

The operation of electric buses by considering changes to the energy production structure in Poland

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Abstract

This article provides a discussion on the results of the author's in-house study on the greenhouse gas (GHG) emissions generated over the life cycle of the electric buses (BEV) used in Poland's public transport services. The life cycle assessment (LCA) method was employed to evaluate the greenhouse gas emissions. The relevant changes to the energy mix, assumed in line with the electricity generation projections for Poland by 2040, have caused a drop in the average greenhouse gas emissions from electric buses in the consecutive years. For the energy mix envisaged for the years 2025, 2030, 2035, and 2040, being the source of the electricity consumed to charge batteries of electric buses, a decline in the mean emissions by 5%, 13.5%, 30%, and 39%, respectively, can be observed in comparison with the 2022 energy mix. Additionally, the article describes an original model for assessing the greenhouse gas emissions from electric buses which enables the GHG emissions to be studied with reference to various sources of electric energy.

Keywords: greenhouse gas emissions, electric buses, life cycle assessment method, public bus transport, maintenance of bus

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Highlights

- Maintenance of electric buses.
- Reducing greenhouse gas emissions from public bus transport.
- Maintenance engineering of public bus public transport.
- Environmental protection in transport.

1. Introduction

The augmented layer of greenhouse gases (GHG), released as a consequence of human activity, disrupts the natural balance in the environment, which exacerbates the greenhouse effect and, in turn, its negative consequences. The main greenhouse gas is carbon dioxide (CO₂). Transport is the sole sector of the economy where greenhouse gas emissions increased by nearly as much as 34% between 1990 and 2019. Almost two-thirds of the European Union's population dwell in urbanised areas, such as cities and agglomerations. Moreover, these areas are the sources of nearly 85% of the European Union's GDP and account for as much as 75% of the greenhouse gas emissions

[1,2]. In Poland, cities and agglomerations cover approx. 7% of the country's area and are inhabited by nearly 60% of its population. In order to address the challenges of efficient urban management, the concept of a smart city has been developed. It is applied to a city which makes the most of innovative solutions to improve the efficiency and interoperability of urban infrastructure, including: urban transport, energy services, and water supply networks [1]. On account of the very high concentration of various types of human activity, cities and large agglomerations are characterised by a particularly polluted environment, especially in terms of air quality. This is precisely why local authorities in charge of cities and agglomerations should strive to improve energy efficiency and reduce the emission of pollutants, also by improving transport operations, particularly in the public transport sphere. Sustainable mobility needs to be implemented in cities, leading to air quality improvement, reduced noise impact, optimised use of infrastructure, as well as improved quality of public spaces and safety of their users, all of which can significantly raise the

living conditions in cities [1]. Most of the Polish cities considered to be smart have already implemented projects related to urban transport, involving the use of highly advanced intelligent transport systems (ITS) and the deployment of electric or hybrid buses into public bus transport. 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.

Paper [3] provides a study aimed at assessing the energy consumption by and the corresponding CO₂ emission from conventional diesel-engine buses, hybrid buses, and electric buses operated in Tenerife, being an isle with an isolated energy system heavily dependent on fossil fuels utilised for electricity generation. Having conducted a number of life cycle assessment (LCA) analyses, the author of paper [3] has demonstrated that battery-powered electric buses effectively enable CO₂ emission reduction compared to diesel-powered buses, while also highlighting the negative impact of an energy mix based primarily on fossil fuels on emissions. The paper [4] performed LCA studies in which they analysed in detail the long-term greenhouse gas emissions of entire vehicle fleets in the Korean transport sector, examining scenarios for the pursuit of the net zero target by 2050 and paying special attention to the emissions generated by battery-powered and fuel cell electric vehicles. It has been shown that due to South Korea's limited capacity to produce green hydrogen, the country may be forced to import green hydrogen to effectively reduce greenhouse gas emissions. Paper [5] provides a discussion on the life cycle analyses of public transport buses where the authors compared the energy efficiency of and the greenhouse gas emissions attributable to a fleet of diesel-engine, fully electric, and hydrogen-powered buses operated in Bolzano, Italy. Compared to conventional diesel buses, the electric vehicles showed reduced CO₂ emissions even under the worst-case scenario considered under the study. The paper [5] argue that a transition to hydrogen-powered buses yields highly variable environmental factors: from very positive, where it contributes to further renewable energy dissemination, to virtually non-existent, where hydrogen obtained from steam methane reforming is utilised, to explicitly

