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HOW EMISSIONS AT SOURCE AFFECT ENVIRONMENTAL AND ECONOMIC EFFICIENCY OF ELECTRIC BUSES? A COMPARATIVE CASE ANALYSIS

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Purpose: The purpose of the research is to compare the impact of inclusion emissions at source on environmental and economic performance of replacement of combustion engine powertrain with the electric or hybrid one, given the transport work on a selected public transport line on urban areas. It provides the gross emissions of pollutants and greenhouse gases related to total transport work executed on given bus line.
Design/methodology/approach: Primary data was collected from one of the public transport operators running its business in Upper-Silesian and Zaglebie Metrpolis, covering the western part of its territory. The company is undergoing the multiannual process of fleet replacement, justifying its investment decision with environmental factors, including emissions. The operator provided the author with the following data: consumption of diesel fuel depending on bus size and Euro emissions standards, consumption of power for charging electric buses, average daily and annual mileage. It facilitated the author to construct scenarios of annual transport work per vehicle and analyze the emissions respectively.
Findings: Electrification of public transport delivers positive environmental effects resulting in reduction of local emissions of pollutants and greenhouse gases. If the emissions of the source of power are included in the calculations, the benefits are lower, but it is possible to increase them by modification of the energy mix of supplied power, by significant increase of share of environmentally neutral or green energy.
Research limitations/implications: If possible, there could be conducted further research covering emissions related to production of diesel fuel and hydrogen (per unit), as no other fuels are practically in use.
Practical implications: Analyzed case provides the public transport operators with knowledge on their actual emissions and facilitates them to adjust the structure of the fleet in use to lower the environmental impact.
Originality/value: The paper addresses the issue of zero-emission transport. Originality of the approach results from inclusion of the environmental effects of power generation source in the environmental effects of electrification of fleet in public transport.
Keywords: public transport emissions, electromobility, electric bus, hybrid bus, diesel bus.
Category of the paper: research paper.

1. Introduction and literature review

Massive electrification of public transport, however sometimes considered as controversial, is one of the central areas of interest and investment carried out on European, national and local level. Transport sector, including public transport is one of the major sources of pollution, noise and greenhouse gases on densely developed urban areas, so lowering its negative impact on quality of life and health of the inhabitants of the cities plays a vital role in public policy. Since year 2007 European policy has been concentrated around reduction of emissions and consequently, major financial streams have been diverted to investments in low-emission fleet, alternative fuels, as well as changing the habits of the citizens, encouraging them to swap their private cars with unimodal or multimodal public transport, as well as with micromobility solutions (i.e. scooters, bicycles, e-bikes or walking) (Bachanek, 2020). Polish practice in greening of public transport is basically founded on the Act of 11.01.2018 of Electromobility and Alternative Fuels (AEAF), which defines the framework and milestones that are supposed to me achieved in terms of share of zero- and low-emission vehicles circulating in the cities and in intercity connections (Act of Electromobility and Alternative Fuels of 11 January 2018 with amendments, 2018).

This legislation provides also clarification on the definition of a "zero-emission bus". Based on the general definition of a "bus" as a motor vehicle designed to carry more than 9 people, including the driver, the term "zero-emission bus" is restricted to vehicles that meet specific technical criteria. Only those vehicles that are powered by:

- electricity generated from hydrogen fuel cells, or
- engines whose life cycle does not result in the emission of greenhouse gases or other substances covered under the greenhouse gas emissions management system,

are considered zero-emission buses.

Therefore, the legislation excludes diesel-powered vehicles, which have been the predominant type in public transport fleets, as well as vehicles increasingly found in such fleets - those with liquid or compressed natural gas (LNG/CNG) or hybrid powertrain.

AEAF also established new obligations for local governments. These include the following requirements:

- they must ensure that electric vehicles make up at least 30% of their total fleet (excluding service vehicles used by the utility sector),
- for other public tasks (excluding public transport), local authorities are required to use electric or gas-powered vehicles, with the number of such vehicles equaling or exceeding 30% of all vehicles used for these tasks, or to commission a third party to perform these tasks with a fleet that meets the same criterion.

Local governments must either directly provide or contract urban public transport services from an entity whose fleet contains at least 30% zero-emission buses (Pietrzak, Pietrzak, 2020).

The AEAF also outlined a gradual increase in the proportion of zero-emission buses in the public transport fleet, with the following target milestones:

- 5% by the end of 2020,
- 10% by the end of 2022,
- 20% by the end of 2024,
- 30% by the end of 2027.

Another factor affecting mobility in the cities is traveling habit of the people. The indicator of motorization for some EU countries is high, so it means that their citizens may demonstrate high reluctance to changing their mobility habits. The number of cars per 1000 inhabitants for EU member states is provided in fig. 1.

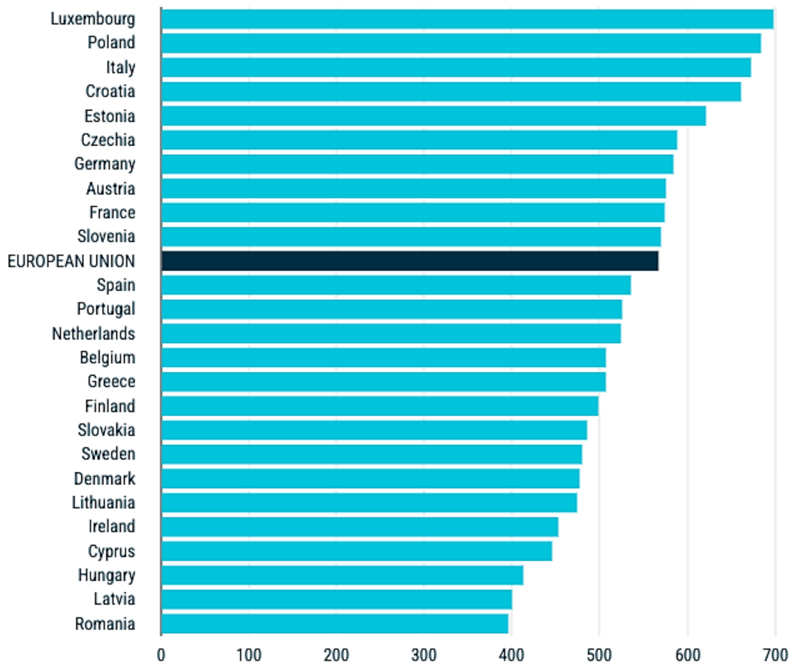


Figure 1. Motorization rate in the EU for year 2021.

