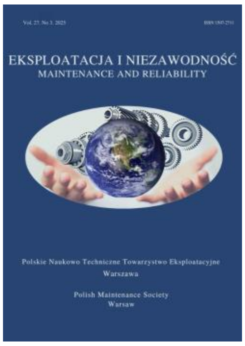

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Application of the life cycle assessment method in public bus transport

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Highlights

- Environmental engineering in the maintenance of public bus public transport.
- Determining the costs of climate change in public bus transport.
- Reducing greenhouse gas emissions from transport.
- Environmental protection in transport.

Abstract

This paper provides and comments upon the results of an in-house study of the greenhouse gas emissions generated over the life cycle of diesel-fuelled (DF) and electric buses (BEV) used by a chosen municipal transport company (MTC) operating in the urban area officially referred to as the Metropolis of Upper Silesia and Dąbrowa Basin (GZM). Based on real-life data obtained from the municipal transport company in question, comparative analyses of the relevant greenhouse gas (GHG) emission rates, established in line with the cost-benefit analysis (CBA) and life cycle assessment (LCA) methodologies, were conducted. The CBA methodology currently in use does not take several key environmental aspects into account in the calculations performed for purposes of carbon-neutral public bus transport, which is why the solution proposed in this paper entails using the LCA method to calculate GHG emissions with the aim to expand and add detail to the methodology employed when calculating climate change costs under cost-benefit analyses performed with an outlook extending to the year 2027.

Keywords

cost-benefit analysis, electromobility, life cycle assessment method, public bus transport, maintenance of bus

1. Introduction

The provision of transport services by municipal transport companies is an important problem from the perspective of how sustainable transport functions in cities. The vehicles most typically operated by municipal transport companies at present are diesel-powered buses compliant with different exhaust emission standards, having negative effects on air quality and causing emission of harmful substances while combusting fuel. However, they also offer some advantages associated with how common they have become, namely lower purchase prices and lack of additional financial expenditures on the electric battery charging infrastructure as well as the necessary technical facilities. The implementation of electromobility in cities is primarily related to reducing the negative environmental impact of vehicles. There is a number of diverse solutions introduced in urban areas to curb greenhouse gas emissions and limit the impact of hazardous pollutants on human health, including electric buses, which are becoming increasingly popular. The authors of paper [1] have proposed an original bus replacement model aimed at helping public transport operators to gradually upgrade their existing vehicle fleets. The model takes external costs into account in a comprehensive manner, including external climate costs, external health costs, and the

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costs/benefits associated with the recycling of used batteries. The authors applied this model to real-life data obtained from a public transport company operating in Singapore. In paper [2], based on assessments of environmental costs and total costs of ownership, the authors have proposed concepts for early replacement of old diesel-powered buses. They claim [2] that city buses with very long track record contribute significantly to overall environmental impacts. They conducted economic and environmental analyses of a transition to more eco-friendly bus fleets in Israel, following the concept of early replacement of older, yet still operational, buses while exploring several drive system alternatives. An electric bus proved to be superior in terms of environmental costs, but at the expense of the highest overall costs. Paper [3] provides a discussion on the method proposed for the sustainable public bus system planning in the cities of Calgary (Canada) and Beijing (China). The authors have defined three criteria aligned with the three premises of sustainability, namely the environmental, social, and economic dimensions, and identified all the stakeholders associated with public bus transport systems. The authors of paper [4] imply that hydrogen and electric buses represent a good option for the decarbonisation of the public transport sector. They studied modelling of bus drive systems by taking real-life data concerning the buses operated in Italy into consideration. The subject of paper [5] is a study of city buses powered by diesel fuel, electricity, and hydrogen, conducted by the life cycle assessment (LCA) method. The authors conducted comprehensive emission and cost analyses, considering both energy production and bus operation cycles in their entirety. According to the authors of paper [5], when analysis is limited to fuel consumption only, electric buses show by far the lowest carbon emissions. In paper [6], greenhouse gas (GHG) emissions related to urban road transport have been subject to an LCA-based analysis using the Chinese city of Chongqing as an example. The authors have examined five scenarios comprising vehicles propelled by different drive systems. The analysis results discussed in paper [6] imply that all the adopted scenarios will reduce fuel consumption and GHG emissions between 2016 and 2035. The authors of paper [7] applied LCA to study the environmental effects of the urban bus fleet replacement with electric buses using the example of the city of Krakow. The authors of paper [7] developed three models of buses powered by diesel, hybrid, and electric engines. They analysed the environmental impact of all these buses at the stages of their production and operation, as well as the effect of diesel fuel and electricity production. The analysis results provided in paper [7] pertain to four categories: human health, ecosystem quality, climate change, and resources. The authors have concluded that increasing the proportion of electric buses in public transport companies can be highly beneficial for all of these four categories under the condition that the electricity used to power the electric buses is generated from low-emission or carbon neutral energy sources. Using LCA, the authors of paper [8] conducted economic and environmental analyses of the transformation of local public bus transport fleets in Italy. Their studies have confirmed that, in cities, the pre-adopted scenario of using electric buses only exerts the least negative environmental impact. Paper [9] covers a study of CO_2 emissions based on real-life data concerning electric and hydrogen buses. The authors have found that the buses subject to analysis enable significant CO_2 emission reductions compared to diesel-powered vehicles. The authors of paper [10] analysed the replacement of diesel buses with electric ones, and their results imply that switching to electric buses is a promising alternative in the pursuit of environmental goals, since electric buses ensure a 68% reduction in total emissions compared to their diesel counterparts. The authors have further highlighted that electric buses may in fact cause direct emissions attributable to their operation.

The authors of papers [1–10] conducted various LCA-based analyses concerning the concept of replacing diesel-powered buses with electric vehicles to be used in urban public transport. What they analysed in the first place was the effect attributable to the replacement of buses on CO_2 emissions and their total cost of ownership. These studies did not address the overall body of problems related to estimating the climate change costs associated with the GHG emission reduction, which should indeed be estimated when buses are replaced with electric vehicles under the cost-benefit analysis (CBA) methodology. The CBA methodology currently in use does not take several key environmental aspects into account in the calculations performed for carbon neutral public bus transport. That is precisely why the authors of this paper have proposed that the LCA method be used to calculate greenhouse gas emissions in order to expand and add detail to the methodology employed while determining climate change costs under the cost-benefit analyses spanning the period until 2027.

