Article citation info:
Borkowski A, Zawiślak M. Comparative analysis of the life-cycle emissions of carbon dioxide emitted by battery electric vehicles using various energy mixes and vehicles with ICE. Combustion Engines. 2023;192(1):3-10. https://doi.org/10.19206/CE-147159

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Polish Scientific Society of Combustion Engines

Comparative analysis of the life-cycle emissions of carbon dioxide emitted by battery electric vehicles using various energy mixes and vehicles with ICE

ARTICLE INFO

Received: 31 December 2021
Revised: 16 February 2022
Accepted: 6 March 2022
Available online: 13 March 2022

The research aims to find an effective way to reduce real-world CO_2 emissions of passenger vehicles, by answering the question of what kind of vehicles in various countries generates the smallest carbon footprint. Emissions were calculated for vehicles from three of the most popular segments: small, compact, and midsize, both with conventional body and SUVs. Each type of vehicle was analyzed with various types of powertrain: petrol ICE (internal combustion engine), diesel ICE, LPG ICE, petrol hybrid, LPG hybrid and BEV (battery electric vehicle) with four different carbon intensity of electric energy source. The final conclusion provides guidelines for environmentally responsible decision-making in terms of passenger vehicle choice.

Key words: *sustainable mobility, vehicle CO_2 emission, Life Cycle Assessment, carbon footprint, GHG reduction*

1. Introduction

According to the current state of scientific knowledge about the environment and climate, global warming caused mainly by anthropogenic CO_2 emissions is a problem that requires global action aimed at the fastest and most effective reduction of greenhouse gases (GHG) emissions [20]. The results of scientists' research contributed to the signing of the Paris Agreement. It is a legally binding agreement, signed by 190 countries from around the world. Its goal is to limit the phenomenon of global warming below 2 degrees Celsius and the effects of climate change as effectively as possible.

As a result, one of the activities of the European Parliament and the EU Council was to establish a regulation (EC) 443/2009 [9], setting CO_2 emission standards for new passenger cars. For 2020, the fleet-wide average emissions target was set at 95 g CO_2/km, which corresponds to fuel consumption of around 4.2 dm^3/100 km of petrol, 3.7 dm^3/100 km of diesel or 6.2 dm^3/100 km of LPG (*Liquefied Petroleum Gas*). The levels of average fuel consumption seem very unlikely to be obtained, but due to a few additional rules, manufacturers do not really have to obtain such low values of average fuel consumption. Some of the most questionable rules are as follows:

– excluding 5% of the most emitting new cars in calculations (in 2020),
– granting bonuses for eco-innovations that do not demonstrate a CO_2 reduction effect during the test procedures (up to 7 g/km credit),
– giving additional incentives for cars emitting less than 50 g/km (in 2020 these cars are counted as 2 vehicles, in 2021 as 1.67, in 2022 as 1.33),
– considering only direct emissions (TTW, tank to wheel),
– basing CO_2 emissions on unrealistic and outdated NEDC driving cycle, while fuel consumption levels are already measured with more realistic WLTP cycle,
– considering electric cars as vehicles with zero emission.

The exclusions described above are the result of a compromise between the EU authorities and the automotive industry lobby, linking interests of car manufacturers with alleged success in limiting the impact of passenger vehicles in the EU on global warming. Assuming that the global warming is a real and serious threat to the Earth and humanity, the success of achieving 95 g CO_2/km goal on paper, because of its simplifications and exceptions, should not be qualified as real progress in reducing the influence of transport on climate changes. The result of research carried out by Jato Dynamics [15] shows growing average CO_2 emissions of a new passenger cars in Europe in the years 2016-2019, despite increase in electric vehicle market and considering outdated NEDC driving cycle. In 2016, the average CO_2 emission of new car in Europe was 117.7 g/km, and by 2019 it had increased to 121.6 g/km. In 2020, thanks to increased sales of plug-in hybrids and pure electric vehicles, the number dropped to 106.7 g/km, so theoretically average CO_2 emissions of new cars in the EU started to decrease. As electric vehicles are treated as zero-emission, while in real life they emit CO_2 indirectly, mainly due to electric energy consumption, the success may not be as beneficial for climate as it may appear. The problem of emission from BEVs has already been described in the paper [23], with recommendation to use well-to-wheels methodology for calculating GHG emissions. It provides much more realistic results of GHG emissions of BEVs, but still does not account for emissions from vehicle production and maintenance, which may be very important, especially for BEVs used in countries with very low carbon intensity of electric energy production.

