

The Future of Transportation: LCA Emissions Comparison Between EV and ICE Vehicles in Urban Settings

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ABSTRACT: Due to the increasing awareness of the impacts GHGs have on global warming, various cities have started to implement newer and greener public transportation alternatives with the goal of reducing their total emissions. Simultaneously, many automakers have begun to offer a broader range of electric vehicles as a sustainable alternative to their internal combustion counterparts. This study aims to compare the lifetime emissions of 2 cars and 2 buses in both internal combustion and electric powertrains, operating in two cities with different energy mixes, to determine which option is the most sustainable. To address this challenge, this study uses models that take into account: the average distance each mode of transportation travels on average before it's scrapped, the cradle-to-grave emissions of the analysed vehicle, and the CO₂ emissions from energy production in both cities. The results from this analysis show that, even though buses by themselves produce more pollutants than cars, the fact that they can carry more people and have longer lifespans distributes their impact, making them the greenest option overall. It also proves that, even with an energy mix that relies heavily on fossil fuels, electric vehicles still produce less greenhouse gas emissions than their internal combustion counterparts.

KEYWORDS: Mechanical Engineering, Life Cycle Assessment, Electrification, Public Transport, Emissions Comparison, Urban Transport.

■ Nomenclature

Electric Vehicle	(EV)
Battery Electric Vehicles	(BEV)
Internal Combustion Engine	(ICE)
Compressed Natural Gas	(CNG)
Life Cycle Assessment	(LCA)
Kilowatt-hour	(kWh)
Megajoule	(MJ)

■ Introduction

As of 2021, the transport industry is the second most polluting sector worldwide, surpassed only by the energy sector.¹ Even though ICE had been the only viable powertrain option for decades, rising GHG emissions have led to the creation of various alternatives to gasoline or diesel vehicles that promise to cut down on emissions. Technologies such as hydrogen fuel cells and CNG vehicles have been proposed as possible solutions, but the most popular of these and the one that has stood the test of time is the electric powertrain.²

As a result, numerous cities have started to electrify their public transportation systems, and most automakers now offer a wide range of both fully electric and hybrid vehicles in addition to their standard ICE offerings. This has also been accompanied by changes in infrastructure, such as the widespread adoption of BEV chargers in many cities worldwide, the introduction of a standard BEV plug, and incentives that many countries have implemented to encourage people to consider greener vehicles over their gasoline alternatives. Many previous studies have focused on the differences in emissions between ICE powertrains and BEVs within the same vehicle

category or compared various methods of transportation within one city.^{3,4} However, they usually avoid comparing methods of transportation in cities where the energy mix is way more reliant on fossil fuels.

Identifying and comparing the emissions these modes of transport produce in different scenarios can help reduce GHG emissions worldwide more quickly and efficiently, since incentivizing the wrong kind of transportation can result in slower progress towards combating climate change or even increase the carbon footprint of a community. Understanding how the emissions of these vehicles change depending on factors such as vehicle lifespan, occupancy rate, and fuel production emissions can aid policymakers in making educated decisions, depending on their current situation, and gradually move towards environmentally friendly transportation. Implementing solutions that are compatible with existing infrastructure or require a smaller investment can serve as a stepping stone before switching to greener alternatives, which may come at a higher price.

The objective of this work is to conduct an LCA of the emissions produced by cars and buses in both electric and ICE powertrains in two cities with vastly different energy mixes, hoping to prove that, even in places with a higher reliance on fossil fuels, switching to electric transport decreases GHG emissions. The LCA methodology provides a holistic approach that covers the entire lifespan of each vehicle from material extraction, production, maintenance, all the way to its eventual end-of-life disposal. In addition to this, the emissions that come from fuel production in both instances have also been included, since this is another aspect that many other stud-

ies fail to cover for both powertrains. This approach brings a higher accuracy compared to previous assessments, taking into consideration all variables that go into the use of each of the transportation options, helping us find the one that produces the least overall emissions in more than one scenario. The findings of this study aim to identify the cleanest transportation option for a broader range of countries, including those with a large percentage of fossil fuels within their energy mix.

Materials and methods

1. Scope definition:

This paper aims to provide an emissions analysis of two of the most popular modes of transportation within big cities, taking into account one scenario that favours green electricity production and another that almost completely depends on fossil fuels. This study makes some assumptions regarding resource extraction, manufacturing, and disposal in both cities, but it does account for the differences in emissions from the different energy grids in each country. The boundaries of this study are detailed in Figure 1.