2. The cost-benefit analysis (CBA) methodology

The cost-benefit analysis (CBA) methodology is based on general guidelines set by the European Commission (EC) as well as on methodological studies commissioned by the EC. In Poland, details of the CBA methodology were initially developed by the Road and Bridge Research Institute, later to be expanded by JASPERS and the Centre for EU Transport Projects (CEUTP) [11,12]. The cost-benefit analysis methodology dedicated to the public transport sector in cities, agglomerations, and regions, as defined for the years 2018 and 2021, was described in detail in the Blue Paper on public transport [13] as well as in Stakeholder's Vademecum [11], while the principles of the relevant cost-benefit analyses were proposed in 2024 in the document entitled Blue Paper on the public transport sector in cities, agglomerations, and regions [14]. Document [14] is recommended by Poland's Ministry of Development Funds and Regional Policy which, along with CEUTP, commissioned JASPERS to develop an update to the manual in question [13], which had been used throughout the previous financial perspective, to take into account the new EC regulations for the 2021–2027 financial perspective. This Blue Paper [14] constitutes an update and supplement to the previous editions of the manual developed in 2006, 2008, and 2015, and in terms of the underlying premises and the methodology for performing CBA, it follows the principles outlined in Economic Appraisal Vademecum 2021–2027, General Principles and Sector Applications [15].

While estimating the effects of the emission of harmful substances on the environment and human health, one should also determine climate change costs. For all of the variants envisaged under the CBA methodology, i.e. investment exclusive (IE variant) and investment inclusive (II variant), climate change costs, i.e. the costs of the impact of public transport on greenhouse gas emissions, represent total climate change costs (expressed as CO_2 equivalent) determined as total CO_2 equivalent emission multiplied by a unit cost. The methodology proposed in the said guidebook [14] is aligned with the European Investment Bank (EIB) Project Carbon Footprint Methodology, which consists in assessing the impact of GHG emissions, mainly from the operational phase, i.e. of vehicular traffic in different road networks. Emissions of greenhouse gases other than carbon dioxide, such as methane (CH_4) and nitrous oxide (N_2O), are not taken into account, since their impact is considered negligible. Consequently, the GHG emission rates being calculated can be considered indicative of carbon dioxide emission only.

According to the methodology envisaged for analysing environmental aspects, proposed for purposes of cost-benefit analyses in the Blue Paper [14], in order to determine GHG emissions, one must estimate the following:

- absolute emissions, i.e. total emissions produced over a typical year of operation (Mg CO_2 eq);
- relative emissions, i.e. difference in emissions between the investment inclusive (II) and investment exclusive (IE) variants, as described in the CBA for a given year of operation (Mg CO_2 eq), expressed in incremental terms (increase/decrease).

Greenhouse gas emission costs are calculated by multiplying the annual relative CO_2 emissions, stablished as above, by unit costs.

In the case of public bus transport, the estimation of annual relative emissions depends on the emissions generated by buses in a given road network, and this concerns the greenhouse gas emission rates which must be multiplied by the relevant transport work value. The emission values depend, on the other hand, on the fuel/energy consumption by buses. As per the assumptions adopted for the operating costs of vehicles [14], fuel consumption depends primarily on speed, vehicle category, as well as road pavement condition and geometry. With regard to road traffic, the methodology envisaged for calculating the costs of greenhouse gas emissions for buses powered by internal combustion engines takes only direct emissions related to the operating phase into account, while for electric buses, only indirect greenhouse gas emissions connected with the generation and supply of the energy required to operate electric vehicles (i.e. the grid factor) are considered. Determined in such a manner, annual GHG emission values are then to be multiplied by the unit economic costs of CO_2 equivalent provided by the European Central Bank (ECB). In line with the GHG emission analysis methodology assumed for CBA, as specified in guidebook [14], the GHG emission rate for electric vehicles in the year (baseline) 2021 was 668.68 [g CO_2/kWh]. This value was established on the basis of the GHG emission coefficient envisaged for the electric energy obtained from the national power grid, as stated by National Centre for Emissions Management (KOBiZE) in 2019, i.e. 719 [g CO_2/kWh], by taking into account the following assumptions adopted for the sake of adequate simplification: fraction of grid electricity generated from coal and lignite in 2019, estimated flexibility of greenhouse gas emissions associated with grid electricity relative to changes in the share of hard coal and lignite in Poland's energy mix, and projected share of hard coal and lignite in Poland's energy mix as per Poland's Energy Policy until 2040. Another factor taken into account was the projected GHG emission rate based on the adopted Energy Policy of Poland until 2040, as provided in Table 1 [14].

Following an analysis of the CBA-aligned GHG emission methodology defined in document [14], it was found that, in 2021, the estimated values of electric energy consumption equalling 2.175 [kWh/vehicle-km] and GHG emission rate of 1,454.38 [g CO_2 eq/vehicle-km] were only provided for a single vehicle referred to as a "standard urban electric bus." The foregoing values pertain to the total emissions associated with the generation and transmission of the grid electricity consumed by the bus as well as the emissions associated with its fuel consumption. Both the energy consumption and GHG emission rate values were determined under the CEUTP-JASPERS in-house study based on EIB Project Carbon Footprint Methodologies of July 2020 and the CO_2 emission factor defined for grid electricity end users for 2019 by KOBiZE [14].

Table 1. Projected national greenhouse gas emission rates for grid electricity generation. Source: authors' own compilation based on [14]

Year	2021	2025	2030	2035	2040
g CO_2 eq/kWh	668.68	645.57	579.05	446.40	373.31

In accordance with the CBA guidelines for the assessment of fleet upgrading through the implementation of carbon neutral buses, it was concluded that an adequate assessment of the relevant capital expenditures should take into account both the bus fleet itself and the infrastructure associated with the drive system alternatives considered (e.g. new charging stations, necessary infrastructure upgrades). A CBA-aligned analysis of the expenditures envisaged towards operation and maintenance costs should reflect vehicle operating conditions in the field [14].

CO_2 emissions under the baseline scenario (BS) should be assessed against the actual fleet of buses and foreseeable changes, without referring to statutory requirements [16,17], in a breakdown by drive system type and conformity with emission standards, and by taking the relevant emission rates into consideration. Monetisation is determined on the basis of the unit cost per emission of 1 Mg of CO_2. And since the damage caused by global warming is evidently global in nature, it does not matter what the greenhouse gas emission source is and where in Europe the emissions actually occur. It is precisely for that reason, as well as to compare the costs of climate change, that identical cost factors [4] are used in documents and projects being developed across all EU countries.