The main goal of the scientific research is to find solutions that could help limit real CO_2 emissions of passenger vehicles in Europe and potentially also in other countries by estimating a life-cycle CO_2 emissions of a variety of vehicles used in a few countries with different carbon intensity of energy production. The research aims to show the most effective way to limit real CO_2 emissions by passenger vehicles, and to answer the question what kind of vehicle people should use if they intend to limit the carbon footprint.

2. Methodology

From the perspective of climate change, tailpipe greenhouse gases emissions are as important as emissions related to all other activities, such as:

- extraction of materials for production of vehicle, fuel, spare parts, tires, fluids,
- production of vehicle, fuel, spare parts, tires, fluids,
- generation of energy for charging BEVs (Battery Electric Vehicles) and PHEVs (Plug-in Hybrid Electric Vehicles),
- vehicle maintenance,
- end of vehicle's life.

As there are no methods to directly measure GHG emission associated with all the activities above, to assess the life cycle emissions there is a need to use other methods, such as Life Cycle Assessment (LCA). The method allows to estimate the impact of the whole life cycle of a product or service on various environmental aspects. Based on the principles of the LCA method, the paper presents a simplified method of assessing lifetime emissions of passenger vehicles, that could potentially replace current standards of assessing GHG emissions of vehicles that include only tailpipe CO_2 emissions. The new method allows for obtaining more realistic values of GHG emissions than tailpipe emission itself and could be implemented to better assess the real influence of vehicles on global warming.

Total GHG emission of a vehicle during its life (E_{tot}) can be estimated as a sum of 5 main contributors with the greatest global warming potential:

- emission of vehicle production (E_{vp}), excluding battery cells in hybrid vehicles and BEVs,
- emission related to production of battery cells (E_{bp}),
- tailpipe emission (E_t),
- emission related to production of fuel and energy for use of the vehicle (E_{ep}),
- emission related to basic maintenance activities (E_m): replacement of engine oil, tires, and brakes.

The relation is represented by formula (1):

$$E_{tot} = E_{vp} + E_{bp} + E_t + E_{ep} + E_m \quad (1)$$

Based on a literature review [5, 12, 21, 22], it was concluded that end-of-life emission is still very difficult to estimate, especially as an industry-scale process of recycling batteries from electric vehicles is still under development. There are different methods for the end of life of each part of a vehicle, such as reuse, upcycling, recycling, downcycling, combustion, or landfill. Each method for each part of vehicle would result in different carbon footprint, so calculating the footprint without knowledge about processes that will be available in 10–20 years, at the end of life of currently new vehicles, could result in significant errors. Additionally, considering that in other studies the end-of-life carbon footprint is very low relative to other parts of vehicle life cycle, this component is excluded from the calculations.

Based on the results of LCA research of 10 Audi vehicles with different material composition [19, 26–29], carried out in accordance with ISO 14040 standard and verified by TÜV NORD CERT GmbH, the influence of the content of the materials of which passenger cars are mainly built was determined using the least squares method and set to 3 kg CO_2-eq per kg of steel, 12 kg CO_2-eq per kg of light metals (aluminum alloys, magnesium alloys) and 6 kg CO_2-eq per kg of the rest of the vehicles. For vehicles with low content of light metals (60% of steel, 10% of light metals, 30% of other materials), the calculated average GHG (greenhouse gas) emission of production stage is equal to 4.8 kg CO_2-eq per 1 kg of vehicle's empty weight without driver. For vehicles with high content of light metals (40% of steel, 30% of light metals, 30% of other materials), the calculated average GHG emission of production stage equals 6.6 kg CO_2-eq per 1 kg. For hybrid vehicles, PHEVs and BEVs, the weight of the materials for calculation of emission from production stage should exclude weight of battery cells. Therefore, emission of vehicle production can be estimated using the formula (2):

$$E_{vp} = 3 \cdot M_{steel} + 12 \cdot M_{al} + 6 \cdot M_{other} \quad (2)$$

where: E_{vp} – GHG emission of vehicle production excluding battery cells [kg CO_2-eq], M_{steel} – mass of steel and iron in vehicle [kg], M_{al} – mass of aluminum and aluminum alloys in vehicle [kg], M_{other} – mass of other materials in vehicle, apart from battery cells [kg].

Mass of each material may be calculated or estimated using mass of the vehicle (without battery cells) and the content percentage of each material type.

Although this method can be applied to estimate vehicle production stage emissions for most currently manufactured vehicles, it is not appropriate for vehicles with high content of carbon fiber reinforced polymers (CRFP).