negative, where the electricity mix used for electrolysis originates predominantly from fossil fuels. The authors of paper [6], on the other hand, have analysed the application of diverse technologies and different size lithium-ion batteries in electric buses, having concluded that their environmental impact depends largely on the efficiency and technology of the batteries, and that a lower capacity battery based on the same technology is not necessarily more environmentally friendly. In their life cycle assessment of electric buses, the authors considered three types of batteries against a typical bus service life of 10 years as well as an extended service life of 20 years. The paper [7] analyses the bus rapid transport networks in the four largest cities in Spain: Madrid, Barcelona, Valencia and Seville. Ten different routes were selected in each city, and their driving cycles were modelled using the real-time data extracted from diesel-engine, hybrid, and electric buses. The life cycle analysis provided in paper [7] is aimed to compare greenhouse gas emissions projected up to 2050, considering the stages of bus production, operation, maintenance, and finally end-of-life. Compared to the results obtained for the diesel buses, the results characteristic of the hybrid and electric buses show a 40 and 60% reduction in CO₂ emissions, respectively, over the entire life cycle of the buses analysed. On the other hand in [8], a life cycle analysis (LCA) was conducted to estimate CO₂ emissions from electric buses operated in Shenzhen, China. The results of calculations have shown that electric buses make it possible to reduce CO₂ emissions by nearly 22% compared to conventional diesel-powered vehicles. Furthermore, the authors have concluded that the reduction in CO₂ emissions is more pronounced if the distance between stops exceeds 2 km or the average bus speed between stops is below 25 km/h. The paper [9] analyzed the future energy consumption, greenhouse gas emissions and pollution attributable to entire bus fleets in representative Canadian cities. Analyses carried out in accordance with the adopted scenarios showed that the reduction of greenhouse gas emissions by bus fleets operating in Toronto, Montreal, Edmonton and Halifax could range from 19 to 35% between 2019 and 2030. Papers [10,11] describe the detailed analyses of the deployment of electric buses conducted in Germany and Australia. In study [10], the researchers have compared the environmental impact of diesel-engine and electric buses over their entire life cycle and analysed the impact

of electricity generation in relation to the variations in electric bus charging times. In paper [10], on the other hand, the authors have analysed the correlation between the charging time of electric buses and their environmental impact, defined various charging scenarios, and estimated the potential CO₂ emission reductions resulting from the replacement of diesel buses with electric ones. In study [11], electric buses were assessed in terms of CO₂ emission reduction, capital costs, maintenance and energy expenditure, concluding that, given the market prices of electricity and hydrogen in Australia, electric buses offer the best prospects for CO₂ emission reduction and cost savings.

Based on the literature [3–11] and our own research, it was that to the environmental impact assessment of the greenhouse gas emissions attributable to public bus transport, it is prerequisite that one should apply the LCA method in its comprehensive format, i.e. covering the well-to-wheel (WTW) scope. The main purpose of the paper is to analyse the emissions generated throughout the fuel life cycle of city buses in Poland. As part of the studies and analyses performed by the author, the greenhouse gas emissions from electric buses were assessed using the real-life data obtained from the chosen municipal transport company operating in Poland. A new approach is to include in the analyses conducted actual data on the consumption of diesel fuel used for heating in the analyzed electric buses. The GHG emissions attributable to electric buses were studied by considering changes to the energy production projections using the WTW until 2040. Based on the calculations and analyses concerning the greenhouse gas emissions identified in public bus transport, the author proposed an original computational model enabling the greenhouse gas emission values to be determined over the life cycle of the fuels intended for an electric bus.

2. Electromobility in the public bus transport in Poland

Digitisation, autonomisation, shared mobility services, and electromobility are currently by far the most important trends affecting the evolution of the global and European automotive industry. Virtually all car manufacturers have been investing in the development of electric vehicles, which has led to a significant increase in the number of low- and zero-emission vehicle models available on the market over the recent years. According to the data provided by the European Automobile

Manufacturers' Association (ACEA) [12,13] and the contents of a report compiled by the Polish Automotive Industry Association (PZPM) [14], in 2022, buses powered by diesel fuel internal combustion engines still represented the most popular type in Poland, accounting for 75% of all new bus sales. The total share of electric and hybrid buses was nearing 19%. Recently, the use of electric buses has been observed to increase both across the entire EU and specifically in Poland [15–17], where 1,731 electric buses were in operation in 2025, representing a considerable quantitative growth compared to 2022 when there were 753 such buses in service [15,17]. Having analysed the data provided in Figure 1, one can conclude that, over the recent years, and especially since 2020, a dynamic increase has been observed in the number of electric buses operated in Poland, especially by municipal transport service providers.

