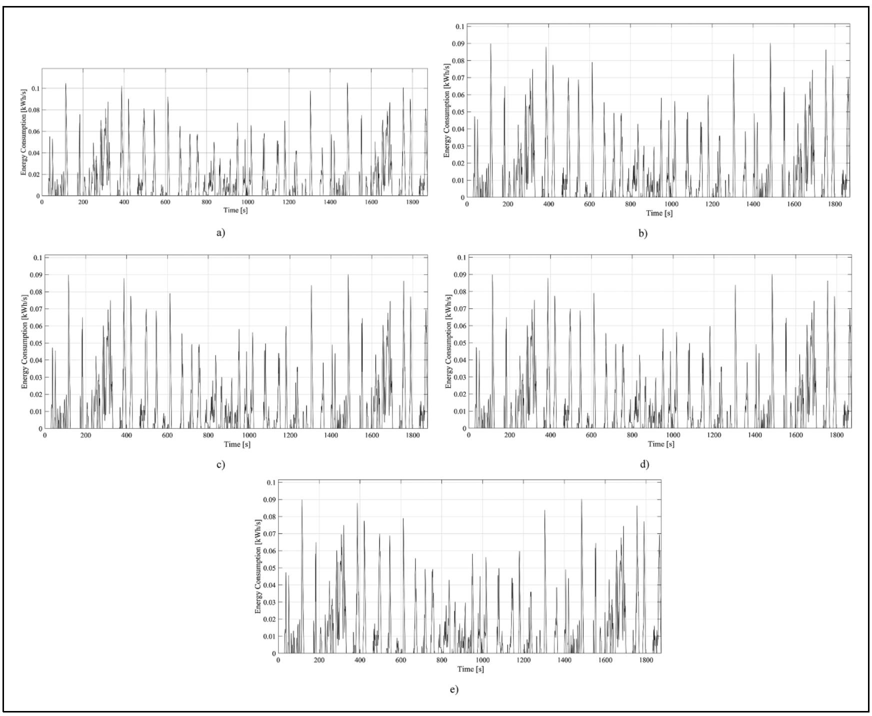

Figure 5. Energy consumption data from power plants for (a) Washington, (b) New York, (c) Texas, (d) Indiana, and (e) West Virginia.

The maximum instantaneous energy consumption of EVs for Washington, New York, Texas, Indiana, and West Virginia states are 2.5, 5.7, 18.9, 18, and 22.2, respectively. The primary reason for the variations in these figures can be attributed to alterations in fuel consumption data and the thermal efficiency of power plants across the states, contingent upon the technology employed in each state.

CO_2 emission

While EVs are generally considered more environmentally friendly, CO_2 emission data varies depending on the fuel type used by the power plant, emission filter technology, and total power plant efficiency. In GPV, CO_2 emissions were calculated based on the engine map, assuming stoichiometric combustion depending on the amount of fuel consumption. Figures 6 and 7 display the obtained data for EVs and GPV.

Figure 6 shows instantaneous CO_2 emission of the selected GPV at FTP-75 driving cycle. The CO_2 emissions were calculated on the basis of the gasoline consumption in accordance with the stoichiometric combustion conditions. According to the results, the maximum instantaneous CO_2 emission of the GPV is 7.6 g/s.

Power plants emit exhaust gases of varying amounts and compositions, depending on the fuel source. Figure 7 shows CO_2 emissions of EVs depending on power plants in Washington, New York, Texas, Indiana, and West Virginia states. The CO_2 emission value was calculated using data published by the states and the CO_2 emission value released by the power plants per unit of energy.

The maximum instantaneous CO_2 emission of EVs for Washington, New York, Texas, Indiana, and West Virginia states are 0.105, 0.09,0.087, 0.081, and 0.084, respectively. As illustrated by the graphs, the CO_2 emissions from EVs that rely on power plants are significantly greater than those from GPVs in many states. This variation largely depends on the implementation of renewable energy and the technology employed in power plants.

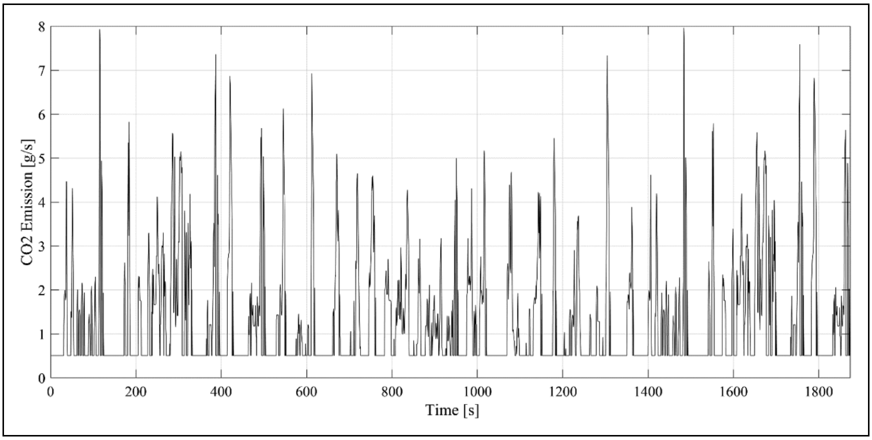

Figure 6. CO_2 emission data for gasoline-powered vehicle.