The CBA methodology proposed in documents [13,14] does not take several key aspects into account in the calculations run for carbon neutral public bus transport. Carbon neutral buses are deployed primarily to inhibit the greenhouse effect processes which result from the emission of CO_2 into the higher layers of the atmosphere. The methodological manuals used in the EU and concerning CO_2 emission propose two methods for the valuation of CO_2 emission costs. One takes the fundamental effects of climate change into account, while the other also comprises the consequences of extreme and abrupt weather conditions. In the EU, the emission valuation solution proposed by the European Investment Bank (EIB) is widespread, corresponding to the first of the said methods. Given Poland's current energy mix, investing in carbon neutral buses does not contribute to reducing the greenhouse effect, since reduced emissions from public transport are replaced by high emissions from coal-fired power plants. In this case, the greenhouse gas emission results from the fuel consumption by buses, the distance they have covered, and their exhaust emission standards. In order to estimate GHG emissions on an annual basis, average diesel fuel consumption for each group of buses is taken into account, broken down by type and exhaust standard. The environmental effect of CO_2 emission reduction through reduced fuel consumption is most often shown under the relevant cost-benefit analysis as the amount of emission reduction attributable to phasing out diesel buses and replacing them with electric ones. Where this is the case, the value of what is referred to as avoided CO_2 emissions for diesel fuel is determined as the product of the mean annual fuel consumption by the buses planned for decommissioning and the emission rate.

3. Methodology of LCA-based analyses

In the transport sector, the life cycle assessment (LCA) method [18, 19] is applied by way of the well-to-wheel (WTW) fuel life cycle analysis, making it possible to assess the energy consumption and greenhouse gas emissions attributable to fuel production, transport, and distribution. The WTW analysis spans two phases: well-to-tank (WTT) and tank-to-wheel (TTW). WTT comprises the environmental burdens associated with the sourcing of the raw material from which fuel is produced, the fuel production itself, as well as its transport and storage. TTW takes into account the environmental burdens associated with the fuel consumption by means of transport, as well as the refuelling and fuel combustion associated with vehicle operation.

Over the course of the study, the greenhouse gas emissions attributable to buses were established by the LCA method [18, 19] using the Simapro v. 9.5.0.2 software along with the Ecoinvent v.3.9 database [20, 21]. The solution used to conduct the environmental impact assessment was the IPCC method, developed by the Intergovernmental Panel on Climate Change [20, 21], intended to enable evaluation of greenhouse gas emissions over the entire life cycle of products [22]. The IPCC method applied in the analyses made it possible to calculate the greenhouse gas emission rate based on what is referred to as global warming potential (GWP), which expresses the radiative forcing of the greenhouse gases released into the environment, converted into equivalent kilogrammes of carbon dioxide [21]. The analyses performed by the authors included comparing greenhouse gas emissions generated by electric buses and those powered by internal combustion engines. With reference to the standards covering the LCA method, the scope and purpose of the analyses were defined along with the system boundary, basic analytical assumptions, and the functional unit. The analyses performed under the study covered the life cycle of the fuels used in the buses operated by the selected municipal transport company. The results of these analyses refer to the year 2022, and the functional unit is 100 kilometres covered by individual buses. The input and output data used for individual bus life cycle phases in the paper are actual distance travelled and fuel consumption data obtained from the municipal transport company. What the analyses concerning electric buses also took into account was the additional fuel consumption associated with the heating system used in the operation of these electric buses.

The assumptions related to the structure of the gas and dust emissions from the operation of road transport vehicles in Poland, as adopted for the study, were developed by referring to the 2021 data from the Central Statistical Office (GUS) [23], while the emissions from diesel engine buses were assumed on the basis of the data provided by KOBiZE [24,25]. The data concerning the energy supply systems used for the charging of electric bus batteries were based on national data [26,27]. The electricity production in Poland in 2022 has been summarised in Table 2 in a breakdown by energy source.

Table 2. Electricity production by energy source in Poland in 2022. Source: authors' own compilation based on [26,27]

Electricity source	Electricity production [TWh]
Hard coal	79
Lignite	47.3
Gaseous fuel	11.7
Hydropower	2
Solar power	8
Wind power	19.4
Biogas	1.4
Biomass	4.3
Pumped storage power plants	1.1
Biomass co-firing	1.9
Other industrial power stations	2.9

4. Assumptions and data inventory

The body responsible for managing the collective public transport in Metropolis of Upper Silesia and Dąbrowa Basin (Metropolis GZM) is Metropolitan Transport Authority (ZTM), appointed to make sure that passenger transport services are rendered in the metropolitan area, while there are currently 22 entities providing bus, tram, and trolleybus transport services within this territory. Municipal transport companies hold the largest share in the bus transport market, as they are responsible for more than 60% of passenger transport services. In 2021, the number of buses in operation in the GZM area was 1,386, with an average vehicle age of almost 12 years [28].

The municipal transport company (MTC) chosen for the assessment of the GHG emission rates under the study is among the largest entities providing public bus transport services in Metropolis GZM. In 2022, this company delivered passenger transport services using a fleet of 242 buses. Buses running on diesel fuel constitute the most numerous group. Electric buses (BEV), make up a steadily increasing fraction of the total number of vehicles, and these represented 8% in 2022. The most numerous group of buses used in MTC to serve the transport network in the GZM territory in 2022, with the share of 84%, is that of internal combustion engine vehicles meeting the Euro V EEV and Euro VI emission standards (Figure 1).