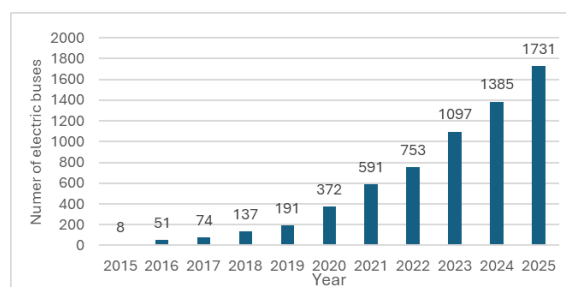


Figure 1. Number of electric buses operated in Poland. Source: author's own compilation based on [15,17].

The increasing number of registrations and the expanding market share of electric buses suggest that this technology has been enjoying growing popularity. Along with the decline in the sales of buses powered by internal combustion engines, the foregoing implies a rising interest in zero-emission buses among municipal transport companies and passenger transport operators, which should promote sustainable and environmentally friendly public transport.

In order to achieve the targets set for the sale of new zero- and low-emission vehicles in all EU Member States, new investments in charging and refuelling infrastructure must be made, and significant incentives must be introduced to encourage the purchase of vehicles with alternative drive systems. As early as in 2017, with reference to the relevant EU directive [18], the Polish Ministry of Energy published the required document and established a task force for the deployment of the Electromobility Development Programme. One of the team's most important tasks was to prepare a concept

for the development of electromobility in Poland. The resultant Electromobility Development Programme became the foundation for the creation of a regulatory package including the following components:

- “Energy for the Future” Electromobility Development Plan for Poland [19],
- Act on Electromobility and Alternative Fuels [20].

The main goal of document [20] is to promote the expansion of electromobility and the use of alternative fuels in Poland’s transport sector, mainly by establishing a legal framework for the development of electric vehicle charging and alternative fuel infrastructure. The said act provides for a significant growth of the refuelling or charging network, especially in densely populated urban areas.

The pursuit of the EU’s net zero target also involves making the most of zero-emission buses in public transport across European cities. In the years to come, Poland may secure significant funding for the climate transition of the most problematic industries, including the transport sector. Complete electrification of Poland’s urban bus fleets should lead to a reduction in CO₂ emissions and improve the air quality in the country’s agglomerations. The costs of bus electrification, which local authorities and transport companies must bear for that purpose, can be significantly reduced by implementing financial support schemes for the conversion of bus fleets from conventional to electric [21]. The implementation of such an ambitious programme, involving the construction of the necessary infrastructure and the purchase of electric buses, will require financial support for local authorities. The support facilities deployed to date for the purchase of electric buses provided for the co-financing of up to 80% of eligible costs. The cost-benefit analyses (CBAs) of the use of zero-emission buses conducted by local authorities, arising directly from the Act on Electromobility [20], clearly indicate that, without considerable financial aid, the purchase of such vehicles is not economically viable at this point. Hence the essential need for significant financial assistance offered to local authorities, provided from both foreign and domestic sources [21,22]. In 2020, the EU adopted the *greenest* budget in its history, accompanied by additional financial instruments. The funds allocated to Poland for the pursuit of its specific climate and energy targets amount to approx. €29 billion in grants and approx. €12.5 billion

available in loans [21]. The decarbonisation of public transport has been included in the National Recovery Plan as proposals to subsidise the purchase of zero-emission city buses as well as the purchase and installation of the necessary charging and refuelling infrastructure which, however, will only suffice for the electrification of a mere 10% of the current urban bus fleet in Poland. Within the framework of national funds, the main depositary of the funds assumed to serve climate and environmental purposes is the National Fund for Environmental Protection and Water Management (NFOŚiGW), which also manages the Low-Carbon Transport Fund, performing a significant role in supporting the development of low- and zero-emission public transport.

The replacement of conventional buses with zero-emission vehicles may also generate a considerable impetus for further expansion of the electric bus manufacturing sector and the necessary charging infrastructure in Poland, as well as for the development of clean transport zones in cities. Adopted in 2020, another important document is Poland’s Energy Policy by 2040 [23], one of whose priorities is complete electrification of public transport by 2030 in cities with a population of over 100,000.