Source: European Automobile Manufacturers' Association.

All the aforementioned activities should result in improvement of the air quality, lowering the congestion and making a city more comfortable and livable place.

According to the statistics provided by the European Environment Agency, Poland is one of the countries with the highest CO_2 emission from transport, reaching the level of 136,8 g/km, comparing to the EU average of 110 g/km (Sustainability of Europe's mobility systems, 2024).

ACEA (European Automobile Manufacturers' Association) data confirm, that there can be observed a declining trend of sales of new diesel buses, and growth of sales of electric ones (EVs). The share of hybrid and other (natural gas and hydrogen) fueled buses remains stable, as presented in fig. 2.

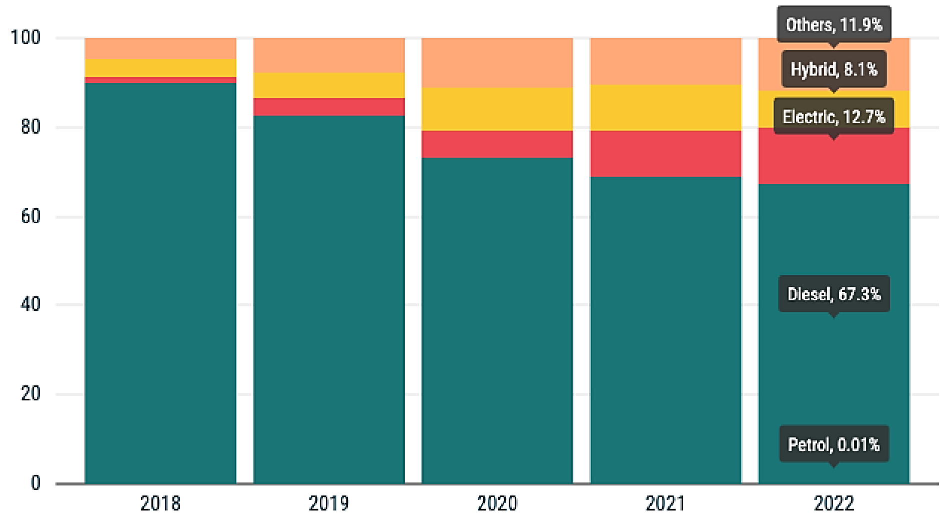


Figure 2. Structure of sales of new buses in years 2018-2022.

Source: European Automobile Manufacturers' Association.

According to the ACEA report *Vehicles in Use 2023*, in the EU only 1,4% of bus fleet is EV, 1,8% hybrid-electric (HEV), and 3,9% natural gas fueled (LNG, CNG or LPG). The share of hydrogen-powered fuel-cell vehicles (FCEV) is not revealed (ACEA Report - Vehicles on European roads, 2024).

Electromobility may become a critical factor of sustainable and eco-friendly mobility in the future, contributing to the reduction of air pollution and greenhouse gas emissions. Reduction of local emissions of air pollution by EVs or FCEVs is particularly important in urban areas because they are characterized by high population density and heavy traffic. It is therefore assumed that e-mobility and H_2-mobility may become the dominant technologies applied in future mobility in urban agglomerations.

For the needs of public policy, it is assumed that EVs are considered to be zero-emission and climate neutral during their operations. Naturally, this approach does not take into account the whole product life cycle, energy and material consumption required on all stages of its economic and operational life as well as manufacturing-derived carbon footprint. In order to create a more comprehensive image of consequences of public transport electrification on its operational stage of the life cycle of the vehicles and following the tendency of internalization of costs, the external costs of emissions to the environment related with power generation and distributions should be also taken into overall account, as they may seriously affect the economic rationale of electrification of public transport. The differentiation of economic costs will be also dependent on the energy mix of particular place, e.g. a country or an area having specific sources of electricity.

There are different measures undertaken by the administration to reduce traffic congestion and improve the environmental conditions in the city, particularly in terms of climate and pollution issues, among which there can be identified:

- pedestrianization of areas in the city (Pooley et al., 2013; Song et al., 2017),
- creation of car-free zones (Ellison et al., 2013),
- creation of clean transport zones (Heijlen, Crompvoets, 2017),
- introduction of low- and zero-emission vehicles (Kendall et al., 2017; Ranaei et al., 2016),
- construction of multimodal changing centers, park and ride or kiss and ride facilities,
- construction of dedicated bus lanes available also for individual electric vehicles,
- fiscal legislation promoting low- and zero-emission vehicles.

Combination of the aforementioned activities shall lead to significant improvements in terms of pollutants and GHGs emissions locally, however, investigation results of the overall general effects of pro-environmental projects are still yet to be published. This paper provides a part of such analysis, where only electrification of fleet on selected bus line was taken into consideration. Using differential approach there was conducted an analysis comprising emissions of pollutants, GHGs specific for combustion powertrains, emissions of the source of power taking into account current energy mix of the country, and – basing on them – there was calculated an environmental net effect of electrification. Having these values, they were subject to monetization in order to determine the economic benefits and costs of powertrain transformation of the fleet in public transport (Pietrzak, Pietrzak, 2021).