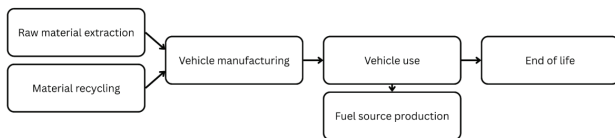


Figure 1: Flow chart describing the variables taken into account per vehicle in this study.

2. Cities:

The cities that were chosen for this study are Paris, France, as our best case scenario, and Mexico City, Mexico, as our worst case scenario. Our best-case scenario was chosen because of its world-leading use of clean energy, with more than 35% of its total electricity coming from nuclear power alone, which is a stark contrast to our worst-case scenario, since it relies heavily on fossil fuels for electricity (Figure 2).

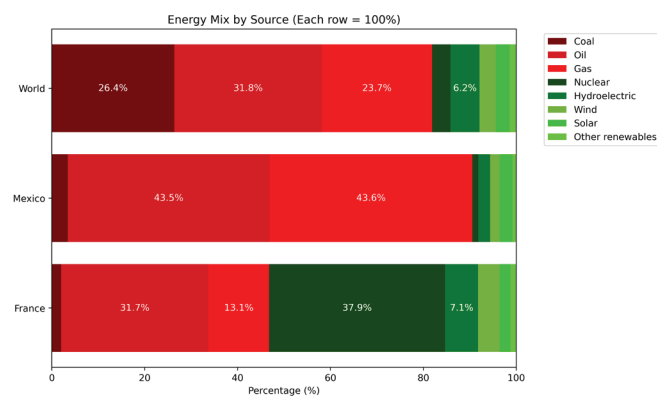


Figure 2: Bar graph describing the source of electricity production by percentage in France, Mexico, and the world in 2024, data extracted from Our World in Data.⁵

3. Vehicles:

For this section, the previous LCA studies' results were used as a reference. In this case, the study from Pero *et al.* was used as a model for both cars, and the studies by Lubecki *et al.* and

Jakub *et al.* were used as a reference for the bus models.^{3,6,7} The information used can be seen in Table 1.

The study by Pero *et al.* contains an analysis of the car model created by the AffordabLe LIghtweight Automobiles AllIaNCE (ALLIANCE) project, an initiative where European automakers like Daimler-Benz AG, Volvo Car Corporation, Volkswagen AG, and Opel Automobile GmbH set out to design a more sustainable and efficient car.^{3,8} This resulted in the creation of vehicle models that mix elements from cars of all segments to create more affordable, lighter, and more sustainable vehicles in both ICE and EV powertrains, which makes them ideal for studies where two comparable vehicles are required. It is also important to note that each of these models was calculated with only one occupant in mind and no additional mass added to the vehicle, as well as a lifespan of 150,000 km driven in total for each vehicle.

The study by Lubecki *et al.* focuses on the importance of assumptions in LCA studies and their effect on the results. For this, multiple bus models were created with data from previous studies, from which specifications like weight and efficiency were taken to calculate their emissions.^{6,7}

From these models, the ones considered for this study were created to represent a conventional ICE bus –labeled as D1– and an equivalent BEV bus –labeled as E1–.⁶ These were analyzed with the same passenger capacity of 50 people and total distance driven within each vehicle's lifespan of 675,700 km. The exact weight from each vehicle was taken from Jakub *et al.*, since it was the source used for the previous study.⁷ In addition, to test the model's sensitivity, a second and third set of buses were added, which have a reduced occupancy rate according to the global average (O) of 35% and a reduced lifetime (L) of 337,850 Km respectively.

Table 1: Table containing the parameters used during the emissions calculations of each vehicle. Vehicles with worldwide average occupancy (O) and reduced lifespan (L) are also included.