3. Methodology of analysis, assumptions, and data surveying

The research discussed in this paper involved an assessment of the greenhouse gas emissions associated with the use of electric buses (BEV) in Poland in 2022 using one of the major municipal transport companies operating within the metropolitan area known as Górnośląsko-Zagłębiowska Metropolia (Metropolis of Upper Silesia and Dąbrowa Basin), or GZM, as an example. The European Commission (EC) recommends that the life cycle assessment (LCA) method [24,25] be applied to the studies of the transport sector, specifically by way of the *well-to-wheel* (WTW) fuel life cycle analysis. Over the course of the studies, the WTW method was employed to analyse the relevant greenhouse gas emissions [26–28] by considering specific environmental impacts related to such aspects as the extraction of the raw materials from which fuel was produced, fuel production, transport, and storage, as well as fuel consumption in transport, refuelling, and fuel combustion associated with vehicle operation. The author analysed the most significant impact category attributable to electric buses, namely

greenhouse gas emissions, against some other factors of significance.

Table 1. Consumption of electricity and fuel for heating as well as distance travelled by 18 m electric buses (MEGA class) between January and December 2022. Source: author's own compilation based on the data obtained from the municipal transport company.

January			February			March		
Distance travelled	Diesel fuel	Electricity	Distance travelled	Diesel fuel	Electricity	Distance travelled	Diesel fuel	Electricity
[km]	[l]	[kWh]	[km]	[l]	[kWh]	[km]	[l]	[kWh]
2,666.70	551.98	4,030.75	2,057.50	365.80	2,875.78	2,577.30	365.16	3,358.74
3,316.50	654.04	5,560.12	2,984.00	494.41	4,451.98	965.10	127.37	1,528.92
4,067.65	744.37	6,151.77	3,727.50	565.34	5,560.06	4,170.30	409.44	6,376.15
3,735.10	686.88	4,721.53	3,389.30	459.43	5,215.25	2,904.75	256.64	4,365.01
3,814.55	655.27	6,254.56	4,305.85	605.26	6,648.68	5,015.70	451.73	7,898.36
5,199.75	970.86	7,367.42	4,612.00	719.07	6,151.14	5,901.15	781.15	6,447.70
4,554.70	869.95	6,888.21	4,108.65	642.86	5,932.30	4,977.65	566.23	7,510.16
4,899.80	928.26	6,927.00	3,668.65	427.73	5,021.71	4,913.75	527.11	7,087.64
3,091.90	597.41	4,902.58	5,224.25	766.46	7,433.85	5,858.95	634.55	8,280.80
4,265.35	700.42	5,933.05	4,564.80	576.96	6,365.82	4,584.60	529.69	6,121.16
39,612.00	7,359.44	58,736.98	38,642.50	5,623.32	55,656.57	41,869.25	4,649.07	58,974.63
April			May			June		
2,268.50	235.52	2,977.26	2,436.55	33.47	3,386.77	2,501.55	22.31	3,940.86
3,300.05	320.34	4,958.01	3,954.40	113.11	5,937.83	2,951.80	20.74	5,077.75
4,483.75	328.09	6,371.25	4,045.70	47.50	5,719.66	3,503.45	29.62	5,295.84
1,058.35	148.26	1,717.33	1,388.05	2.44	2,001.85	3,386.40	23.87	4,933.62
3,405.65	292.30	4,774.63	1,918.60	42.16	2,627.37	1,964.20	0.00	3,312.21
4,520.00	412.55	5,283.90	5,620.70	109.00	7,576.86	4,862.70	26.00	6,675.64
4,764.95	421.06	6,831.25	5,288.35	110.41	7,576.72	5,708.10	0.00	8,388.20
5,184.50	459.87	7,136.24	5,110.25	103.54	6,756.04	5,393.45	0.00	7,715.20
4,547.20	418.85	6,273.45	5,682.40	83.30	7,711.70	4,594.60	31.90	6,742.65
4,679.80	408.12	5,870.23	5,143.55	116.46	6,783.18	4,459.50	25.00	6,471.87
38,212.75	3,444.96	52,193.54	40,588.55	761.39	56,077.98	39,325.75	179.44	58,553.82
July			August			September		
2,719.70	0.00	4,003.28	2,186.75	0.00	3,352.77	2,229.35	69.29	3,090.32
3,384.85	41.49	5,760.10	3,362.40	0.00	5,584.06	3,592.80	214.03	5,148.01
3,409.85	0.00	5,093.45	4,716.10	0.00	7,484.52	4,307.30	227.67	6,384.09
3,288.00	0.00	4,703.65	2,151.85	0.00	3,170.66	1,023.40	14.00	1,388.08
2,280.90	0.00	3,734.58	2,395.05	0.00	3,692.25	3,802.10	185.88	5,339.57
6,132.05	0.00	8,130.91	6,388.15	0.00	9,306.68	5,418.15	229.17	7,276.35
5,786.75	24.36	8,944.95	422.05	0.00	460.69	0.00	0.00	0.00
4,903.95	33.08	6,813.84	5,703.75	0.00	7,708.55	5,284.80	212.15	6,789.44
550.80	0.00	231.22	4,911.45	0.00	7,267.74	5,470.25	235.51	7,354.13
4,339.90	20.01	6,448.07	6,013.05	0.00	9,222.36	4,469.65	145.63	6,422.93
36,796.75	118.94	53,864.05	38,250.60	0.00	57,250.29	35,597.80	1,533.33	49,192.91