One of the biggest source of uncertainty in determining greenhouse gases emission of vehicles is battery production. The production of 1 kWh battery cells generates, depending on the literature sources, from 38 to 490 kg of CO_2-eq. According to the review of 50 LCA publications from the years 2005-2020 [3], the median value of battery cells GWP is 120 kg CO_2-eq per 1 kWh of battery capacity. There is a possibility that real emissions of battery production for certain vehicles may be significantly smaller, as producers may reduce the emissions related to the production processes, e.g. by investing in renewable energy sources. The level of emissions may be as well much higher, when batteries are produced with high-carbon energy sources. The lower level of uncertainty was set to 70 kg CO_2-eq per 1 kWh of battery capacity, level corresponding to 25th percentile from the review [3], while the higher level was set to 175 kg CO_2-eq per 1 kWh of battery capacity, the 75th percentile from the same review. Emission of battery cells production can be estimated using the formula (3):

$$E_{bp} = 120 \cdot B_{ec} \quad (3)$$

where: E_{bp} – GHG emission of battery cells production [kg CO_2-eq], B_{ec} – overall energy capacity of battery cells [kWh].

Fuel and energy consumption of various types of vehicles has been determined by analysis of a few different sources: tests conducted by the ADAC association (ADAC Ecotest) [2], fuel consumption results submitted by users of spritmonitor.de website [24], honestjohn.co.uk website

[13], official website of the United States Environmental Protection Agency dedicated to fuel economy of vehicles (fueleconomy.gov) [10] and author's own research on fuel economy of LPG-powered vehicle.

Life cycle tailpipe emission can be estimated using the formula (4):

$$E_t = \frac{FC}{100} \cdot CI_{fb} \cdot TDD \tag{4}$$

where: E_t – total tailpipe GHG emission [kg CO_2-eq], FC - average fuel consumption of vehicle [dm^3/100 km], CI_{fb} - carbon intensity of burning particular fuel [kg CO_2-eq/dm^3], TDD – total distance driven by vehicle [km].

Carbon intensity of burning different fuels (CI_{fb} – carbon intensity of fuel burning) was assumed on the basis of Defra (Department for Environment, Food & Rural Affairs)/DECC (Department of Energy & Climate Change) guidelines [7]:

- gasoline (average biofuel blend): 2.2423 kg CO_2-eq/dm^3,
- diesel (average biofuel blend): 2.5835 kg CO_2-eq/dm^3,
- LPG: 1.5326 kg CO_2-eq/dm^3.

Production of fuel and electricity also contributes to total GHG emissions and it is included in the proposed estimation method in form of the formula (5):

$$E_{ep} = \left(\frac{FC}{100} \cdot CI_{fp} + \frac{EC}{100 * CH_{eff}} \cdot CI_e\right) \cdot TDD \tag{5}$$

where: E_{ep} – total GHG emission related to the production of fuel and energy for use of the vehicle [kg CO_2-eq], FC - average fuel consumption of vehicle [dm^3/100 km], CI_{fp} – carbon intensity of the production of particular fuel [kg CO_2-eq/dm^3], EC – average electric energy consumption of vehicle [kWh/100 km], CH_{eff} – overall efficiency of charging electric vehicle [-], CI_e – carbon intensity of electricity production [kg CO_2-eq/kWh], TDD – total distance driven by vehicle [km].

Emission related to production of fuel (CI_{fp} – carbon intensity of fuel production) was assumed on the basis of data available in Defra/DECC guidelines [7] and the following values were assumed for the calculations:

- gasoline (av. biofuel blend): 0.4750 kg CO_2-eq/dm^3,
- diesel (average biofuel blend): 0.5837 kg CO_2-eq/dm^3,
- LPG: 0.1918 kg CO_2-eq/dm^3.

Emission related to production of electricity (CI_e – carbon intensity of electricity) for BEVs assumed for the calculations:

- Poland: 0.724 kg CO_2-eq/kWh [8], as a representation of high-carbon intensity of electricity generation,
- USA: 0.417 kg CO_2-eq/kWh [14], as a representation of medium-carbon intensity of electricity generation,
- EU-27 average: 0.226 kg CO_2-eq/kWh [8], as a representation of low-carbon intensity of electricity generation,
- Sweden: 0.013 kg CO_2-eq/kWh [8], as a representation of very low-carbon intensity of electricity generation.