2. Materials and methods of the paper

The research was conducted in several stages. Stage 1 consisted of collection and analysis of literature and reports on development of electromobility, respective legislation and policies. Delivery of public transportation services is a legal duty which must be fulfilled by the local and regional government. In case of Upper-Silesian Metropolitan Area, the entity responsible for this service is Upper-Silesian and Zagłębie Metropolis, with is subsidiary Urban Transport Authority. This organization provides planning, coordination and financing for public transportation and the services are rendered by the operators (carriers) basing on contracts. Urban Transport Authority defines also the minimum requirements concerning fleet used by the operators on different lines, including equipment, powertrain and emissions of the buses. In this case the operators must observe these requirements, but may use the fleet of the higher standard of emissions or equipment.

For this article there were selected two bus lines: A4 and 676, connecting different parts of the municipality of Gliwice, which were subject to electrification in year 2021. The analysis which was carried out in this paper is of the what-if type, where consumption of fuels and power was taken from the real operations of the operator – Urban Transport Company in Gliwice. Considered the emission standard of the withdrawn diesel fleet and its replacement with EVs, there were calculated appropriate emissions which later were subject to monetization.

Stage 2 comprises projection of volumes of transportation work carried out annually on A4 and 676 bus lines and estimation of emissions basing on measured consumption of diesel fuel and actual consumption of electricity registered by the company. Consequently, there were calculated the emissions of pollutants and GHGs of the power supply per kilometer, taken into account the energy mix.

Stage 3 provides comparison of three approaches, namely use of diesel-fueled vehicles vs. EVs excluding emissions at source vs. EVs including emissions of the source. Based on these calculations, monetary unit values of emission are applied to determine environmental economic costs and benefits of respective solutions. Considered the economic and technical life cycle of the vehicles, 10 years period of analysis was applied. For making comparisons of respective approaches, NPV method was used to aggregate the costs and benefits and express them in present values.

3. Operational aspects of analyzed case of electrification of bus lines

Both analyzed bus lines – A4 and 676 operate on densely urbanized areas of the city of Gliwice in Upper-Silesian Metropolis. The first line facilitates changes for the passengers from the tramway to reach the center of the city. Due to high intensity of arrival of passengers, the line operates every 10 minutes in the peak periods of the day and every 15 minutes besides during the week and every 20 minutes during the weekends. Line number 676 operates every 40 minutes and connects northern and southern residential neighborhoods of Gliwice. The diagrams of the lines are provided in figures – fig. 3 for line A4, fig. 4 for 676.

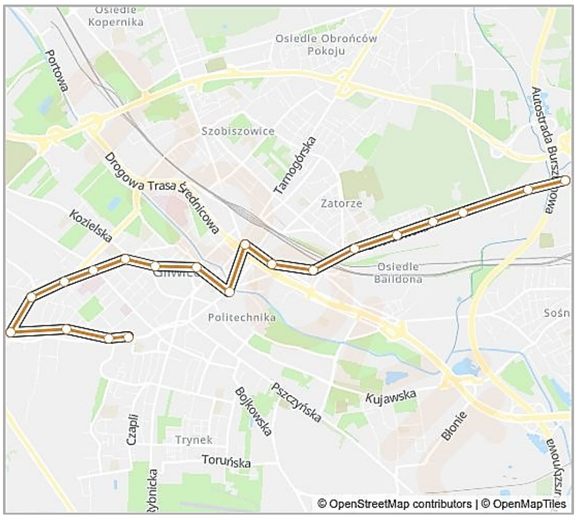


Figure 3. Network diagram of line A4.

Source: own elaboration, OpenStreetMap.

Exploitation work expressed in vehicle-kms is provided in the tables below. The abbreviations BN and CN define sizes of the vehicles, where BN stands for standard 12 meter 2-axis vehicle and CN stands for high capacity 18 meter 3-axis vehicle. Operations on line A4 are provided in table 1.

Table 1.
Operations of A4 bus line in years 2021-2024

Exploitation work in vehicle-kilometers for respective years								
A4	2021		2022		2023		2024	
	BN	CN	BN	CN	BN	CN	BN	CN
Jan	34 553,70	10 413,20	30 762,10	18 969,70	40 489,20	11 090,80	39 954,60	10 267,30
Feb	31 434,00	10 920,00	33 420,30	10 634,90	37 246,40	10 489,30	37 376,20	10 610,00
Mar	34 885,50	12 558,00	38 489,50	15 235,10	41 477,20	11 865,40	39 436,00	10 760,00
Apr	33 594,10	11 460,50	37 100,90	12 245,70	38 765,10	10 184,40	38 164,60	10 620,00
May	34 536,00	10 837,30	39 749,60	10 908,00	40 799,70	11 174,80	39 115,20	10 460,00
Jun	33 584,60	11 440,40	38 722,60	10 827,20	39 702,60	11 078,70	38 356,40	10 388,30
Jul	34 378,50	12 507,60	40 206,00	11 019,40	41 027,40	11 240,10	40 077,70	11 540,00
Aug	32 771,20	14 224,20	40 374,80	11 268,40	41 089,50	11 571,30	39 730,80	10 829,10
Sep	26 675,60	23 186,80	39 241,30	11 215,50	39 157,30	10 783,80	38 436,40	10 667,80
Oct	28 157,00	21 932,40	40 371,70	11 032,70	39 810,20	11 187,50	40 197,40	11 466,20
Nov	27 791,00	21 006,70	40 017,50	10 868,00	38 505,50	10 615,40	38 331,00	10 073,20
Dec	32 037,20	17 937,60	40 351,30	11 053,10	39 220,00	9 430,90	38 471,10	9 169,40
Tot.	384 398,40	178 424,70	458 807,60	145 277,70	477 290,10	130 712,40	467 647,40	126 851,30
	562 823,10		**604 085,30**		**608 002,50**		**594 498,70**	

Source: own elaboration.

Figure 3. Network diagram of line 676.

Source: own elaboration, OpenStreetMap.

Operations on line 676 are provided in table 2.