The WTW-based life cycle assessment made it possible to identify environmental burdens related both directly and indirectly to the life cycle of a bus. The results thus obtained were analysed with reference to the year 2022, while the functional unit assumed for the analyses was 100 km of the distance covered by individual buses over the course of their operation by the municipal transport company. What these analyses also took into account was the additional fuel consumption associated with the heating system used in these electric buses, having a negative impact on the direct emissions in winter months.

Yet another goal of these analyses was to highlight determinants for the assessment of the greenhouse gas emissions associated with the operation of the electric buses used to deliver municipal transport services in Poland.

The LCA-based calculations were performed using version 9.5.0.2 of the Simapro software powered by the Ecoinvent v.3.9

database [29,30]. For purposes of the study, the relevant input and output data were subject to detailed identification and analysis – a process known as a life cycle inventory (LCI), which makes it possible to survey all the data necessary for life cycle assessment. This is an important component of LCA analyses, demonstrating the reliability of the analysis results obtained. Therefore, it is important that LCA should be based on real-life data, as in the case of the studies addressed in this article, rather than secondary data extracted from a literature review.

The main assumptions and the set of inputs and outputs envisaged in this paper, actually used at individual phases of the bus life cycle, are real-life data obtained from the chosen municipal transport company. The data concerning the energy systems used for charging of the electric bus batteries were processed with reference to data specific to Poland. A method referred to as IPCC after the Intergovernmental Panel on

Climate Change [29,30], where it had originated, was used for the environmental impact assessment. The IPCC method is intended to enable greenhouse gas emission assessment over a product life cycle. Using the IPCC method made it possible to calculate an index based on the global warming potential, being a measure which expresses the radiative forcing of the greenhouse gases released into the environment as converted into equivalent kilograms of carbon dioxide [30].

The WTW analyses conducted by the author concerned electric buses, and they took into account both the life cycle of the electricity used to charge the bus batteries as well as the diesel fuel consumed for bus heating purposes. The analyses were conducted by referring to the real-life data obtained from the chosen municipal transport company for each month of 2022, broken down into diesel fuel and electricity consumption by the entire stock of individual buses. On account of the sheer number of buses operated by the transport company, the data assumed for the analyses addressed in this paper concerned 18 m long vehicles. Sample data showing the actual distance travelled as well as the electricity and heating fuel consumed by the electric buses (MEGA class) between January and December 2022, as provided by the municipal transport company in question, have been provided in Table 1. Having analysed the data compiled in Table 1, the author found that the only month in which the electric buses did not consume diesel fuel for heating purposes was August. Diesel fuel consumption was recorded in all other months of 2022, while its highest consumption for bus heating took place in January and December, coming to 7,359.44 and 7,083.19 litres, respectively. The use of diesel fuel in electric bus heating systems entails its negative impact on the direct emissions generated at bus operation sites as well as on the indirect emissions associated with diesel fuel production.

The system boundary set for the electric buses comprised electricity generation at large, taking all the sources of the energy produced in Poland into account. Based on the data compiled for electricity production [31] and rendered available by Agencja Rynku Energii S.A. in 2023 [32], the percentage share of individual energy sources in 2022, as adopted in this study, has been shown in Figure 2.

The following life cycle inventory data were used to perform the WTW analysis of the electric buses under the study: distance covered by each bus in each month of the analysis, electricity

consumption for battery charging, diesel fuel consumption for bus heating, dust and gas emissions related to diesel fuel consumption for heating of 18 m buses conforming with the Euro 6 standard [33].

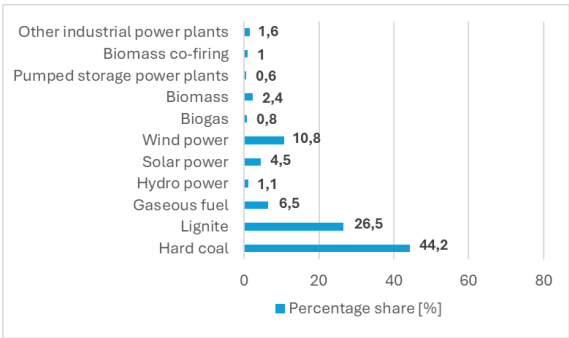


Figure 2. Electricity production by energy source in Poland in 2022. Source: author’s own compilation based on [31,32].