Emission related to maintenance activities can be estimated using the formula (6):

$$E_m = Oil_{cap} \cdot Oil_n \cdot CI_{oilp} + Br_{wt} \cdot Br_n \cdot CI_{brp} + \\ + 4 \cdot Tire_{wt} \cdot Tire_n \cdot CI_{tirep} \tag{6}$$

where: E_m – emission related to maintenance of vehicle [kg CO_2-eq], Oil_{cap} – average amount of engine oil for oil change [dm^3], Oil_n – number of oil changes over vehicle's life cycle [-], CI_{oilp} – carbon intensity of engine oil production [kg CO_2-eq/dm^3], Br_{wt} – weight of brake components that need to be periodically replaced [kg], Br_n – number of replacements of brake components over vehicle's life cycle [-], CI_{brp} – average carbon intensity of brake components production [kg CO_2-eq/kg], $Tire_{wt}$ – weight of single tire in size corresponding to vehicle specification [kg], $Tire_n$ - number of tire sets changes over vehicle's life cycle [-], CI_{tirep} – carbon intensity of tires production [kg CO_2-eq/kg].

The weight of replaceable brake components is assumed to be proportional to the weight of the vehicle, and can be estimated using the formula (7), based on [4] and [11]:

$$Br_{wt} = \frac{EVWT}{64} \tag{7}$$

where: Br_{wt} – weight of brake components that need to be periodically replaced [kg], EVWT – empty vehicle weight [kg].

Additional assumptions for GHG emission assessment:

- CH_{eff} – overall efficiency of charging electric vehicles: assumed value of 0.9,
- annual distance travelled: 15,000 km,
- vehicle lifespan: 20 years, TDD (total distance driven) = 300,000 km,
- battery of electric vehicles lasts for the whole lifespan of the car,
- energy density of battery cells: 250 Wh/kg, used to calculate empty vehicle weight without battery cells,
- Oil_n (number of engine oil changes) = 20, change of engine oil every year (all vehicles with internal combustion engines),
- Br_n (brakes changes over vehicle's life cycle) = 2 for petrol, diesel and LPG vehicles, 1 for hybrid petrol, hybrid LPG and LPG with eco-driving (thanks to reduced brake wear achieved by limited use of braking system), 0 for BEVs (thanks to greatly reduced brake wear achieved by highly effective regenerative braking),
- $Tire_n$ (tires changes) = 3 (75,000 km lifespan of tires, all vehicles),
- CI_{oilp} (life cycle GHG emission of engine oil production) = 5 kg CO_2-eq/dm^3 [17],
- CI_{brp} (average carbon intensity of brake components production) = 4 kg CO_2-eq/kg, based on [4] and [11],
- CI_{tirep} (carbon intensity of tires production) = 4 kg CO_2-eq/kg [25],

Assumptions concerning parameters of all analyzed types of vehicles are presented in Table 1. The author has made every effort to ensure that the assumptions about the vehicles are as close as possible to the values that characterise typical vehicles from each group. The list of exemplary vehicles from which the data were collected is as follows:

- small (B-segment) – e.g. Ford Fiesta, Honda Jazz, Hyundai i20, Opel Corsa, Peugeot 208, Peugeot e-208, Renault Clio, Renault ZOE, Toyota Yaris, and Volkswagen Polo as small cars with conventional body, Ford EcoSport, Honda HR-V, Hyundai Bayon, Hyundai Kona, Hyundai Kona Electric, Opel Crossland, Opel

Mokka, Opel Mokka-e, Peugeot 2008, Peugeot e-2008, Renault Captur, Toyota Yaris Cross, Volkswagen T-Cross, and Volkswagen T-Roc as small SUVs,
- compact (C-segment) – e.g. Ford Focus, Honda Civic, Hyundai i30, Opel Astra, Peugeot 308, Renault Megane, Toyota Corolla, Volkswagen ID.3, and Volkswagen Golf as compact cars with conventional body, Hyundai Tucson, Kia Sportage, Nissan Qashqai, Opel Grandland, Peugeot 3008, Renault Kadjar, Toyota C-HR, and Volkswagen Tiguan as compact SUVs,
- midsize (D-segment) – e.g. Ford Mondeo, Opel Insignia, Peugeot 508, Tesla Model 3, Toyota Camry, and Volkswagen Passat as midsize cars with conventional body, Ford Mustang Mach-E, Honda CR-V, Hyundai Santa-Fe, Kia Sorento, Nissan X-Trail, Peugeot 5008, Renault Koleos, Tesla Model Y, Toyota RAV-4 as midsize SUVs.