Vehicle parameters				
Vehicle	Weight (kg)	Lifespan (km)	Average number of occupants (# people)	Efficiency (L/km) for ICE (kWh/km) for EV
Car (ICE)	1,357	150,000	1	0.0584
Car (EV)	1,596	150,000	1	0.1666
Bus (ICE)	10,930	675,700	50	0.4
Bus (EV)	12,030	675,700	50	0.9
Bus (ICE) - O	10,930	675,700	17.5	0.4
Bus (EV) - O	12,030	675,700	17.5	0.9
Bus (ICE) - L	10,930	337,850	50	0.4
Bus (EV) - L	12,030	337,850	50	0.9

4.1. Production:

The production stage was calculated with data from previous studies.^{3,6,7} In this case, this includes calculations for raw material extraction and the manufacturing process of each vehicle component. For both buses, since studies detailing their production emissions could not be found, the emissions pro-

duced by cars were scaled up to match each of the buses using the equation below.

$$emiss_{bus} = \frac{emiss_{car} \cdot weight_{bus}}{weight_{car}} \quad (1)$$

Where:

$emiss_{bus}$ = Emissions produced by the bus of the powertrain in question (in kgCO₂ eq)

$emiss_{car}$ = Emissions produced by the car of the powertrain in question (in kgCO₂ eq)

$weight_{bus}$ = Weight of the bus of the powertrain in question (in kg)

$weight_{car}$ = Weight of the car of the powertrain in question (in kg)

4.2. Use stage:

The use stage was calculated by taking into account a lifespan of 150,000 Km for each car, a lifespan of 675,700 Km for each bus in the optimal and worldwide occupancy rate cases, and a lifespan of 337,850 Km for the buses in the reduced lifespan cases. Each car was considered to have only 1 occupant –the driver–, while each bus was considered to have a maximum capacity of 50 passengers. For the optimal and reduced lifespan cases, an occupancy rate of 100% was used, while a rate of 35% was used in the worldwide average occupancy rate case.⁹

To calculate emissions from fuel production in ICE vehicles, total emissions for every litre of fuel were taken from previous studies, as well as the litres each vehicle used per kilometre, using the WLTC standard for each car model.^{3,6,10} This is described in the equation below.

$$emiss_{fp} = \eta \cdot emiss_{fuel} \cdot range \quad (2)$$

Where:

$emiss_{fp}$ = total emissions produced by the vehicle's fuel production (in kgCO₂)

η = efficiency of the vehicle (in L/km)

$emiss_{fuel}$ = emissions per litre of fuel produced (in kgCO₂/L)

$range$ = lifespan of the car (in km)

Furthermore, to calculate each vehicle's tailpipe emissions, previous information was used for each ICE model and scaled up using Equation 1 for the ICE bus model.³

In the case of BEVs, emissions from fuel production had to be calculated by taking into account the energy mix of each city, the efficiency of each power plant, and the kWh used by each vehicle during its lifespan. For this, data regarding vehicle efficiency, power plant emissions, and the carbon content of each fuel were gathered regarding the three non-renewable fossil fuels used for electricity generation: coal, CNG, and oil.^{3,5,6,11,12} This data was later processed using the following system (Table 2, below).

Table 2: Table describing the equations used to calculate the usage emissions of each vehicle.

Equation	Description
$Y_c = \frac{xMW_x}{xMW_x + xMW_y} \quad (3)$	First, the Carbon mass of each fuel is calculated by using the molar weight of its components.
$\frac{m_{CO_2}}{E_f} = Y_c \frac{MW_{CO_2}}{MW_C} \cdot \frac{1}{LHV} \quad (4)$	With this information, we can calculate the mass of CO ₂ produced per unit of energy using the mass of carbon directly in the fuel, the molar weight of CO ₂ , the molar weight of Carbon, and the LHV. ¹²
$\frac{m_{CO_2}}{E_{el,tot}} = \frac{m_{CO_2}}{E_f} \cdot \frac{1}{\eta_{fp}} \cdot \frac{E_{el}}{E_{el,tot}} \quad (5)$	To calculate the total CO ₂ produced per total mass of electricity produced the percentage of energy production per fuel mix is required in addition to power plant efficiency and mass of CO ₂ per unit of energy. ^{5,11}
$\frac{m_{CO_2,tot}}{E_{el,tot}} (kWh) = (3.6) \left(\sum_{fuel} \left(\frac{m_{CO_2,tot}}{E_{el}} \cdot \frac{E_{el}}{E_{el,tot}} \right)_{fuel} \right) \quad (6)$	The total mass of CO ₂ produced per kWh of fuel is added up to get the total CO ₂ produced per unit of electricity of each fuel.
$emiss_{fp} = range \frac{m_{CO_2,tot}}{E_{f,tot}} (kWh) \cdot \eta_v \quad (7)$	Finally, vehicle emissions are calculated using the total vehicle lifespan, the amount of CO ₂ produced per kWh, and vehicle efficiency.