Table 2.
Operations of 676 bus line in years 2021-2024

Exploitation work in vehicle-kilometers for respective years								
A4	2021		2022		2023		2024	
	BN	CN	BN	CN	BN	CN	BN	CN
Jan	10 870,00	0,00	10 346,00	0,00	12 575,60	0,00	12 689,60	0,00
Feb	10 487,60	0,00	9 887,40	0,00	11 775,60	0,00	12 250,50	0,00
Mar	11 740,70	0,00	11 073,20	0,00	13 200,30	0,00	12 534,20	0,00
Apr	10 638,60	0,00	9 888,80	0,00	11 585,40	0,00	12 250,50	0,00
May	11 285,40	0,00	10 750,40	0,00	12 791,00	0,00	12 629,70	0,00
Jun	11 155,20	0,00	10 531,70	0,00	12 535,20	0,00	12 345,00	0,00
Jul	11 597,00	0,00	10 982,80	0,00	12 819,90	0,00	13 198,60	0,00
Aug	10 224,80	0,00	11 145,90	0,00	13 010,10	0,00	12 808,40	0,00
Sep	11 087,70	0,00	10 889,40	0,00	12 535,20	0,00	13 853,30	0,00
Oct	10 977,70	536,80	11 000,70	0,00	13 023,10	0,00	14 596,70	0,00
Nov	10 719,40	268,40	10 334,70	256,50	12 250,50	385,90	13 398,30	392,00
Dec	10 710,30	0,00	12 058,30	0,00	11 753,90	0,00	13 155,90	0,00
Tot.	131 494,40	805,20	128 889,30	256,50	149 855,80	385,90	155 710,70	392,00
	132 299,60		**129 145,80**		**150 241,70**		**156 102,70**	

Source: own elaboration.

Until the end June 2021 the lines were operated by combustion engines powered buses and in July 2021 all the vehicles were replaced by the EVs. A sample picture of the EV used by the operator is provided in the fig. 4 below.

Figure 4. Electric bus preparing for charging with a high power pantograph connection in the terminal station.

Source: PKM Gliwice sp. z o.o.

Depending on the emissions standard, fuel consumption of the vehicles differed. The details are provided in the table 3. Validity of given standard refers to the manufacturing date of given vehicle. The values are the average ones, measured by the operator in over 4 years of operations.

Table 3.
Consumption of diesel fuel depending on emission standard

`	Validity of the standard	Fuel consumption [dm^3/100 km]
Euro III	10.2000 - 10.2005	47,70
Euro IV	10.2005 - 10.2008	46,13
Euro V/ Enhanced Euro V (EEV)	10.2008 - 12.2012	50,40
Euro VI	from 2013	49,76

Source: own elaboration.

Approximate fuel consumption is used later to determine emissions of pollutants and GHGs to make comparisons of each standard with the electric powertrain of the buses.

4. Results of the research – environmental impact of electrification of the bus lines

Emissions of GHGs and pollutants to the atmosphere is a derivative of the emission standard met by given vehicle, fuel consumption and annual mileage. Given the figures for years 2021-2024, there was developed a projection of exploitation work that is anticipated to be delivered for years 2025-2030, covering average technical and economic life of an EV without the need to conduct major periodic repairs. Naturally, all workload-related repairs need to be conducted in order to maintain the fleet in required condition, however they are comparable in nature, independent from the powertrain.

The historic and projected exploitation work is provided in the figure below – fig. 5.

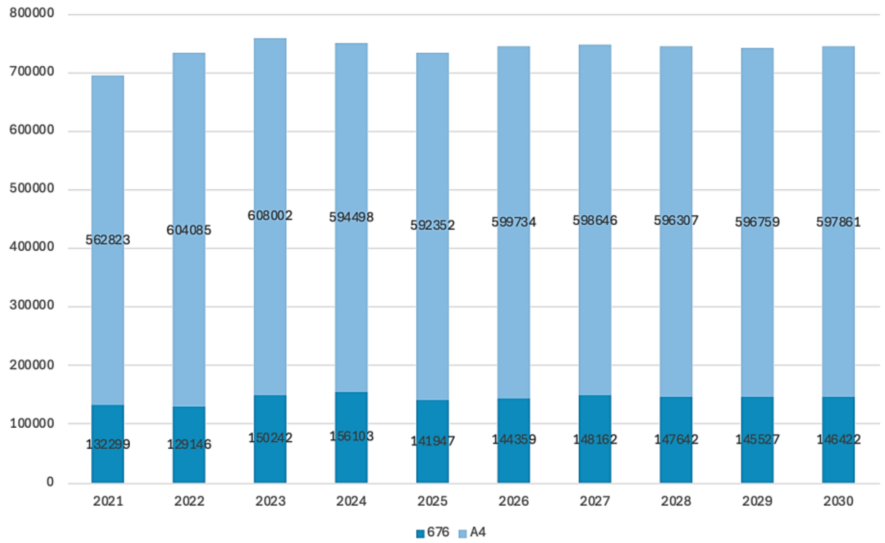


Figure 5. Historical and planned exploitation fork for lines A4 and 676.

Source: own elaboration of data provided by PKM Gliwice sp. z o.o.

Emissions specific for diesel fuels which are regulated by Euro standards cover: particulate matter (PM), hydrocarbons (HC) and non-methane volatile organic compounds (NMVOC), nitrogen oxides (NO_x), expressed in [g/kWh] of energy produced from the fuel. Given the physical and chemical features and constants of diesel fuel density of 0,84 kg/dm^3 and calorific value of 35,8 MJ/dm^3, there were calculated maximum emissions of the aforementioned pollutants per 1 dm^3 of consumed fuel as indicated in table 3. The values are provided in table 4 below.

Table 4.
Emission of pollutants based emission standard per kWh and consumed dm^3

Emissions standard	HC/NMVOC		NOx		PM	
	g/kWh	g/dm^3	g/kWh	g/dm^3	g/kWh	g/dm^3
Euro III	0,66	6,563	5	49,722	0,1	0,994
Euro IV	0,46	4,574	3,5	34,806	0,02	0,199
Euro V/ Enhanced Euro V (EEV)	0,46	4,574	2	19,889	0,02	0,199
Euro VI	0,13	1,293	0,4	3,978	0,01	0,099

Source: own elaboration.