4. Study of the GHG emissions from electric buses considering changes to the energy production structure projected by 2040

In accordance with the outcomes of the analysis of development trends observed in the national power engineering sector, as provided in the strategic document known as *Poland’s Energy Policy Until 2040 (Polityka energetyczna dla Polski do 2040 r.)* [23], specific changes have been identified that will occur particularly between 2030 and 2040 in the structure of electricity production in Poland. These will primarily result from legal and market conditions consistent with the EU climate and energy policy, as adopted and currently applicable. The gross electricity generation projection in a breakdown by fuels, expressed in [TWh] for Poland, and stated in document [23], has been presented in Table 2.

Document [23] highlights the gradual development of renewable energy sources. By 2030, the share of RES in electricity generation is anticipated to have reached nearly 32%, and nearly 40% by 2040. The volume of electricity generated from RES in 2040 is expected to be as much as four times greater than in 2015. The increase in the RES-based energy production, combined with the obligation imposed on coal-fired power plants to purchase appropriate quantities of CO₂ emission allowances under the ETS scheme, will result in a gradual reduction in the share of fossil fuel-fired power stations in the electricity generation mix from almost 75% in 2025 to almost 46% in 2040. Nevertheless, despite the assumed significant

decline in the contribution of fossil fuel-fired power stations to the energy mix, they will continue to function as major sources of electricity in Poland. Another very important element of the national CO₂ emission reduction policy, as set out in document [23], is the development of nuclear energy. It is projected that, by 2035, as much as over 20 TWh of energy may be delivered from nuclear sources, which will account for nearly 10% of Poland's total electricity production. Hence the analyses of the

greenhouse gas emissions attributable to electric buses powered in line with the electricity generation projections adopted in document [23] up to 2040. These analyses and the accompanying calculations were based on the 2022 data concerning electric buses, as provided in Table 1. The electricity generation figures assumed for the emission calculations took into account all energy sources in Poland in 2022 as well as the projections for the years 2025, 2030, 2035, and 2040 (Table 2).

Table 2. Electricity generation projections for Poland by fuel type. Source: author's own compilation based on [23].

Fuel type	Electricity generation projections for Poland by fuel type											
	2025			2030			2035			2040		
	TWh	[%]	Total [%]	TWh	[%]	Total [%]	TWh	[%]	Total [%]	TWh	[%]	Total [%]
lignite	50.4	26.8		49.9	24.8		27.5	12.9		17.3	7.7	
hard coal	72.3	38.5		63.1	31.4		53.2	25.0		45.7	20.2	
gaseous fuel	15.3	8.1		20.7	10.3		31.3	14.7		38.4	17.0	
fuel oil	1.9	1.0	74.5	1.9	0.9	67.4	1.8	0.8	53.5	1.7	0.8	45.7
nuclear power	0	0.0	0.0	0	0.0	0.0	20.4	9.6	9.6	30.6	13.6	13.6
solar power	4.5	2.4		6.8	3.4		10.8	5.1		14.8	6.6	
on-shore												
wind power	23.7	12.6		23.8	11.8		24.2	11.4		24.6	10.9	
off-shore												
wind power	2.7	1.4		14.5	7.2		21.7	10.2		30.6	13.6	
biomass	9.7	5.2		11.6	5.8		11.4	5.4		10.3	4.6	
biogas	2.7	1.4		3.9	1.9		5	2.4		5.8	2.6	
hydropower	2.9	1.5	24.6	3	1.5	31.6	3	1.4	35.8	3.1	1.4	39.5
pumped storage												
hydropower	0.8	0.4	0.4	0.9	0.4	0.4	1.2	0.6	0.6	1.5	0.7	0.7
other	0.9	0.5	0.5	1.1	0.5	0.5	1.2	0.6	0.6	1.3	0.6	0.6
Total	187.8	100	100	201.2	100	100	212.7	100	100	225.7	100	100

Table 3. GHG emissions from electric buses relative to electricity production projections by 2040. Source: author's own compilation.