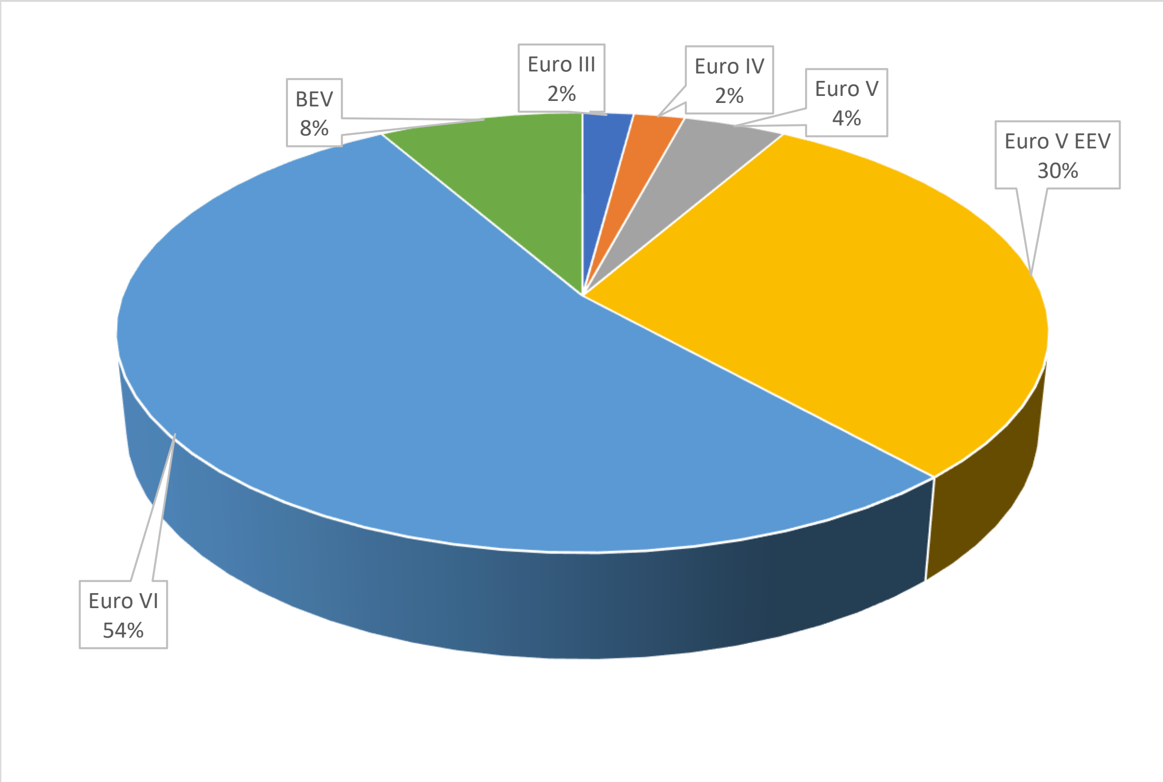


Figure 1. Breakdown of the bus fleet used in 2022 in the MTC transport network according to the Euro exhaust emission standard. Source: authors' own compilation based on [28]

The analyses performed under the study covered the following:

- electric buses, for which distance travelled and electricity consumption were taken into account along with additional diesel fuel consumption for bus heating purposes;
- buses with internal combustion engines, for which distance travelled and diesel fuel consumption were taken into account.

Given that the municipal transport company in question rendered real-life data available for both internal combustion engine vehicles and electric buses, the following designations have been adopted for purposes of the calculations provided in the article:

- 12m bus – 12-metre-long bus, MAXI class, short fleet,
- 18m bus – 18-metre-long bus, MEGA class, long fleet.

The analyses were conducted by considering real-life diesel fuel and electricity consumption data of individual buses, as provided by the chosen municipal transport company for each month of 2022.

Some examples of the data obtained for internal combustion engine buses with Euro VI standards, concerning distance travelled and fuel consumption, have been provided in Table 3, while those concerning electric buses and comprising their actual distance travelled and the consumption of electric energy and fuel for heating – in Table 4. The consumption of diesel fuel in electric bus heating systems results in additional direct emissions at the locations where the bus is being operated as well as indirect emissions related to the production of the diesel fuel used for heating.

Table 3. Fuel consumption and distance travelled by 12m diesel engine buses with Euro VI standardsbetween January and June 2022. Source: authors' own compilation based on the data obtained from the municipal transport company

January		**February**		**March**	
Distance travelled [km]	Diesel fuel [l]	Distance travelled [km]	Diesel fuel [l]	Distance travelled [km]	Diesel fuel [l]
285,520.05	102,378.96	240,965.25	85,463.49	277,578.80	100,974.42
151,617.20	60,191.43	141,008.06	54,533.25	157,094.30	61,691.04
232,808.50	81,361.45	214,797.70	73,036.47	244,931.90	85,114.73
3,620.00	1,364.30	3,117.20	1,158.93	73.00	83.74
673,565.75	**245,296.14**	**599,888.21**	**214,192.14**	**679,678.00**	**247,863.93**
April		**May**		**June**	
Distance travelled [km]	Diesel fuel [l]	Distance travelled [km]	Diesel fuel [l]	Distance travelled [km]	Diesel fuel [l]
282,343.20	101,252.56	276,441.00	102,174.61	263,101.75	98,438.83
138,461.15	53,553.66	150,602.85	57,962.38	144,476.70	57,837.75
227,227.80	79,543.60	233,101.05	81,062.37	214,028.65	75,861.08
59.00	53.03	96.80	84.06	423.10	159.37
648,091.15	**234,402.85**	**660,241.70**	**241,283.42**	**627,611.50**	**235,738.50**

Table 4. Electricity and fuel consumption and distance travelled by 12m electric buses between January and June 2022. Source: authors' own compilation based on the data obtained from the municipal transport company.

January			**February**			**March**		
Distance travelled [km]	Diesel fuel [l]	Electricity [kWh]	Distance travelled [km]	Diesel fuel [l]	Electricity [kWh]	Distance travelled [km]	Diesel fuel [l]	Electricity [kWh]
5,710.85	687.85	5,856.93	5,744.75	542.40	5,659.86	6,914.70	493.46	6,838.02
5,717.55	673.14	5,789.99	5,856.10	544.82	5,353.57	6,606.55	505.49	6,063.34
4,326.90	583.37	4,562.60	2,276.40	284.46	2,294.51	3,031.15	240.82	3,110.51
5,329.25	612.74	5,340.42	5,348.10	545.31	5,139.40	5,931.00	489.74	5,689.40
5,818.95	697.47	6,059.72	5,560.25	543.45	5,574.09	6,138.50	515.49	6,306.95
5,417.30	606.39	5,801.93	5,768.50	542.36	5,682.62	5,715.00	455.58	5,603.38
5,113.95	624.23	4,993.09	3,382.75	362.71	3,218.14	6,082.95	446.51	5,556.78
4,093.90	447.18	4,237.06	4,454.35	409.93	4,398.44	4,760.60	354.84	4,602.03
5,040.80	667.32	5,225.94	4,199.50	446.64	4,163.41	5,017.10	430.64	5,084.11
4,780.05	576.48	4,671.59	5,314.25	519.16	4,844.17	5,826.05	501.92	5,286.79
51,349.50	**6,176.17**	**52,539.25**	**47,904.95**	**4,741.24**	**46,328.20**	**56,023.60**	**4,434.49**	**54,141.29**
April			**May**			**June**		
Distance travelled [km]	Diesel fuel [l]	Electricity [kWh]	Distance travelled [km]	Diesel fuel [l]	Electricity [kWh]	Distance travelled [km]	Diesel fuel [l]	Electricity [kWh]
5,804.25	311.65	5,597.33	6,295.10	67.96	5,797.99	5,197.20	2.34	5,405.27
6,095.25	359.25	5,603.17	6,828.00	96.18	6,285.46	5,491.45	0.00	5,723.86
4,560.95	298.27	4,661.37	4,556.95	75.20	4,480.62	4,575.25	24.68	4,909.01
4,958.65	358.57	4,948.75	5,941.85	92.72	5,628.23	5,155.15	17.75	5,189.08
5,439.85	341.72	5,436.42	6,479.35	125.59	6,202.07	5,911.65	31.89	6,204.64
5,811.05	347.02	5,692.19	5,586.75	47.64	5,282.86	5,280.65	24.35	5,588.34
5,442.95	310.21	5,164.04	6,200.85	94.03	5,574.54	6,162.30	10.00	5,894.12
4,396.85	260.16	4,218.45	4,782.80	77.93	4,686.40	3,826.65	17.49	4,143.65
4,580.95	298.06	4,609.88	5,877.10	64.22	5,932.32	4,810.95	37.53	5,381.28
5,347.25	357.48	4,881.63	5,554.40	73.73	5,026.93	5,131.80	25.78	4,937.96
52,438.00	**3,242.39**	**50,813.23**	**58,103.15**	**815.20**	**54,897.42**	**51,543.05**	**191.81**	**53,377.21**

In the analyses performed for the buses featuring internal combustion engines, the system boundary comprised diesel fuel production and direct emissions over the course of the vehicle operation, including carbon dioxide emissions and on-route exhaust emissions according to the various Euro emission standards.