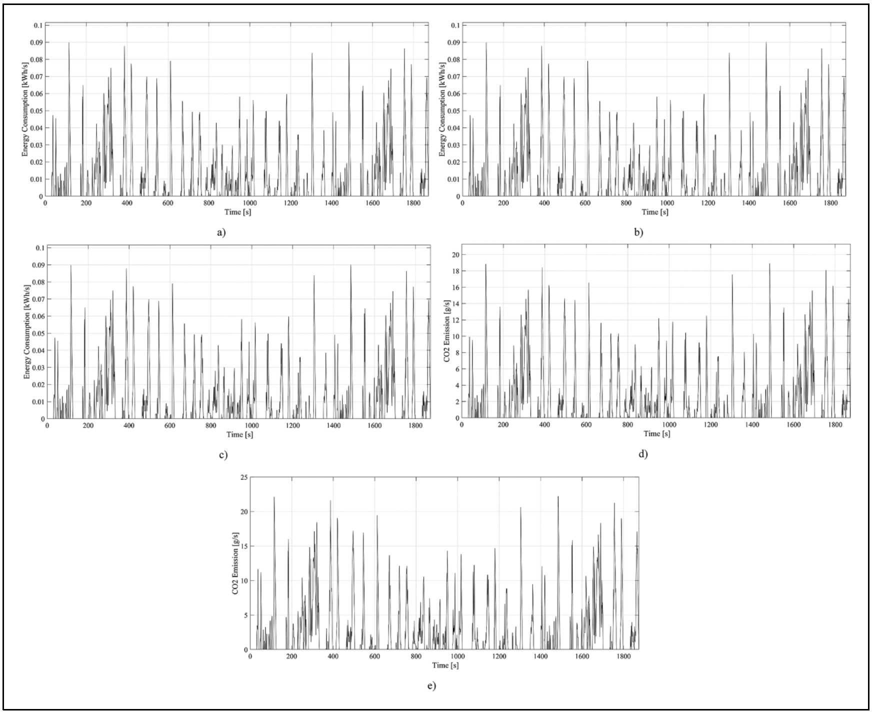

Figure 7. CO_2 emission data depending on power plants for (a) Washington, (b) New York, (c) Texas, (d) Indiana, and (e) West Virginia.

Based on the data from U.S. Energy Administration reports and calculations, energy consumption values are presented in Figure 8. Results for EVs are given considering the efficiency of EVs and power plants during a 100 km journey. For GPV, the fuel consumption is calculated from the fuel consumption map based on the lower heating value of gasoline with the help of MATLAB Simulink. Since GPV do not use the latent heat of vapor in their emissions.[22] With regard to the total energy consumption values per 100 km, the lowest energy consumption was observed in gasoline vehicles. The result obtained can be considered to reflect the greater weight of EVs, due to the weight of the battery and the losses in electrical energy transmission.

The total energy consumed by EVs were calculated for five states and compared to that consumed by GPVs. Figure indicates that EVs will consume more energy than GPVs. The corresponding increase percentages according to the GPVs are 112%, 81%, 75%, 64%, and 69% for Washington, New York, Texas, Indiana, and West Virginia, respectively.

Considering five power plants, GPV and EV, potential CO_2 emission data is shown in Figure 9. CO_2 emission values emitted from power plants were calculated as an average per kilometer based on the FTP-75 cycle by determining specific emission values taken from the reference. The quantity of CO_2 emissions released by a vehicle is contingent

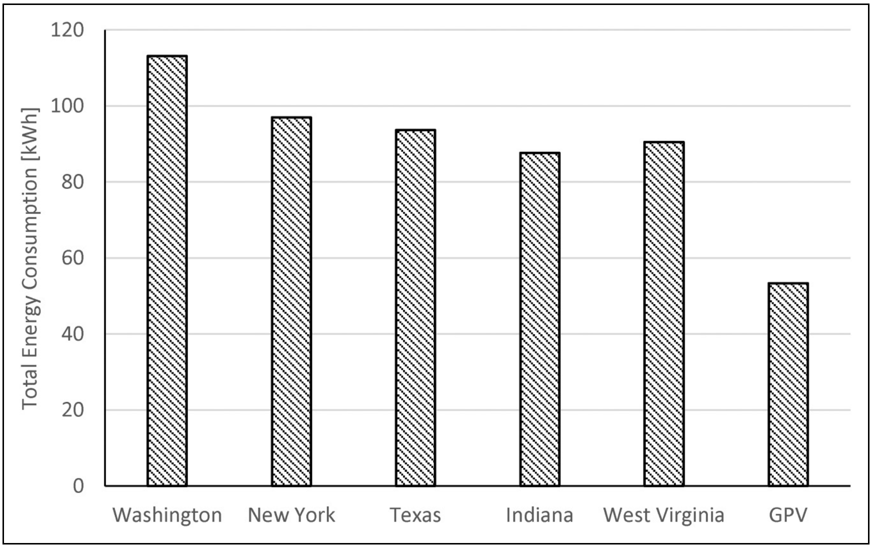

Figure 8. Total energy consumption, calculated by considering the power plant technology.