Year	Greenhouse gas emissions [kg CO ₂ eq/100km]												
	January	February	March	April	May	June	July	August	September	October	November	December	Average
2022	193,47	176,91	163,16	152,70	131,63	136,92	134,22	136,43	139,32	141,62	171,63	197,73	156,31
2025	184,71	168,41	154,84	144,63	123,47	128,13	125,57	127,59	131,16	133,58	163,24	188,53	147,82
2030	171,36	155,43	142,15	132,32	111,03	114,72	112,39	114,11	118,71	121,32	150,45	174,52	134,88
2035	145,01	129,84	117,13	108,06	86,48	88,26	86,38	87,52	94,16	97,14	125,21	146,86	109,34
2040	130,25	115,50	103,10	94,46	72,72	73,44	71,80	72,62	80,40	83,59	111,07	131,37	95,03

The WTW (well-to-wheel) method, specifically designed for electric buses, was used to assess the potential environmental impact of charging electric bus batteries. This method was chosen because it enables the assessment of the entire life cycle of electrical energy and takes an important environmental aspect into account, namely greenhouse gas emissions. The WTW method, developed by the Joint Research Centre (JRC) and endorsed by the EU, is recommended for the analyses of GHG emissions from the transport sector. The WTW analysis was conducted in accordance with the ISO standards [24,25], and using the SimaPro v.9.5.0.2 software with the Ecoinvent v.3.9 database. Following the guidelines of [24], the goal and scope of the study, including the functional unit applied, the system boundary, and the basic analytical assumptions were defined. The second phase consisted in analysing the input and output datasets, i.e. the life cycle

inventory (LCI), comprising a list of all data items required for the WTW analysis (as presented in Chapter 3). Phase three was the life cycle impact assessment (LCIA), which made it possible to define the right values of the environmental impact categories which were to be calculated using the selected assessment methods. The final phase was the interpretation of the results thus obtained. The GHG emission results obtained by the WTW method for the consecutive years, relative to the electricity generation projections extending until 2040, have been provided in Table 3 and illustrated in Figures 3 and 4.

The relevant changes to the energy mix, adopted in line with the electricity generation projections for Poland [23] and the data provided in Table 2, considered against charging of electric bus batteries, have resulted in a reduction in the average greenhouse gas emissions in the consecutive years of analysis compared to 2022 (Figures 4). For the energy mix assumed for

the years 2025, 2030, 2035, and 2040, being the source of the electricity consumed for the charging of electric bus batteries, a decline in the average emissions by 5%, 13.5%, 30%, and 39%, respectively, has been observed in comparison with the 2022 energy mix (Figure 4). The greenhouse gas emission determinants identified for electric buses against the electricity generation projections for 2025, 2030, 2035, and 2040 have been shown in Figure 5. Analyzing the results for the electric buses used in the analyses, shown in Figure 5, it can be concluded that changes in projected electricity production have the greatest impact on greenhouse gas emissions. Reducing the share of fossil fuels (hard coal and lignite) in electricity production from 65.3% in 2025 to 27.9% in 2040 (Table 2) reduces the share of these fuels in greenhouse gas emissions from 62.2% in 2025 to 38.3% in 2040. Additionally, by analysing the results shown in Figure 5, it can be concluded that it is possible to achieve some additional benefits associated with the reduction of the greenhouse gas emissions attributable to electric buses under the condition that diesel-powered heating systems are not used in the electric buses operated in Poland.

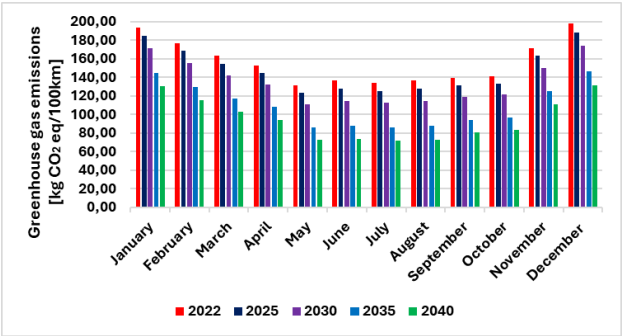


Figure 3. GHG emissions from electric buses relative to electricity production projections by 2040. Source: author’s own compilation.

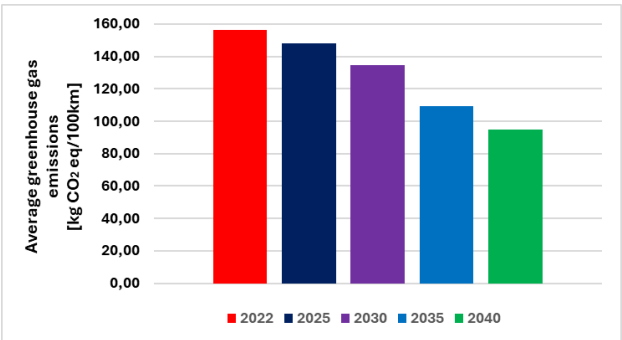


Figure 4. Average greenhouse gas emissions from electric buses in individual years relative to electricity production projections by 2040. Source: author’s own compilation.