Values of empty weight and battery capacity are based on data gathered from technical specifications of vehicles from each vehicle type, as well as from tests conducted by the ADAC association [1]. Data concerning fuel and energy consumption are based on tests conducted by the ADAC association (ADAC Ecotest) [1], official U.S. Environmental Protection Agency website concerning fuel economy of vehicles [10] and data collected by users of websites Spritmonitor.de [24] and Honestjohn.co.uk [16]. Fuel consumption of LPG vehicles is based on consumption of petrol vehicles of the same type, with assumption of 30% increase of volumetric fuel consumption. The value is higher than frequently indicated 20% to compensate for additional petrol consumption during vehicle start-up and warm-up. Fuel consumption of LPG vehicles using eco-driving techniques is based on author's long-term research of LPG consumption of compact vehicle and extrapolated for other vehicle types. Data concerning tire weight are based on technical specifications of tires in typical sizes for each segment, gathered from the catalog of Continental Tires [6]. A higher tire weight was observed in BEVs compared to equivalent vehicles with ICE, probably due to the higher weight of the vehicles caused by lower energy density of battery cells compared to traditional fuels.

3. Results

The results of life cycle GHG emissions were estimated using formulas (1)–(7) and are presented in Fig. 1. The emissions were calculated for vehicles of three of the most popular segments: small (B-segment), compact (C-segment), and midsize (D-segment), divided into cars with conventional body and SUVs. For each type of vehicle, 10 different subtypes were analyzed:

1. Petrol vehicle.
2. Diesel vehicle.
3. LPG vehicle.
4. LPG vehicle used with eco-driving techniques.
5. Hybrid (petrol–electric) vehicle.
6. Hybrid (LPG–electric) vehicle.
7. Battery electric vehicle powered by electric energy in Poland.
8. Battery electric vehicle powered by an average electric energy in the USA.
9. Battery electric vehicle powered by an average electric energy in EU-27.
10. Battery electric vehicle powered by electric energy in Sweden.

Emission of vehicle is divided into five sources:

1. Vehicle production GHG emission (without battery cells production).
2. Tailpipe GHG emission.
3. Fuel/energy production GHG emission.
4. Maintenance GHG emission.
5. Battery cells production GHG emission, with lower and higher uncertainty level according to the values presented in the method section.

The most important results of the research are the values of total life cycle GHG emissions, which determine the impact of vehicle on global warming. In case of the same total distance driven for each vehicle, total emission is directly proportional to emission per kilometer, marked on the right axis of Fig. 1.

To visualize how the estimated total emission is distributed over the lifetime of vehicles with different fuel types and energy sources, Fig. 2 presents calculated cumulative greenhouse gases life cycle emissions over 20 years of compact car usage.

4. Discussion

By analyzing obtained calculation results, they can be summarized as follows:

1. In each type of vehicle, petrol vehicles generate the highest total GHG emission.
2. The average calculated reduction in emission, compared to petrol vehicles was found as follows:
   - 3.7% for diesel vehicles,
   - 10% for BEVs used in Poland,
   - 15% for LPG vehicles,
   - 18% for petrol hybrid vehicles,
   - 25% for LPG vehicles with eco-driving techniques,
   - 30% for LPG hybrid vehicles,
   - 37.5% for BEVs used in the USA, 54.5% for BEVs used in EU-27,
   - 74% for BEVs used in Sweden.
3. The average emission of SUV is 18.6% higher than emission of car with conventional body, 14% in small segment, 20% in compact segment, and 20.9% in midsize segment.
4. The average emission of electric SUV is 17.3% higher than emission of electric car with conventional body, 14.4% in small segment, 19.1% in compact segment, and 18% in midsize segment.
5. The average difference between emission of electric SUV and electric car in Poland is 32 g CO_2-eq/km (17.8% increase), while in Sweden the average difference is smaller: 8.3 g CO_2-eq/km (15.8%).
6. Total emission of electric vehicle used in Poland is 230–250% higher than in Sweden.
7. In countries with high-carbon intensity of electric energy production (such as Poland), total CO_2 emission of conventional cars, regardless of their fuel type is likely to be lower than emissions of BEV SUVs of the same segment, with reduction at the level of approximately:
   - 34% for hybrid LPG car,