Variables used:

Y_c = mass of carbon

xMW = molar weight of fuel component

m_{CO_2} = mass of CO₂

m_f = unit of fuel

MW_{CO_2} = molar weight of CO₂

MW_C = molar weight of Carbon

E_f = unit of energy

LHV = Lower Heating Value

E_{el} = unit of electricity

η_{fp} = efficiency of power plant (coal, oil, or CNG)

$E_{el,tot}$ = total electricity produced

$m_{CO_2,tot}$ = total mass of CO₂ produced

$emiss_{fp}$ = total fuel production emissions per vehicle

$range$ = total vehicle lifespan (in km)

η_v = vehicle efficiency (in kWh/km)

To calculate the total emissions of each vehicle's use, the emissions from fuel production and tailpipe emissions –in the case of ICE vehicles– were added to form our total using the equation below.

$$emiss_u = emiss_{fp} + emiss_{te} \quad (3)$$

Where:

$emiss_u$ = total vehicle emissions in usage

$emiss_{fp}$ = total fuel production emissions

$emiss_{fp}$ = total vehicle tailpipe emissions (for ICE vehicles only)

4.3. Disposal:

The emissions from disposal were calculated taking into account recycling, depollution, and material recoverability.³ For each of the bus models, the results from each car were scaled to the weight of each bus using Equation 1.⁶

5. Limitations:

This study makes heavy use of simple extrapolation as a method of scaling between cars and buses in different life stages. Even though this technique presents certain limitations in terms of accuracy, this approach was deemed sufficient due to a lack of data regarding bus emissions.¹³ In this study, it is assumed that both vehicle types have the same proportions of materials in terms of mass, meaning that for every A quantity of material X, there is a proportional B quantity of material Y in both vehicle types. It is reasonable to assume that buses and cars have similar proportions of materials by mass due to their similarities in construction process and powertrains, meaning they use the same technologies to propel themselves and are produced in similar ways, just on different scales.

To account for the uncertainties this method might bring, six additional bus models were considered in addition to the three optimal cases to test the impact vehicle occupancy and total range have on the final result: three of these buses have an occupancy rate according to the global average in urban areas of 35%, or 17.5 passengers on average, while the other three will have half the range of our original models, which would be 337,850 Km.^{6,9} This can help quantify the impact these factors have on the GHG emissions of the vehicles and show their influence on the final result.

Results

Figure 3 and Table 3 show a comparison of the total emissions each vehicle produces throughout its lifespan in both cities.

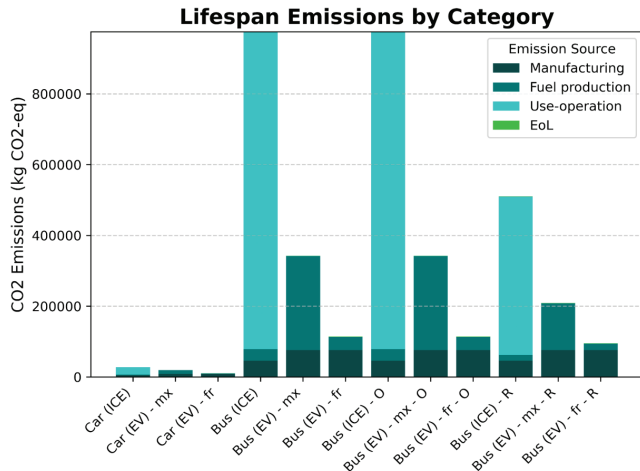


Figure 3: Bar graph describing the missions resulting from each vehicle's total lifespan, divided by life stage.

Table 3: Table describing the results of the investigation by vehicle, classified by emission sources, cut off to two decimal points.