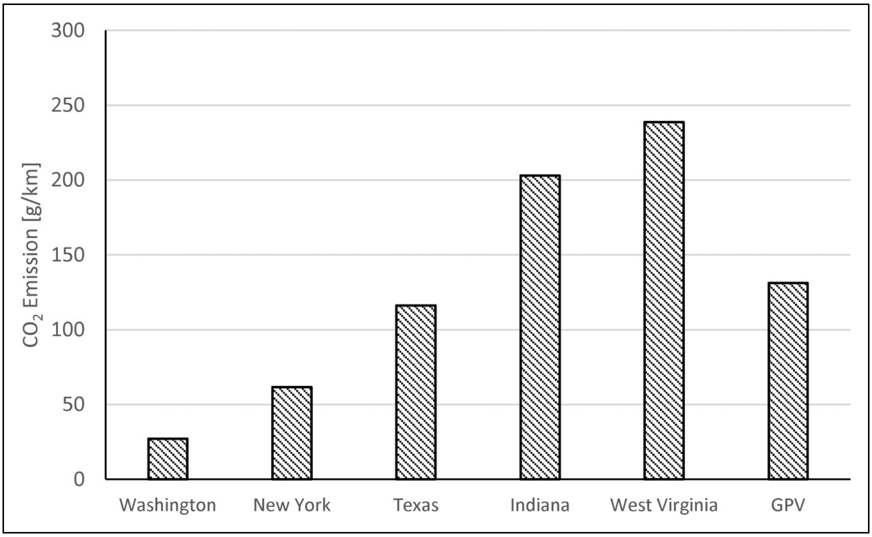

Figure 9. CO_2 emission, calculated by considering the power plant technology.

upon the technology employed in the generation of electrical energy by the power plant in question, as well as the rate at which renewable energy is utilized in said power plant. Consequently, while a notable reduction in CO_2 emissions was observed in states with a more environmentally conscious approach to energy production, an increase in emissions was recorded in power plants that generate electricity from fossil fuels, such as coal.

For GPV, the maximum CO_2 emissions under complete combustion conditions were calculated based on stoichiometric combustion assumptions. The results were obtained using MATLAB Simulink for the FTP75 cycle with reference to the CO_2 emissions release value on the engine map.

CO_2 emission value per km for GPV is 131.2 g. The value for Washington, New York, Texas, Indiana, and West Virginia power plants are 27.16, 61.64, 116.2, 203.1, and 238.7 g, respectively. The figure demonstrates that GPVs can emit less CO_2 than comparable EVs. CO_2 emission of Indiana and West Virginia are 54% and 82% more than GPVs, respectively. For Washington and New York, the emissions calculated for EVs are dramatically lower when compared with GPVs. The emissions calculated for each country are correlated to electricity generation technologies. The case study for China concluded that the greenhouse gas emissions of battery EVs are 50% higher than those of ICEVs,[30] while in the example of Germany, where renewable energy is used for electricity generation, EV emissions are 62% to 64% lower than GPV.[31] The pollutant emissions of EVs directly depend on the power plant technology. For this reason, power plant technology and the use of renewable energy in electrical energy production in states and countries are of great importance.

Conclusions

Increasing efforts toward a sustainable and environmentally friendly future and growing awareness of emissions reduction, air quality improvement, climate change and global health issues are of great importance in the transformation of the transportation sector. The findings of the study highlight the importance of decarbonizing the electricity sector in order to fully realize the environmental benefits of EVs.

The study analyzes the energy consumption and indirect CO_2 emissions associated with EVs. The results indicate that the use of EVs can lead to an increase in energy consumption of up to 80% compared to gasoline vehicles, depending on the inefficiency of power plants and the proportion of fossil fuels used in electricity generation. Notably, in three states the emissions from EVs are worse than those from GPVs. These findings underscore the need to evaluate the environmental effects of EVs and GPVs in relation to electricity production technology and conversion efficiency.

The key factor that determines the environmental benefit of EVs is the source of electricity used for charging. In regions where fossil fuels like coal or natural gas are dominate the energy mix, the impact of EVs may be limited. However, investing in clean energy infrastructure, such as solar or wind power, can maximize the positive effects of EVs on the environment. Advances in battery and charging technology can further increase the eco-friendliness of EVs. Continued efforts in renewable energy development are crucial for achieving sustainable transportation and mitigating climate change.

Authors' contributions

Conceptualization, methodology, software, validation, formal analysis, visualization were done by Y.K. and T.T. Writing—original draft preparation was done by T.T. Writing—review and editing was done by Y.K. and T.T. Supervision was done by Y.K.
All authors reviewed and approved the manuscript.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of conflicting interests

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