For greenhouse gas (CO_2), its emission is independent from the emission standard, as it is constant and dependent only fuel consumption. Given the normative CO_2 equivalent emission per unit of fuel of 3169 kg CO_2eq/kg and the density of fuel, the emission per dm^3 equals 2662 kg CO_2eq.

In order to compare emissions of diesel fueled buses with the EVs, it is necessary to determine the emissions of sources of energy which is delivered to the operator. Taking into account current and future environmental policy of the central government in Poland, there was prepared a projection of the structure of energy mix until the end of year 2030, which is presented in the graph – fig. 6.

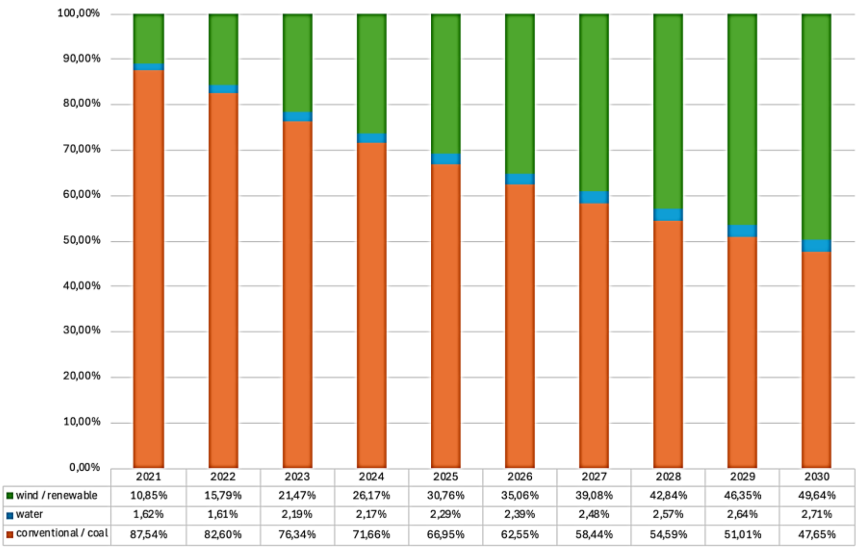


Figure 6. Projection of Poland's energy mix up to 2030.

Source: own elaboration of data provided by the National Center for Emissions Management (KOBiZE).

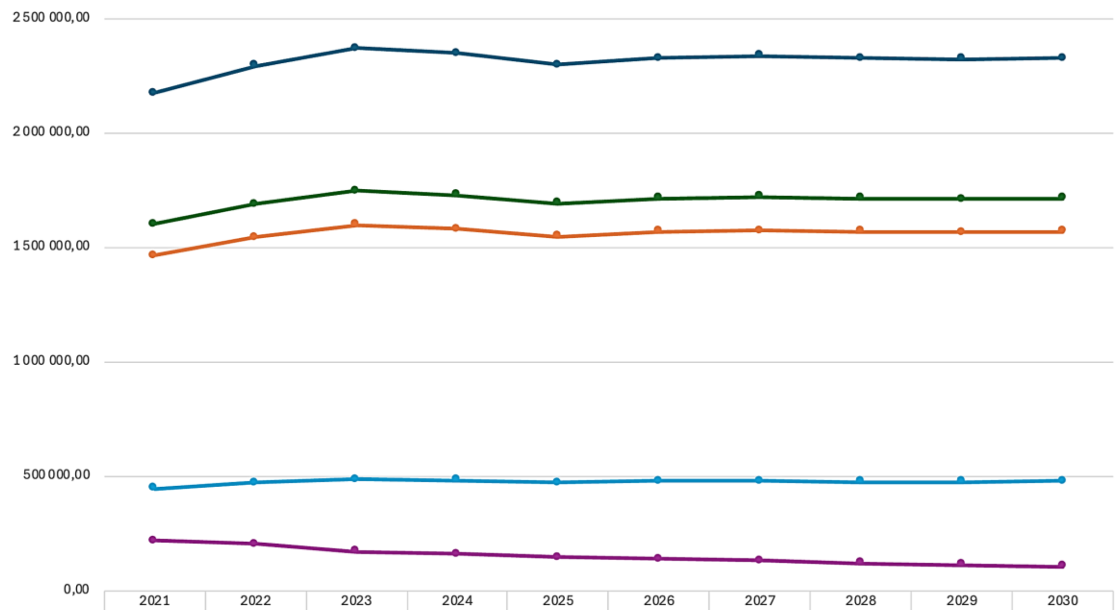
The emissions related to production of electricity was also determined based on the data provided by the National Center for Emissions Management (KOBiZE). For each individual year, this organization gathers data concerning total production of energy, regardless of the source or fuel and total registered emissions of pollutants and GHG. Historic and estimated emissions are presented in the table 5. As they refer to the whole sector of conventional power generation, in order to adjust emission assigned to final consumption of power, the values need to be multiplied by the share conventional power generation in country's energy mix. Since professional power generation sector maintains high level of investment in greening of their operations, the forecast of emissions is rather conservative.

Table 5.
Actual and forecasted emissions of conventional power generation in g/kWh

Component	Actual emissions			Forecasted emissions - *ceteris paribus*						
	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
CO_2	761	788	733	733	733	733	733	733	733	733
NO_x	0,543	0,524	0,481	0,481	0,481	0,481	0,481	0,481	0,481	0,481
PM	0,022	0,021	0,018	0,018	0,018	0,018	0,018	0,018	0,018	0,018
HC/NMVOC	0,3	0,28	0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,25

Source: own elaboration of data provided by the National Center for Emissions Management (KOBiZE).