The system boundary set for the analyses of electric buses comprised the 2022 electricity production of all energy sources in Poland, as provided in Table 3 [26,27].

For the diesel powered buses with internal combustion engines, the following data inventory was assumed:

1. Distance travelled per each analysis month in a breakdown into short fleet (12-metre long) and long fleet (18-metre long) buses;
2. Fuel (diesel) consumption by short fleet (12 m) and long fleet (18 m) buses, including for bus heating;
3. Emissions of gas and dust pollutants according to emission standards: for long fleet (18 m) buses – Euro V EEV and Euro VI, and for short fleet (12 m) buses – Euro V, Euro V EEV, and Euro VI.

For the electric buses (BEV), the following data inventory was used:

1. Distance travelled per each analysis month in a breakdown into short fleet (12-metre long) and long fleet (18-metre long) buses;
2. Fuel (electricity) consumption for battery charging, broken down by short fleet (12 m) and long fleet (18 m);
3. Diesel fuel consumption for bus heating, broken down by short fleet (12 m) and long fleet (18 m);
4. Emissions of gas and dust pollutants according to emission standards: for short (12 m) and long (18 m) fleet – Euro VI.

5. Assessment of greenhouse gas emissions according to the LCA method

Selected in-house studies [29,30] included assessment of the impact of chosen means of road transport on climate change and human health in Poland [29] as well as analysis of greenhouse gas emissions over the life cycle of hydrogen fuel cell vehicles [30]. It was evidenced that the operation of the analysed means of transport was among the most important sources of environmental impact [29]. In the study discussed in paper [29], greenhouse gas emissions were determined by LCA and the impact of the operation of means of road transport on human health in Poland was assessed. Paper [30] provides a life cycle GHG emission assessment of hydrogen fuel cell vehicles, powered by hydrogen derived from coke oven gas, which is a by-product of the coal coking process and contains hydrogen, methane, and other gases. An environmental life cycle assessment was conducted for an electric vehicle powered by hydrogen produced from coke oven gas in Poland. Additionally, some alternative fuels were subject to a comparative analysis and the main determinants of the greenhouse gas emissions attributable to electric vehicles were indicated.

Considering the plans of the selected municipal transport company to purchase new electric buses and to gradually phase out diesel engine buses conforming with the Euro V and Euro V EEV standards in favour of diesel powered buses in line with the Euro VI standard, a comparison of the GHG emissions established for both the Euro VI diesel buses and the electric buses of short (12 m) and long (18 m) fleet has been provided in Table 5. The LCA-based analyses conducted for the electric buses took into account both the life cycle of the electric energy intended for battery charging and the consumption of additional fuel required for in-service bus heating. Figure 2 provides a comparison of the mean values of GHG emissions from Euro VI diesel (DF) engine buses and electric (BEV) buses obtained for the entire analysis year of 2022.

Table 5. GHG emissions from Euro VI diesel (DF) buses and electric buses (BEV). Source: authors' own compilation.

Bus	**Greenhouse gas emission [kg CO_2 eq/100 km]**											
	Jan'22	**Feb'22**	**Mar'22**	**Apr'22**	**May'22**	**Jun'22**	**Jul'22**	**Aug'22**	**Sep'22**	**Oct'22**	**Nov'22**	**Dec'22**
12m DF	114.71	112.47	114.87	113.93	115.11	118.31	115.34	115.91	114.61	116.05	118.07	122.81
12m BEV	130.86	119.05	112.75	107.50	90.27	95.27	92.87	93.21	95.89	95.18	112.06	136.32
18m DF	164.12	160.37	164.95	160.31	161.51	163.03	163.71	164.97	159.28	162.55	165.19	173.27
18m BEV	193.26	176.71	162.96	152.51	131.45	136.73	134.03	136.24	139.14	141.44	171.43	197.51

Based on the GHG emission rates established for the Euro VI standard-compliant diesel buses (DF) and electric buses (BEV), as summarised in Table 5, it was found that, for both the 12 m short fleet and the 18 m long fleet, in January, February, and December, the GHG emissions generated by electric buses were higher. This was due to the fact that diesel fuel consumption for heating in electric buses was taken into account in the LCA-based analyses. Following an analysis of the mean values of the GHG emissions established for the entire year 2022 (as shown in Figure 2), they were found to be lower in electric buses: by 7.97% and 4.58% for the 12 m short fleet and the 18 m long fleet, respectively.

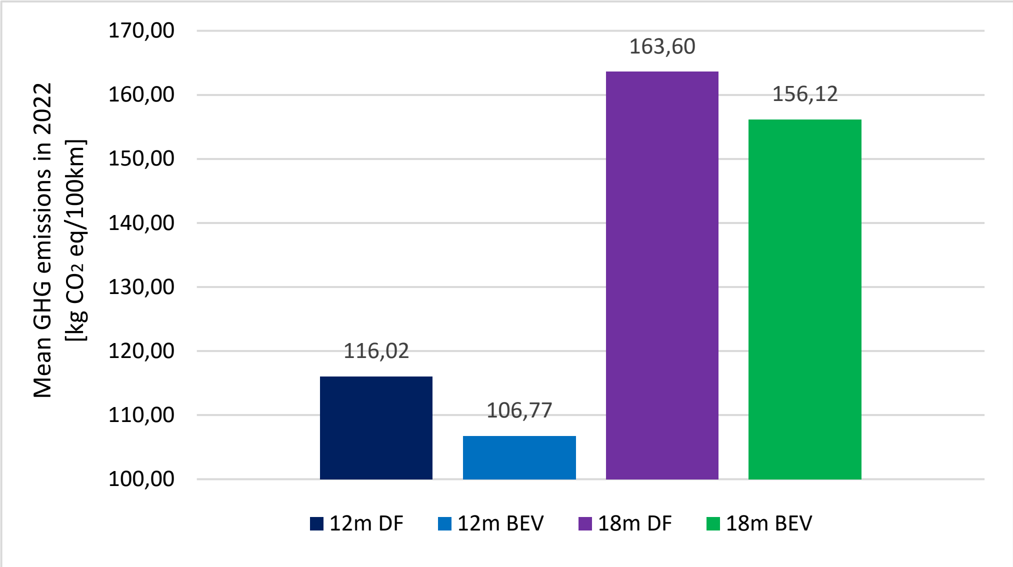


Figure 2. Mean GHG emissions from Euro VI-complaint diesel engine (DF) and electric (BEV) buses for the entire analysed year of 2022. Source: authors' own compilation.