Total lifespan emissions per vehicle (kg CO ₂ -eq)					
Vehicle	Manufacturing	Fuel production	Use-operation	EoL	Total lifespan emissions per person
Car (ICE)	4,973.00	1,752.00	21,400.00	-95.00	28,030.00
Car (EV) - mx	8,974.00	10,948.73	-	-87.00	19,835.73
Car (EV) - fr	8,974.00	1,574.39	-	-87.00	10,461.39
Bus (ICE)	46,259.48	32,433.60	896,723.87	-883.70	974,533.24

Bus (EV) - mx	76,257.13	266,436.55	-	-739.29	341,954.39
Bus (EV) - fr	76,257.13	38,312.68	-	-739.29	113,830.52
Bus (ICE) - O	46,259.48	32,433.60	896,723.87	-883.70	974,533.24
Bus (EV) - mx - O	76,257.13	266,436.55	-	-739.29	341,954.39
Bus (EV) - fr - O	76,257.13	38,312.68	-	-739.29	113,830.52
Bus (ICE) - R	46,259.48	16,216.80	448,361.93	-883.70	509,954.51
Bus (EV) - mx - R	76,257.13	133,218.28	-	-739.29	208,736.12
Bus (EV) - fr - R	76,257.13	19,156.34	-	-739.29	94,674.18

The aspect that stands out the most about Figure 3 is the amount of emissions produced by ICE buses over all other vehicles, since they more than double the amount of emissions of the second most polluting vehicles in the study – those being the BEV buses in Mexico City – within their respective categories. Each ICE bus produces more than five times the emissions of other BEV buses with the same range and occupancy rate.

In Figure 4 and Table 4, we can see a comparison of all vehicles, taking into account their total range and number of passengers:

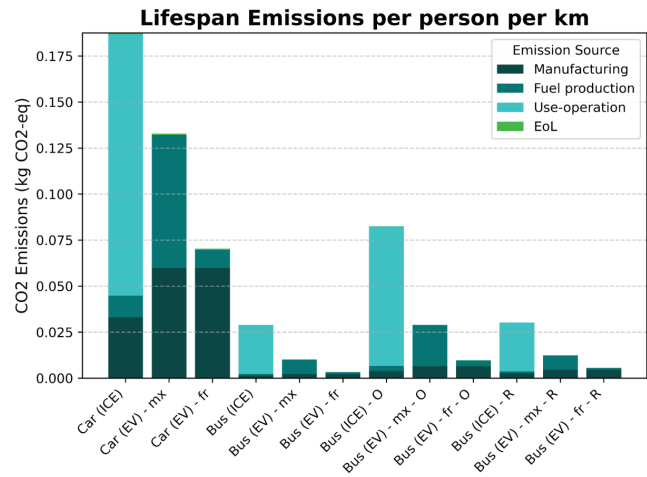


Figure 4: Bar graph showing the emissions produced by a vehicle during its lifetime, divided by the number of passengers each vehicle was considered to carry and the total kilometers each vehicle will drive in its lifetime.

Table 4: Table describing the results of the investigation by vehicle, divided by the number of occupants and amount of kilometers driven in lifespan, classified by emission sources, cut off to five decimal points.

Total lifespan emissions per person per km per vehicle (kg CO ₂ -eq)					
Vehicle	Manufacturing	Fuel production	Use-operation	EoL	Total lifespan emissions per person
Car (ICE)	0.03315	0.01168	0.14267	-0.00063	0.18686
Car (EV) - mx	0.05983	0.07299	-	-0.00058	0.13223
Car (EV) - fr	0.05983	0.01050	-	-0.00058	0.06974
Bus (ICE)	0.00137	0.00096	0.02654	-0.00003	0.02884
Bus (EV) - mx	0.00226	0.00789	-	-0.00002	0.01012
Bus (EV) - fr	0.00226	0.00113	-	-0.00002	0.00336
Bus (ICE) - O	0.00391	0.00274	0.07583	-0.00007	0.08241
Bus (EV) - mx - O	0.00645	0.02253	-	-0.00006	0.02891
Bus (EV) - fr - O	0.00645	0.00324	-	-0.00006	0.00962
Bus (ICE) - R	0.00274	0.00096	0.02654	-0.00005	0.03018
Bus (EV) - mx - R	0.00451	0.00789	-	-0.00004	0.01235
Bus (EV) - fr - R	0.00451	0.00113	-	-0.00004	0.00560

Figure 4 shows very different results compared to Figure 3. Here, the longer lifespan and higher carrying capacity of buses distribute their emissions, resulting in them producing less GHGs than most of the cars examined.