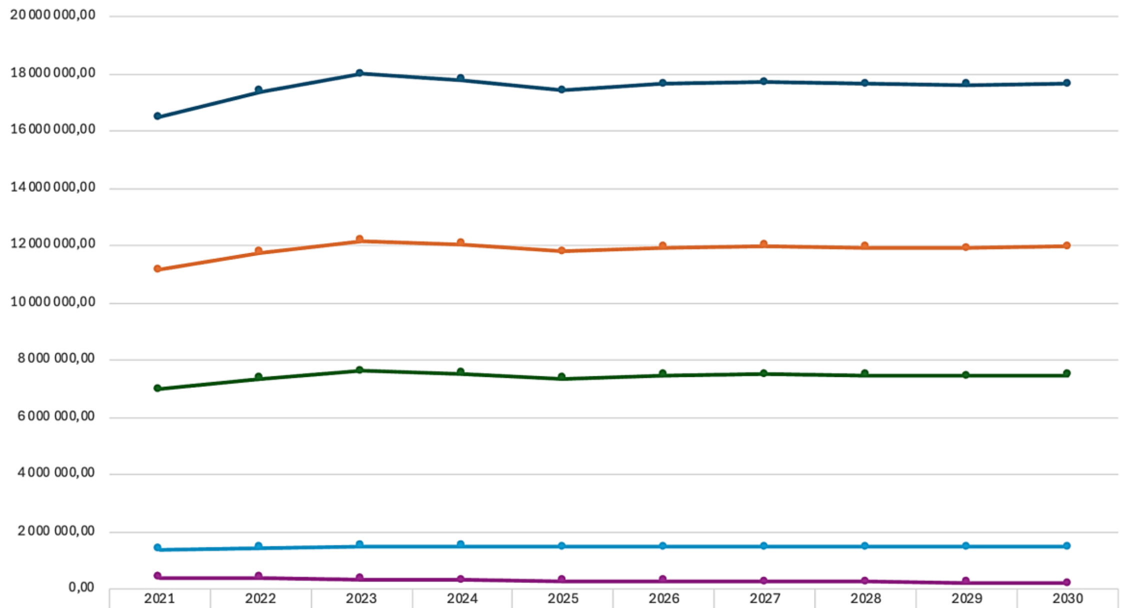
Given the consumption of fuel and power, there were calculated annual emissions of all pollutants and GHG for each class of vehicles meeting given Euro standard. All the classes (categories) of vehicles were mutually compared with EVs. Annual emissions generated by diesel fueled vehicles are provided in the figures below (Fig. 7-10).



	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Euro III	2 176 225,40	2 295 533,62	2 373 842,07	2 349 914,06	2 298 877,22	2 329 539,40	2 338 039,27	2 329 088,57	2 323 882,20	2 330 134,23
Euro IV	1 466 840,34	1 547 257,62	1 600 039,83	1 583 911,64	1 549 511,30	1 570 178,52	1 575 907,69	1 569 874,65	1 566 365,40	1 570 579,45
Euro V/EEV	1 602 617,67	1 690 478,74	1 748 146,71	1 730 525,62	1 692 941,03	1 715 521,29	1 721 780,78	1 715 189,30	1 711 355,22	1 715 959,34
Euro VI	447 162,41	471 677,40	487 767,92	482 851,28	472 364,43	478 664,77	480 411,30	478 572,14	477 502,36	478 787,00
EV	219 054,84	203 510,20	173 651,83	161 364,23	147 482,01	139 624,39	130 921,51	121 846,54	113 581,94	106 400,60

Figure 7. Projection of emissions of HC/NMVOC [g/year].

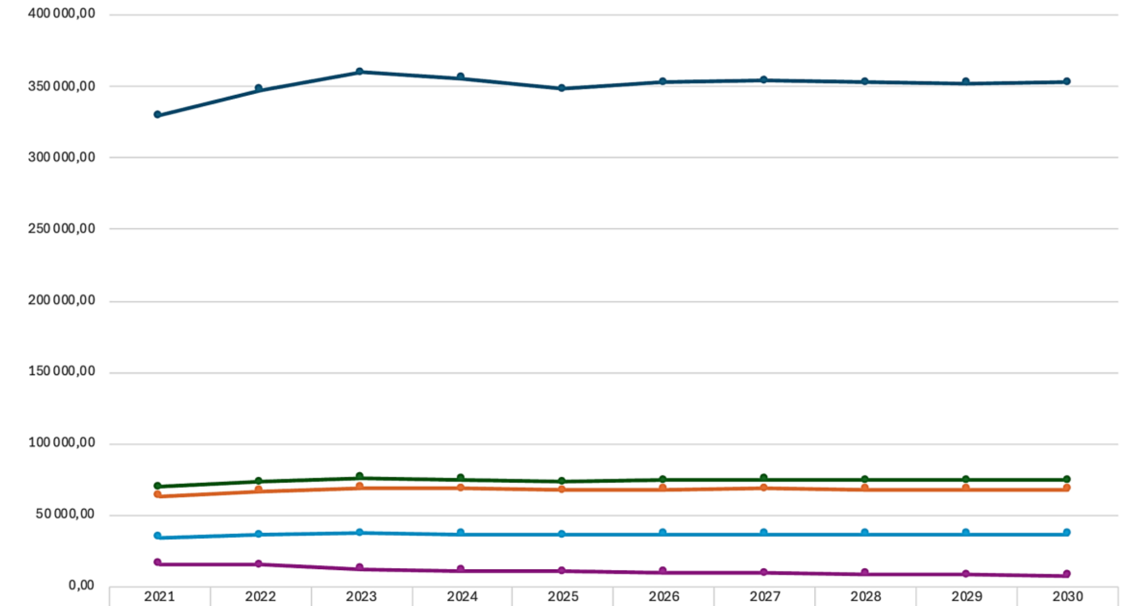
Source: own elaboration.