6. Comparative analyses of GHG emissions based on the CBA and LCA methods

The cost-benefit analyses performed in 2018 and 2021 by third-party companies, commissioned by municipal authorities, included an analysis of the socioeconomic costs associated with the climate change due to positive or negative changes in greenhouse gas emissions. The positive impact of carbon neutral buses is associated with reduced atmospheric emissions and noise levels. For this reason, the following aspects were taken into account in the said CBA of socioeconomic costs:

- greenhouse gas (CO_2) emissions, i.e. the social costs of greenhouse gas emissions in the form of climate change costs;
- non-GHG emissions, i.e. the social costs of local emissions of air pollutants in the form of environment pollution costs, considering reduced road traffic;
- noise levels, i.e. the social costs of noise emissions.

The analysis of the socioeconomic costs disregarded the benefits of an increased number of passengers, assuming identical changes in the number of passengers for each of the investment options envisaged as well as the effects achieved in terms of the generalised transport costs for passengers, since they would not be generated in the event that the fleet was replaced with low-emission vehicles [31]. The additional atmospheric emissions or those avoided should be quantified by adhering to the principles set forth in documents [11–13,31], taking mean values into account once the baseline monetary value of one Mg of carbon dioxide [EURO/Mg CO_2] was assumed at EUR 25 for the year 2010. This cost item is indexed by an annual increase of EUR 1 per one Mg of CO_2 following its conversion to PLN (one should apply the average annual reference EUR/PLN exchange rate announced by the European Central Bank (ECB) in each year of analysis) [31]. Unit costs of CO_2 emission depend directly on the fuel consumption by buses, while as for the conversion rate value, it was to be assumed that, in 2022, one litre of diesel fuel (DF) caused the emission of 2.66 kg of CO_2 [25,31]. Thus calculated, the greenhouse gas emission value then had to be multiplied by the unit CO_2 cost factor, as provided by the European Investment Bank (EIB), for the individual years analysed. The result of the latter computation was the climate change cost established for the individual years of analysis and the total climate change cost for the entire period analysed.

Paper [31] contains detailed rules for developing a cost-benefit analysis for the use of carbon neutral buses in public transport, as required by the act on electromobility and alternative fuels. According to paper [31], when analysing socio-economic costs, one should apply the most recent values obtained using the pollutant emission and climate cost calculator for means of public transport, as developed by KOBiZE [32]. Furthermore, what the analysis of socio-economic costs also uses is the current tables of unit costs proposed for cost-benefit analyses, rendered available on CEUTP's website [33]. The CO_2 emissions attributable to electric buses are calculated by referring to the electricity consumption and the emission rates relevant for Poland's energy mix, as provided in the said pollutant emission and climate cost calculator for means of public transport [25]. The costs related to the emissions of pollutants other than greenhouse gases are to be estimated for the current permissible pollution limits for the specific fuel type analysed and for individual Euro exhaust emission standards applicable to the buses in operation. Additionally, for carbon neutral buses, one should also take into account the reduction of nuisances associated with the noise they generate. The cost factors assumed for external effects of noise emission were adopted by reference to the said tables of unit costs released by CEUTP (unit costs of land transport noise for buses operated in urban areas) [31].

Greenhouse gas emissions were compared in line with the CBA methodology specified in documents [11–13,28,31] on the basis of the real-life data concerning the buses operated by the municipal transport company described in Section 4. Two alternative variants were taken into consideration towards the investment to be implemented by the municipal transport company chosen for the analyses:

I. *II variant* – investment-inclusive option assuming that carbon neutral electric vehicles are deployed in accordance with the requirements of the aforementioned act [16,17];

II. *IE variant* – investment-exclusive option assuming that the existing bus fleet remains in service and that new buses with internal combustion engines meeting the highest emission standards (Euro VI) are deployed in the same number in the years to come as under the *II variant*.

As envisaged in the *II variant*, the existing bus fleet will continue to be operated and will then be successively replaced with carbon neutral electric buses in accordance with the provisions of the said act [16,17]. In order to meet the requirements set forth in the act on electromobility and alternative fuels [16,17], the share of carbon neutral vehicles in the fleet operated by the municipal transport company to provide transport services, which totalled 242 buses as of 2023, should be as follows:

- as of 1 January 2023 – 10%, i.e. 25 buses;
- as of 1 January 2025 – 20%, i.e. 49 buses;
- as of 1 January 2028 – 30%, i.e. 73 buses.