Table 1. Assumed parameters of various vehicle types

Vehicle type	Fuel, energy source	Empty weight without battery cells	Empty weight with battery cells	Steel & iron content	Aluminum alloys content	Other materials content	Average fuel/energy consumption	Battery energy capacity	Engine oil capacity	Tire weight
		kg	kg	%	%	%	dm^3/100 km or kWh/100 km	kWh	dm^3	kg
Small car	Petrol	1100	1100	60	10	30	5.5	0	3.5	7
	Diesel	1150	1150	60	10	30	4.5	0	4	7
	LPG	1130	1130	60	10	30	7.2	0	3.5	7
	LPG eco-driving	1130	1130	60	10	30	6.2	0	3.5	7
	Hybrid Petrol	1170	1176	60	10	30	4.4	1.5	3.5	7
	Hybrid LPG	1200	1206	60	10	30	5.7	1.5	3.5	7
	BEV Poland	1200	1400	56	14	30	14	50	0	8
	BEV USA	1200	1400	56	14	30	14	50	0	8
	BEV EU-27 Avg	1200	1400	56	14	30	14	50	0	8
	BEV Sweden	1200	1400	56	14	30	14	50	0	8
Small SUV	Petrol	1200	1200	60	10	30	6.3	0	3.5	9.5
	Diesel	1250	1250	60	10	30	5.2	0	4	9.5
	LPG	1230	1230	60	10	30	8.2	0	3.5	9.5
	LPG eco-driving	1230	1230	60	10	30	7.1	0	3.5	9.5
	Hybrid Petrol	1270	1278	60	10	30	5	2	3.5	9.5
	Hybrid LPG	1300	1308	60	10	30	6.5	2	3.5	9.5
	BEV Poland	1300	1540	56	14	30	16	60	0	10.5
	BEV USA	1300	1540	56	14	30	16	60	0	10.5
	BEV EU-27 Avg	1300	1540	56	14	30	16	60	0	10.5
	BEV Sweden	1300	1540	56	14	30	16	60	0	10.5
Compact car	Petrol	1250	1250	60	10	30	6.4	0	4	8.5
	Diesel	1330	1330	60	10	30	5.2	0	4.5	8.5
	LPG	1280	1280	60	10	30	8.3	0	4	8.5
	LPG eco-driving	1280	1280	60	10	30	7.2	0	4	8.5
	Hybrid Petrol	1350	1356	60	10	30	5	1.5	4	8.5
	Hybrid LPG	1380	1386	60	10	30	6.5	1.5	4	8.5
	BEV Poland	1400	1640	56	14	30	16	60	0	10
	BEV USA	1400	1640	56	14	30	16	60	0	10
	BEV EU-27 Avg	1400	1640	56	14	30	16	60	0	10
	BEV Sweden	1400	1640	56	14	30	16	60	0	10
Compact SUV	Petrol	1400	1400	60	10	30	7.8	0	4	11
	Diesel	1500	1500	60	10	30	6.3	0	4.5	11
	LPG	1430	1430	60	10	30	10.1	0	4	11
	LPG eco-driving	1430	1430	60	10	30	8.8	0	4	11
	Hybrid Petrol	1500	1508	60	10	30	6.1	2	4	11
	Hybrid LPG	1530	1538	60	10	30	7.9	2	4	11
	BEV Poland	1600	1900	56	14	30	19	75	0	12
	BEV USA	1600	1900	56	14	30	19	75	0	12
	BEV EU-27 Avg	1600	1900	56	14	30	19	75	0	12
	BEV Sweden	1600	1900	56	14	30	19	75	0	12
Midsize car	Petrol	1500	1500	60	10	30	7.2	0	4.5	10
	Diesel	1600	1600	60	10	30	5.9	0	5	10
	LPG	1530	1530	60	10	30	9.4	0	4.5	10
	LPG eco-driving	1530	1530	60	10	30	8.1	0	4.5	10
	Hybrid Petrol	1600	1608	60	10	30	5.7	2	4.5	10
	Hybrid LPG	1630	1638	60	10	30	7.4	2	4.5	10
	BEV Poland	1600	1900	56	14	30	18	75	0	11
	BEV USA	1600	1900	56	14	30	18	75	0	11
	BEV EU-27 Avg	1600	1900	56	14	30	18	75	0	11
	BEV Sweden	1600	1900	56	14	30	18	75	0	11
Midsize SUV	Petrol	1650	1650	60	10	30	9	0	4.5	12
	Diesel	1750	1750	60	10	30	7.3	0	5	12
	LPG	1680	1680	60	10	30	11.7	0	4.5	12
	LPG eco-driving	1680	1680	60	10	30	10.1	0	4.5	12
	Hybrid Petrol	1750	1758	60	10	30	7.1	2	4.5	12
	Hybrid LPG	1780	1788	60	10	30	9.2	2	4.5	12
	BEV Poland	1800	2140	56	14	30	22	85	0	13
	BEV USA	1800	2140	56	14	30	22	85	0	13
	BEV EU-27 Avg	1800	2140	56	14	30	22	85	0	13
	BEV Sweden	1800	2140	56	14	30	22	85	0	13