	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Euro III	16 486 556,04	17 390 406,24	17 983 652,07	17 802 379,22	17 415 736,53	17 648 025,73	17 712 418,74	17 644 610,41	17 605 168,21	17 652 532,05
Euro IV	11 160 741,74	11 772 612,33	12 174 216,12	12 051 501,62	11 789 759,92	11 947 010,46	11 990 601,96	11 944 698,42	11 917 997,62	11 950 061,06
Euro V/EEV	6 967 902,93	7 349 907,54	7 600 637,86	7 524 024,42	7 360 613,18	7 458 788,23	7 486 003,39	7 457 344,78	7 440 674,86	7 460 692,79
Euro VI	1 375 884,32	1 451 315,08	1 500 824,36	1 485 696,25	1 453 429,01	1 472 814,69	1 478 188,61	1 472 529,67	1 469 238,02	1 473 190,77
EV	396 489,26	380 854,80	334 106,13	310 464,78	283 755,38	268 637,33	251 892,99	234 432,74	218 531,65	204 714,76

Figure 8. Projection of emissions of NO_X [g/year].

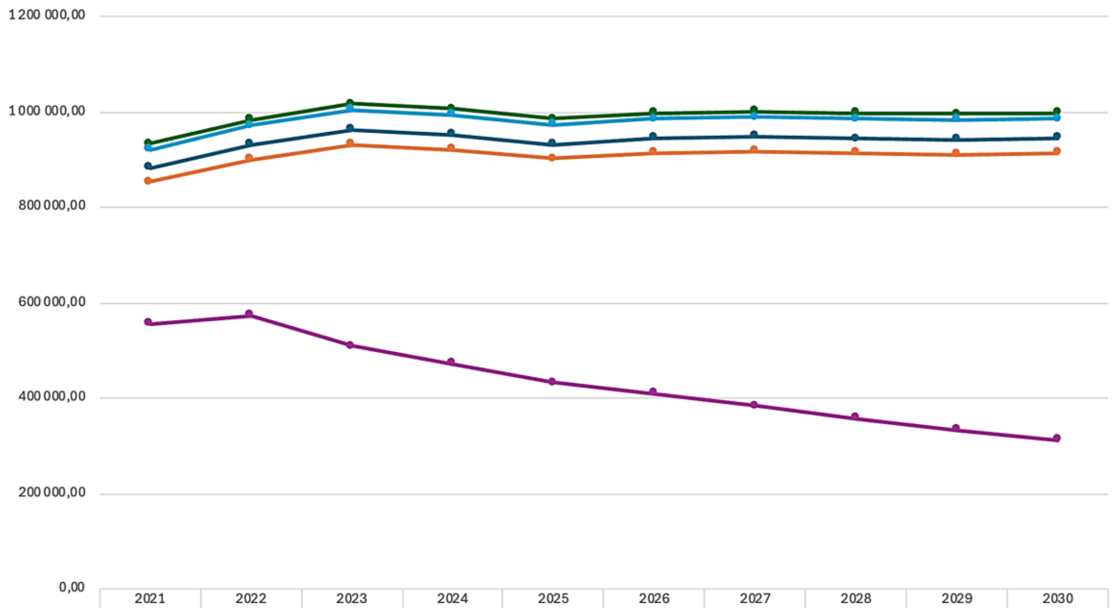
Source: own elaboration.



	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Euro III	329 731,12	347 808,12	359 673,04	356 047,58	348 314,73	352 960,51	354 248,37	352 892,21	352 103,36	353 050,64
Euro IV	63 775,67	67 272,07	69 566,95	68 865,72	67 370,06	68 268,63	68 517,73	68 255,42	68 102,84	68 286,06
Euro V/EEV	69 679,03	73 499,08	76 006,38	75 240,24	73 606,13	74 587,88	74 860,03	74 573,45	74 406,75	74 606,93
Euro VI	34 397,11	36 282,88	37 520,61	37 142,41	36 335,73	36 820,37	36 954,72	36 813,24	36 730,95	36 829,77
EV	16 064,02	15 263,26	12 502,93	11 618,22	10 618,70	10 052,96	9 426,35	8 772,95	8 177,90	7 660,84

Figure 9. Projection of emissions of particulate matter [g/year].

Source: own elaboration.



	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Euro III	882 634,58	931 023,67	962 784,05	953 079,31	932 379,77	944 815,75	948 263,13	944 632,90	942 521,30	945 057,00
Euro IV	853 583,50	900 379,91	931 094,93	921 709,62	901 691,38	913 718,04	917 051,96	913 541,21	911 499,11	913 951,35
Euro V/EEV	932 595,03	983 723,12	1 017 281,26	1 007 027,20	985 155,98	998 295,88	1 001 938,40	998 102,69	995 871,56	998 550,79
Euro VI	920 752,55	971 231,40	1 004 363,40	994 239,55	972 646,06	985 619,11	989 215,38	985 428,37	983 225,57	985 870,78
EV	555 669,11	572 735,85	509 147,18	473 119,92	432 417,25	409 378,72	383 861,88	357 254,05	333 022,24	311 966,56

Figure 10. Projection of emissions of CO_2 [kg/year].

Source: own elaboration.

Given the calculated emissions, it is possible to determine avoided emissions related to electrification of the public transport fleet. For the time horizon of 10 years, the environmental benefit for replacement of diesel fueled buses with the EV is presented in the table below – table 6.

Table 6.
Total 10-year-avoided emissions resulting from electrification of public transport fleet

Component of the exhaust	Euro III	Euro IV	Euro V/EEV	Euro VI
HC/NMVOC [kg]	21 627,64	14 083,03	15 527,08	3 238,32
NO_x [kg]	172 457,61	115 815,32	71 222,71	11 749,23
PM [kg]	3 396,67	568,12	630,91	255,67
CO_2 [Mg]	5 048,62	4 739,65	5 579,97	5 454,02

Source: own elaboration.