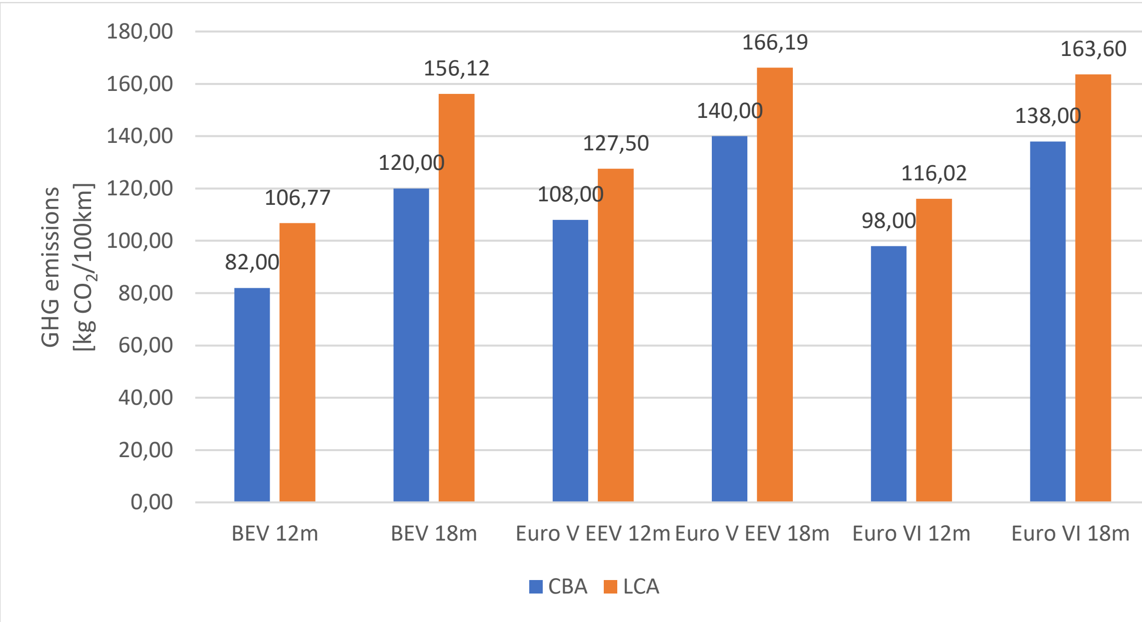
In accordance with the applicable law [16,17], given the fixed fleet quantity of 242 buses and considering the 20 carbon neutral buses currently in operation, the number of carbon neutral buses in service as of 1 January 2028 should be 73. Under stage one, i.e. by 1 January 2023, the act's requirement to use 25 electric buses had not been met. In 2023, 20 electric buses were operated by the municipal transport company analysed, which corresponds to 8.26%. The failure to meet the requirement of 10% of carbon neutral buses in operation as of 1 January 2023 was due to the applicable recommendations and conclusions derived from the cost-benefit analysis performed in 2021 [28], under which Metropolis GZM, including the municipal transport company, was exempted from the said obligation to achieve the share of carbon neutral buses in the fleet, as provided in the act [16,17], for the next 36 months. The CBA document in question [28] reads as follows: "The results obtained imply that there is no financial/economic benefit of using carbon neutral buses. Consequently, in accordance with the provisions of article 37(5) of the act on electromobility and alternative fuels, the Organising Party is not obliged to fulfil the obligation to achieve the set share of carbon neutral buses. The investment is only to be considered viable where an external source of funding is obtained to cover at least 82% of the eligible costs." [28] In the second stage of the project aimed at upgrading the fleet to serve the transport network managed by the municipal transport company, i.e. as of 1 January 2025, it is planned that new battery electric vehicles, namely 25 and 27 electric buses, are purchased and put into operation in 2024 and 2025, respectively. Similarly to stage one, these buses will replace the diesel engine vehicles which meet only the lowest Euro V EEV emission standard. This will bring the share of the electric buses operated by the municipal transport company as of 1 January 2025 to the level of 29.75% (72 buses), meaning that the relevant requirements of the law [16,17] will be met, and even with some surplus. What stage three entails is that the fleet will continue to be upgraded by deploying further 25 new carbon neutral electric buses in 2026, thus ensuring compliance with the 30% share requirement as of January 2028. On account of the assumptions adopted for the *II variant*, in 2028, the transport network where the municipal transport company operates should be served by a total of 97 electric buses, corresponding to 40.08% of the company's fleet in service. Importantly, it should be noted that the above assumptions were adopted for a fixed bus number in the fleet, i.e. 242 vehicles. Detailed quantitative data concerning the bus fleet in the analysis period spanning the years 2024–2028, broken down by drive system type, for the *II variant* have been provided in Table 6.

Table 6. Breakdown of the bus fleet operated by the municipal transport company by drive system type for the II variant and the years 2024–2028. Source: authors' own compilation based on data provided by the municipal transport company.

Drive system	No. of buses				
	2024	2025	2026	2027	2028
Electric	45	72	97	97	97
Hybrid	22	22	22	22	22
Euro V EEV	47	20	0	0	0
Euro VI	128	128	123	123	123
Total	242	242	242	242	242

The *IE variant* adopted under the study assumes that bus transport is to be developed by providing collective transport services based on the vehicles currently in operation, including all the necessary investments in the bus fleet upgrading. In order to compare greenhouse gas emissions under both variants, it was assumed that the buses to be purchased by 2028 under the *IE variant* were only to be models equipped with internal combustion engines conforming with the Euro VI emission standard, and in the same number distributed over consecutive years as envisaged under the *II variant* for electric buses. The data illustrating the bus fleet upgrade and replacement in the successive years until 2028, broken down by drive system type, have been provided in Table 7.

a)



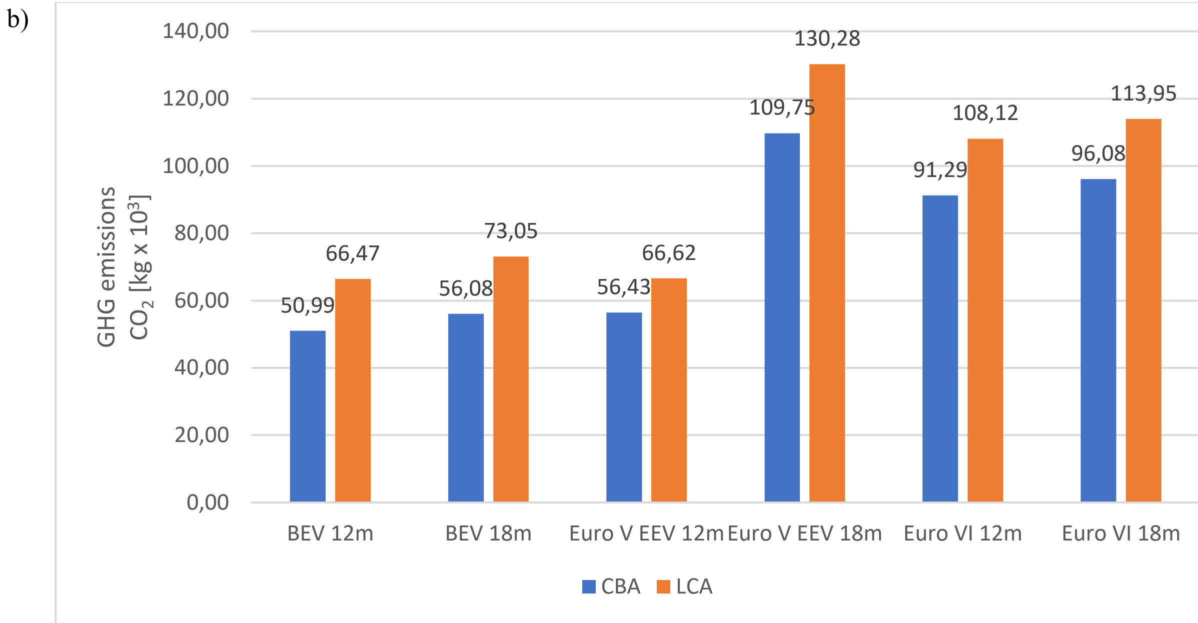


Figure 3. CO_2 emissions from one bus in 2022 a) kg CO_2/100km, b) in kg CO_2. Source: authors' own compilation.