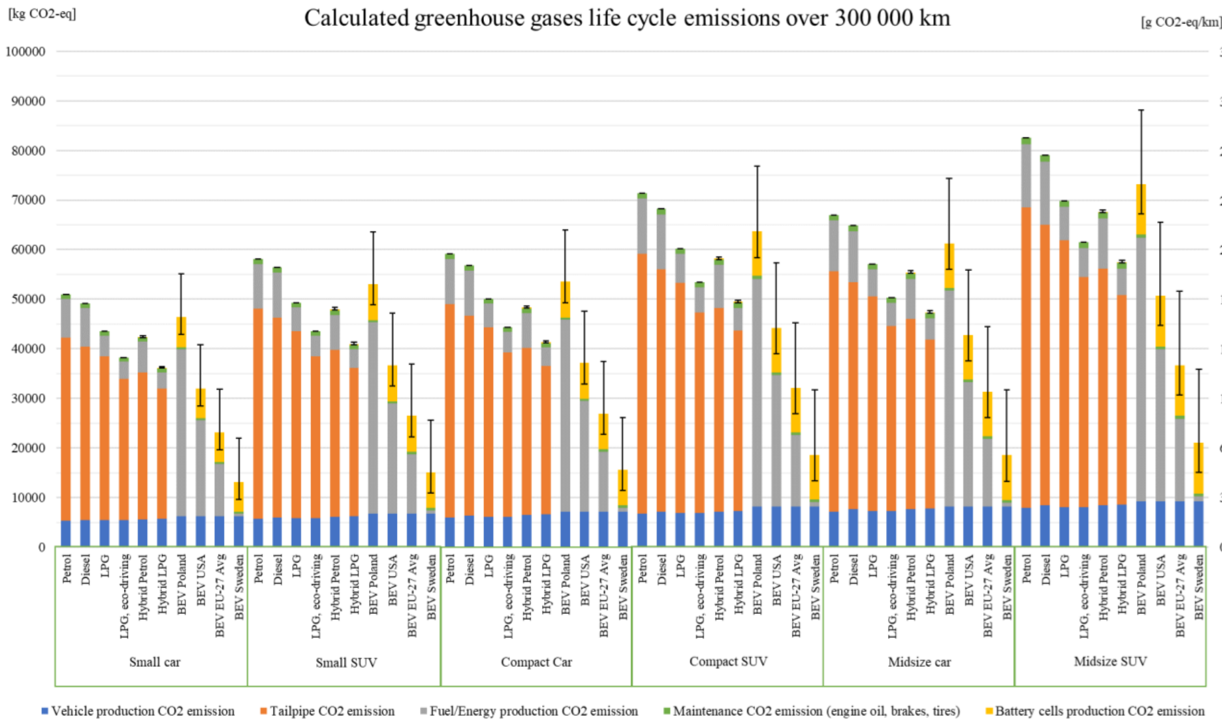

Fig. 1. Calculated greenhouse gases life cycle emissions of passenger vehicles over 300 000 km

Fig. 2. Calculated cumulative greenhouse gases life cycle emissions over 20 years of compact car usage

- 30% for LPG car with eco-driving techniques,
- 23% for hybrid petrol car,
- 20.5% for LPG car,
- 10% for diesel car,
- 6.5% for petrol car.

8. In countries with medium-carbon intensity of electric energy production (such as the USA) total GHG emissions of BEV SUVs are similar to emissions of cars of the same segment with conventional body and LPG hybrid (on average 5% lower total emission than BEV SUV in the USA) and economically driven LPG powertrain (on average 1% higher total emission than BEV SUV in the USA). Some more emissions are generated by cars with petrol hybrid (on average 11.4% higher total emission than BEV SUV in the USA) and LPG powertrain (on average 15% higher total emission than BEV SUV in the USA). Emissions of diesel and petrol cars are on average higher than BEV SUVs in the USA by respectively 30% and 35%.
9. In countries with low-carbon intensity of electric energy production (EU-27 average), total emissions of electric vehicles are much lower than vehicles with internal combustion engines of the same segment, on average by 46.4%. However, average emission per 1 km of electric

vehicles: compact SUV (107.2 g CO_2-eq/km), midsize car (104.5 g CO_2-eq/km) and midsize SUV (122.3 g CO_2-eq/km) exceeds 95 g CO_2-eq/km level set by UE authorities as a target tailpipe emission level for passenger vehicles in 2020, while small SUVs (88.2 g CO_2-eq/ km) and compact cars (89.9 g CO_2-eq/km) are also close to the value. The small differences between emission of midsize BEV SUV in EU-27 (122.3 g CO_2-eq/km) and smaller vehicles with internal combustion engines: small hybrid LPG car (120.6 g CO_2-eq/km, 1.4% less than midsize BEV SUV), economically driven small LPG car (127.5 g CO_2-eq/km, 4.2% more than midsize BEV SUV) and compact hybrid LPG car (137.7 g CO_2-eq/km, 12.6% more than midsize BEV SUV) shows that even with low-carbon intensity of electric energy production not all BEVs offer significant potential to reduce CO_2 emission compared to vehicles with internal combustion engines with relatively low level of CO_2 emission.