■ Discussion

This study follows the LCA methodology in the process of calculating emissions for the most common forms of transport in cities, with the goal of proving which of them produces the smallest amount of emissions in different contexts. To achieve this, twelve vehicle models were created using existing information: two equivalent cars and two equivalent buses, each in both BEV and ICE variants.^{3,6,10} These models were later modified to fit each of the cities included in this study, specifically, each of the BEV vehicles' fuel production emissions was calculated using energy mix data from each of the corresponding cities.⁵ Furthermore, a sensitivity analysis was conducted to test the scaling method used to model each bus by using different occupancy rates and lifespans to determine their impact on GHG emissions. Resulting from this was the information described in Figures 3 and 4, which have similar conclusions to other studies that focus on the LCAs of ICE vehicles and BEVs, even with the use of different energy mixes.^{3,6,14,15}

A factor that ended up drastically changing the conclusion was presenting the data as kgCO₂eq per-passenger-per-km since it demonstrated the higher efficiency of buses, even though they produce more GHG emissions in total. Taking into account the number of occupants and the lifespan of each vehicle means that vehicles with a higher passenger capacity, even though their emissions are higher, can surpass the efficiency of cars if they carry enough people. This proved crucial, specifically when testing buses with different occupancy rates, since this factor had a larger impact on total GHG emissions than range.

The initial prediction of this study was also proven wrong because of one potential outcome: switching from an ICE bus to a BEV car can increase emissions by a factor of more than 270%, depending on the energy mix in question. This is due to the higher amount of emissions produced during the manufacturing stage of an EV, specifically during the fabrication of the high-voltage battery and other drivetrain components, which, depending on the battery chemistry considered, can account for more than 50% of the total emissions from the manufacturing process.³ Another key factor that is very influential to this outcome is the larger lifespan and carrying capacity of the ICE bus, since it helps distribute its lifetime emissions over a longer period of time and over a larger number of people.

This result, as counterintuitive as it might seem, demonstrates that a grand majority of cities are not taking the most efficient approach when trying to reduce GHG emissions related to urban transport and could potentially increase their carbon footprint. Most governments have encouraged the switch from ICE to EV cars for more than a decade, while very few encourage their citizens to use public transit. This means switching from an electric car to an ICE bus would seem counterproductive to the majority of the population due to the current push for electrification. Another important fac-

tor is the lack of maintenance and safety some public transport systems suffer from, especially in marginalized or developing communities, which are major factors to consider when making a switch to buses in these contexts.

■ Conclusion

This study has proved that, in most instances, using an electric vehicle produces fewer emissions in comparison to an ICE vehicle. The scenario that differs from this statement is switching from an ICE bus with a high occupancy rate to a BEV car. This is an example of vehicles with a higher carrying capacity and longer lifetime distributing their emissions throughout a larger amount of time and passengers, making them a cleaner alternative to single-passenger vehicles, even though their total lifespan emissions are higher.

Another key takeaway from this study is the impact a country's energy mix has on BEV emissions. Although in all instances BEVs never surpass the GHG emissions produced by their ICE counterparts, a higher reliance on fossil fuels during energy production has a great impact on electric vehicle emissions. For example, in the case of the BEV car model studied, fuel production emissions go from being a fraction of manufacturing emissions with France's energy mix to surpassing them in Mexico's.

This information can be useful for cities with a larger reliance on ICE cars, making ICE buses a stepping stone into greener transportation for everyone, especially in large cities. These conclusions can also be used to make educated decisions on making transportation greener in most countries, since they take into account a country with a higher-than-average reliance on fossil fuels.

■ Acknowledgments

This research article was written within the Indigo Research IRIS 2025 Summer Program with the guidance of Dr. Andrea Giusti and Marcin Kedziera and feedback from Indigo's Writing Fellows team.

The author acknowledges the use of ChatGPT (OpenAI) to generate initial code templates for data visualization, which were subsequently reviewed manually. The prompts used to generate these templates are the following: "Make a piece of code to create a graph using matplotlib, numpy, pandas, or seaborn, which has an input for one CSV file. This piece of code must create six vertical bar graphs with input for different colours in the form of a list within the code itself. These bars should be divided into the following categories: Manufacturing, Fuel production, Use-operation, EoL, and Total lifespan emissions. Make a piece of code to create a graph using matplotlib, numpy, pandas, or seaborn, which has an input for one CSV file. This piece of code must create three bar graphs that add up to 100% and are divided into the following categories: coal, oil, gas, nuclear, hydropower, wind, solar, and other renewables. This graph must only have three rows with categories that stack horizontally, as well as have labels for each percentage value on top of each bar".

I attest that the ideas, graphics, and writing in this paper are entirely my own. – Jesús Santiago Mendiola López.

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