Table 7. Breakdown of the bus fleet operated by the municipal transport company by drive system type for the IE variant and the years 2024–2028. Source: authors' own compilation based on data provided by the municipal transport company

Drive system	No. of buses				
	2024	2025	2026	2027	2028
Electric	20	20	20	20	20
Hybrid	22	22	22	22	22
Euro V EEV	47	20	0	0	0
Euro VI	153	180	200	200	200
Total	242	242	242	242	242

Based on the calculations and analyses performed in line with the LCA method, the results of which have been described in Section 4, as well as the CBA methodology [11–13,28,31], the CO_2 emissions expected to be generated by a single bus in the year 2022 were determined and expressed in Mg. The emission values obtained for both electric buses and diesel engine buses meeting the Euro V EEV and Euro VI standards, based on real-life data, have been provided in Figure 3. Hybrid drive buses were disregarded under the analyses conducted by the authors since no real-life data concerning their operation by the municipal transport company were available.

Based on the data provided in Figure 3, the results obtained by calculating the CO_2 emission reduction rates [Mg] for each year and for the investment inclusive (II) and exclusive (IE) variants analysed were compiled in accordance with the CBA and LCA methodologies for determining GHG emissions. They have been summarised in Table 8.

Table 8. CO_2 emissions under variants II and IE. Source: authors' own compilation.

Environmental effects	Year									
	2024		2025		2026		2027		2028	
	CBA	LCA	CBA	LCA	CBA	LCA	CBA	LCA	CBA	LCA
IE variant CO_2 emission [Mg]	19,339	23,045	19,596	23,351	19,808	23,602	19,808	23,602	19,808	23,602
II variant CO_2 emission [Mg]	18,335	22,014	17,508	21,204	15,442	18,911	15,442	18,911	15,442	18,911
CO_2 emission reduction [Mg]	1,004	1,032	2,088	2,146	4,366	4,691	4,366	4,691	4,366	4,691
CO_2 emission reduction [%]	5	4	11	9	22	20	22	20	22	20

Having analysed the results given in Figure 3, namely the CO_2 emission values expressed in both [kg CO_2/100 km] and in [Mg], for 12 m and 18 m electric buses, the authors concluded that the values determined using LCA were approx. 23% higher than those obtained by following the methodology recommended in CBA manuals. The same is also true for internal combustion engine buses conforming with the Euro V EEV and Euro VI standards. In this case, for both 12 and 18 m long buses, the emission rates determined by LCA were approx. 16% higher than those established using the methodology recommended for CBA. The differences in the greenhouse gas emission rates obtained for electric buses are primarily attributable to the fact that the calculations following the LCA method included the direct emissions resulting from the combustion of diesel fuel used in the heating systems of these buses, while the differences in the GHG emission rates observed for the diesel engine buses are mainly due to having included in the LCA calculations not only the direct emissions resulting from the diesel fuel combustion, but also the indirect emissions caused by the production of diesel fuel and the emission of pollutants associated with that process.

Analysis of the CO_2 emission levels calculated and expressed in Mg for the assumed variants II and IE (Table 8) clearly shows that the values obtained by both LCA and CBA are higher for the IE variant, i.e. the one which assumes investing only in buses with internal combustion engines. In the subsequent years of the analysis, a significant reduction in greenhouse gas emissions can be observed for the II variant, corresponding to an emission reduction of 17,251 [Mg] in the years 2024–2028 for the bus fleet analysed, the calculations having been conducted in line with LCA.

7. Conclusions

With reference to the results of the studies discussed in this paper and in accordance with the guidelines specified in the Blue Paper on the public transport sector in cities, agglomerations and regions [4], it has been concluded that public bus transport can be among the most important factors for creating a more sustainable and climate-friendly transport system in cities and urban agglomerations across the EU. This goal will be achieved primarily by increasing the number of public transport passengers, but also by undertaking all the necessary measures required to improve fleet efficiency and to reduce greenhouse gas emissions. Therefore, in the case of public bus transport, the use of low- or even zero-emission technologies in the coming years will be increasingly often included in the plans made by transport companies to adapt their fleets in this respect to the requirements of the applicable law [16,17]. What seems particularly relevant in this regard is adequate preparation for and drafting of cost-benefit analyses (CBA) with an outlook up to 2027, which should enable gradual upgrading of the bus fleets operated by municipal transport companies striving to meet the requirements of the act on electromobility and alternative fuels. Replacing buses with low-emission or carbon neutral vehicles should produce the expected results by improving the quality and attractiveness of public transport, increasing the efficiency of the bus system operation and maintenance, and significantly reducing the impact of bus operations by lowering direct and indirect greenhouse gas emissions.

The solution proposed in the article is using the LCA method to calculate greenhouse gas emissions for public bus transport in order to expand and add detail to the methodology applied when evaluating environmental aspects under the cost-benefit analysis. Based on the calculations and analyses provided in the article, concerning the comparison of the greenhouse gas emission rates established for public bus transport by way of the cost-benefit analysis (CBA) methodology and the life cycle assessment (LCA) method, the following conclusions have been formulated:

1. The methodologies mentioned in the literature on the subject as well as in the manuals recommended for estimating greenhouse gas emissions, employed for various purposes, including cost-benefit analyses developed in accordance with the act on electromobility, conducted for the sake of implementation of low-emission or carbon neutral vehicles in public bus transport, used to rely on overly simplistic assumptions, which may explain why the results of the calculations performed in this regard were approximate in nature.
2. The cost-benefit analyses conducted in 2018 and 2021 comprised overgeneralised and estimated results with regard to how GHG emissions should be determined correctly, which may have had a significant impact on the

choice of the variants recommended under CBA. The methodology applied to determine the GHG emissions for purposes of the CBA in question disregard the following aspects:

- projected changes in the energy mix used for charging of electric buses over the consecutive years subject to analysis,
- additional direct emissions from electric buses, associated, for instance, with the diesel fuel consumed for heating, and additional indirect emissions attributable to internal combustion engine buses, associated with diesel fuel production.

3. In the cost-benefit analyses conducted with an outlook up to the year 2027:

- in order to compare the greenhouse gas emissions of the current and planned bus fleet based on detailed bus operation data, one should rely on the recommended well-to-wheel (WTW) type LCA methodology when calculating actual GHG emission rates. Using the LCA method for analysis will make it possible to assess the effects of climate change mitigation by accurately determining the relevant climate change costs and comparing the variants taken into account in an adequate manner;
- with regard to electric buses, on top of the pre-established carbon dioxide emissions, it is necessary to consider an additional source of CO_2 emissions, e.g. diesel fuel, associated with the energy consumed to power on-board systems, such as heating or air conditioning. In such cases, the recommended solution is to estimate the actual fuel/energy consumption by buses against specific local conditions.

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