10. Even in countries with very low-carbon intensity of electric energy production such as Sweden, BEVs are not completely zero emission vehicles, as there are still emissions related to production of vehicle, battery and maintenance. Total calculated GHG emissions for BEVs in Sweden range from around 13 tonnes CO_2-eq for small car (43.9 g CO_2-eq/km) to around 21 tonnes CO_2-eq (70.2 g CO_2-eq/km) for midsize SUV. However, the total emissions of electric vehicles in Sweden are much lower than vehicles with internal combustion engines of the same segment, on average by 69%.
11. Results visualized in Fig. 2 show that increased GHG emission of the production stage of BEVs can be compensated in just 3–5 years compared to vehicle with ICE, but only with very low carbon intensity of electricity production. The higher the carbon intensity of electricity production, the longer it takes to compensate.

The results of the study demonstrate similarities with other studies on assessing the impact of vehicles on global warming. Study [18] also found that "… in Polish conditions, introducing cars with electric engines into circulation at the expense of withdrawing cars with internal combustion engines is not unequivocally positive." It also found that not only GHG emission of BEVs may be at similar level to those of vehicles with ICE, but also other pollutants, such as NO_x (nitrogen oxides), PM (particulate matter), and SO_2 (sulphur dioxide).

Another study [16] concluded that LPG may be a good alternative to petrol in terms of emissions and showed a 15–18% decrease in CO_2 emission, which is in line with findings in the current paper.

Each method of assessing GHG emission has its own limitation and is susceptible to input data. The presented method was developed to compare GHG emissions of different vehicles in a simple, yet effective way, with data available for customers of vehicles. Currently, customers are informed only about TTW (tank to wheel, tailpipe) CO_2 emission, which in case of battery electric vehicles does not exist. As there is a strong need to limit CO_2 emissions, the method can effectively help people choose the right vehicle that under certain conditions of use would also be the least harmful in terms of climate changes.

5. Conclusion

The final conclusions resulting from the conducted research are summarized as follows:

– in countries with high and medium-carbon intensity of electric energy production, driving a fuel-efficient hybrid or LPG vehicle may result in less total CO_2 emission than driving a battery electric vehicle (BEV), therefore BEVs are not always the best solution for limiting CO_2 emissions of transport,
– in countries with low and very low-carbon intensity of electric energy production, total CO_2 emission of BEVs is lower than that of similar vehicles with internal combustion engines,
– SUVs with both electric and internal combustion powertrains generate around 18% more CO_2 emissions than vehicles with conventional body of the same class and powertrain. In order to achieve real reductions of CO_2 emissions, popularity of SUVs should be reversed as soon as possible,
– LPG installation can decrease total CO_2 emission of petrol and hybrid vehicles by around 15%,
– eco-driving techniques can decrease total CO_2 emission of LPG vehicles by around 12% compared to normal, non-aggressive driving,
– national policies concerning passenger vehicles and their impact on climate change, covering aspects such as subsidies, excise duties, and taxes should take into account not tailpipe, but life cycle emissions of vehicles,
– low energy consumption of electric vehicle is essential in limiting its indirect CO_2 emissions, therefore it should be treated as a crucial parameter in the design process,
– high longevity is crucial in decreasing CO_2 emission per kilometer driven of electric vehicles. Reduced longevity would significantly increase emission of BEV per kilometer, as the emissions related to production of vehicle and battery would be divided by a shorter distance.

Battery electric vehicles are possibly the future of individual passenger transport, but it is crucial to recognize not only their advantages, but also their drawbacks. In order to minimize the impact of passenger transport on the environment, it is too early to simply replace all internal combustion vehicles with BEVs. In order to make these cars friendly to climate, they should use as little energy as it is possible and have a long service life. Electric vehicles with high energy consumption may hamper and prolong the transition to renewable energy, without which BEVs are not necessarily less harmful to the climate than fuel-efficient vehicles with internal combustion engines.

Nomenclature

BEV	battery electric vehicle
ICE	internal combustion engine
LPG	liquefied petroleum gas
CO_2-eq	carbon dioxide equivalent
GHG	greenhouse gas
SUV	sport utility vehicle

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