5. Discussion of the results – economic outcome of electrification of the bus lines

For projects which are unlikely to generate financial profit and positive financial rate of return, it is necessary to determine the economic outcome. It may either improve or deteriorate the welfare of given community affected by their execution. From the financial point of view, public projects are seldom characterized by positive rates of return and profitability. They rather require financial transfers in order to secure continuous delivery of given public service. However, apart from financial outcome, there must be assessed their economic impact, as environmental benefits directly and indirectly affect welfare of the people.

For this reason the Center for European Transportation Projects periodically publishes unit costs assigned to given environmental effects of their implementation. In this case avoidance of emissions may be considered as a benefit. Unit costs of emissions for the 10 year period are provided in the table below – table 7.

Table 7.
Unit costs of emissions – current prices

Component of the exhaust	**2021**	**2022**	**2023**	**2024**	**2025**
HC/NMVOC [PLN/kg]	2 536,86	2 814,12	3 364,12	3 753,65	3 856,54
NO_x [PLN/kg]	53 274,15	59 096,59	70 646,61	78 826,68	80 987,26
PM [PLN/kg]	1 021 993,94	1 133 689,76	1 355 261,59	1 512 185,36	1 553 633,11
CO_2 [PLN/Mg]	188,61	204,51	210,20	215,88	221,56
Component of the exhaust	**2026**	**2027**	**2028**	**2029**	**2030**
HC/NMVOC [PLN/kg]	3 980,94	4 100,12	4 201,61	4 305,97	4 410,12
NO_x [PLN/kg]	83 599,72	86 102,48	88 233,73	90 425,40	92 612,50
PM [PLN/kg]	1 603 749,80	1 651 761,81	1 692 647,08	1 734 691,36	1 776 647,96
CO_2 [PLN/Mg]	227,24	232,92	238,60	244,28	249,96

Source: Center of European Transportation Projects.

To determine the value of benefits resulting from electrification of the public transport fleet, it is necessary to calculate annual benefits and aggregate it. The most useful method for this is the Net Present Value approach, taking into account the changes of value of money in time. As advised by the European Commission, the interest rate applied for calculations of economic NPV (ENPV) must equal 3%. Comparison of economic effects of electrification of fleet are provided in the table 8.

Table 8.
Environmental economic benefits of electrification of fleet [PLN]

Economic value of avoided emissions	**Euro III**	**Euro IV**	**Euro V/EEV**	**Euro VI**
ENPV HC/NMVOC	70 216,19	45 758,88	50 440,04	10 603,67
ENPV NO_x	11 743 946,01	7 887 991,40	4 852 324,88	803 635,10
ENPV PM	4 439 129,93	745 217,66	827 210,73	337 172,56
ENPV CO_2	1 062 786,10	923 510,09	1 087 341,64	1 062 786,10
Total ENPV	**17 316 078,23**	**9 602 478,04**	**6 817 317,29**	**2 214 197,43**

Source: own elaboration.

It may be concluded, that regardless of choice of emission standard of the buses to be withdrawn from circulation, there will be generated environmental benefit of various scale. However, according to the legislation mentioned in the introductory part, EVs are considered to be zero-emission, which is only partially true. Unless they generated any environmental costs, as they should be, according to the law, ENPV of these costs should equal zero. As it was confirmed earlier in the text, power generation is not absolutely zero-emission, so taking into consideration the emissions of powerplants and the consumption of energy by EVs for traction, the actual economic costs are the following, as presented in the table below – table 9.

Table 9.
Annual economic costs of emissions at source for EVs – current prices [PLN]

Component of the exhaust	2021	2022	2023	2024	2025
HC/NMVOC	555,71	572,70	584,19	605,71	568,77
NO_x	21 122,63	22 507,22	23 603,47	24 472,91	22 980,57
PM	16 417,33	17 303,81	16 944,74	17 568,91	16 497,57
CO_2	104 803,22	117 132,68	107 020,33	102 135,34	95 805,14
Component of the exhaust	**2026**	**2027**	**2028**	**2029**	**2030**
HC/NMVOC	555,84	536,79	511,95	489,08	469,24
NO_x	22 458,01	21 688,61	20 684,88	19 760,81	18 959,15
PM	16 122,43	15 570,08	14 849,51	14 186,13	13 610,62
CO_2	93 026,45	89 408,75	85 240,83	81 351,00	77 979,77

Source: own elaboration.

Economic NPV of costs these emissions is the following:

- HC/NMVOC - 4 813,04 PLN,
- NO_X - 192 521,96 PLN,
- PM - 140 576,24 PLN,
- CO_2 - 846 407,80,
- Total ENPV: 1 184 319,04 PLN.

So, using the legislators reasoning, total ENPV of environmental costs of zero-emission buses should equal 0, which actually is not true. As it was confirmed, ENPV of actual environmental costs generated by electrification of fleet during 10 years equals almost 1,2 millions of PLN. What should be noticed and underlined, is the fact that increase of share of green energy in the energy mix (e.g. renewable – wind, solar, water) and decline of conventional sources improves the environmental efficiency of electrification projects and in the extreme case, where the whole demand for power is covered by zero-emission sources, annual and aggregated environmental costs may equal 0.

Conclusions

Policy makers put strong emphasis on implementation of green solutions in public transport. Legislators defined strict regulations related to the share of zero-emission fleet which must be used for delivery of public services, still the overall environmental effect of electrification of vehicles is strongly affected by the energy mix of given country. In order to cut the emissions effectively, it is necessary to readjust it and increase significantly the share of renewable sources of energy, or – at least – environmentally neutral sources of energy. Purchase of EVs may lead to achievement of the electromobility objectives defined on a national level, however, the overall benefit of greening the fleet will be disturbed by constantly high share of conventional powerplants in supplies of energy. In such case the emissions will take place, but elsewhere in terms of location, so then the positive environmental effect is dubious. Regardless of all, withdrawal of diesel-fueled vehicles and their replacement with EV, excluding the investment outlay, is economically and environmentally profitable, but the scale of this benefit is highly dependent on the condition and emission standard of the liquidated fleet.

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