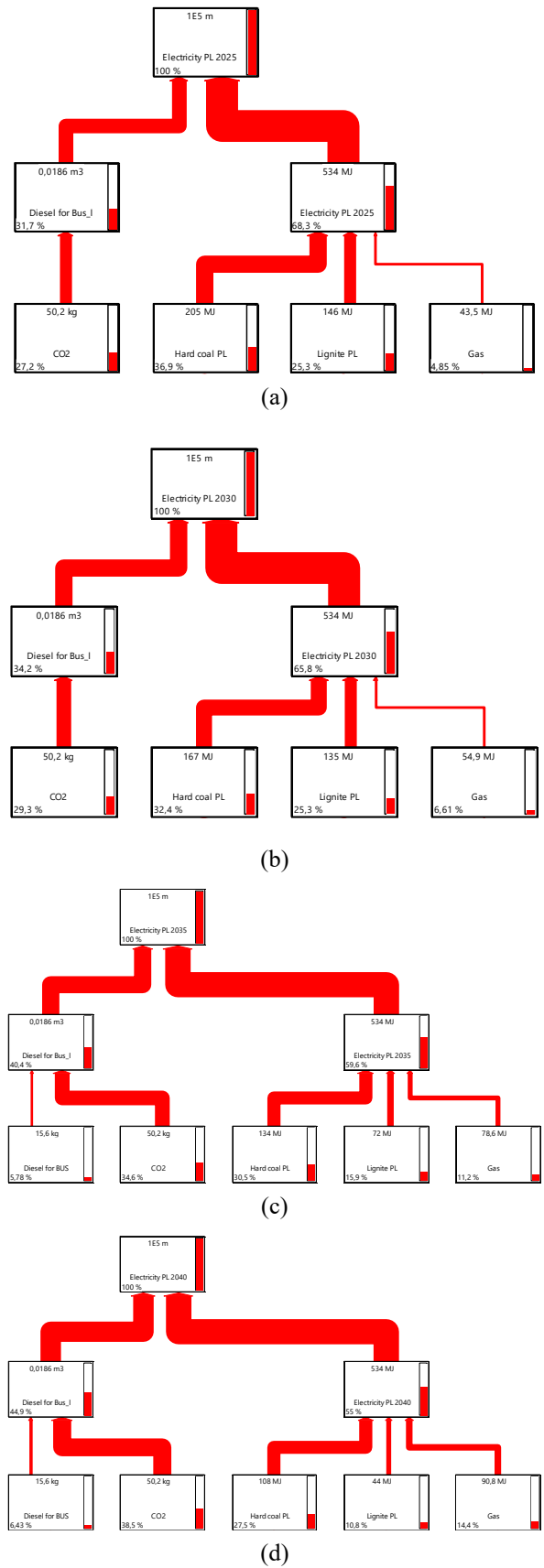


Figure 5. Determinants of GHG emissions from electric buses against projected electric energy production in: (a) 2025, (b) 2030, (c) 2035, (d) 2040. Source: author’s own compilation.

5. GHG emission assessment model applied to electric buses

Based on the analyses performed under the study, it has been established that the key factor determining the assessment of the greenhouse gas emissions attributable to electric buses in Poland is the electricity used for bus battery charging. With that inference in mind, a model has been proposed for assessing greenhouse gas emissions from electric buses, taking into account the methodology of fuel life cycle analysis, which in this particular case involves the life cycle analysis of the electricity used to charge the batteries installed in electric buses. The model in question enables assessment of GHG emissions for various sources of electricity, which makes it a universal model that can be employed to study GHG emissions over the life cycle of fuels in different countries.

Based on a literature review and the author's in-house studies, the main energy sources used for the electricity generation within the EU and in Poland have been identified (Table 4). As part of the research explored in papers [34-36] greenhouse gas emissions were assessed for individual sources of electricity. The data required to calculate greenhouse gas emissions for the life cycle of electric buses are as follows:

- percentage share of individual sources of electricity,
- GHG emission values calculated for each source of electricity,
- average electricity consumption for bus charging per 100 km,
- average consumption of diesel oil for bus heating,
- calculated GHG emissions from the production of 1 litre of diesel oil.

A breakdown of electricity production according to energy sources in Poland has been depicted in Figure 2. In order to calculate the relevant GHG emissions, an LCA of individual electricity sources was performed based on the IPCC's method using the SimaPro v.9.5.0.2 software with the Ecoinvent v.3.9 database [29,30]. The LCA analysis of the production from the electricity sources in question was conducted in line with the ISO 14000 series standards [24, 25]. The greenhouse gas emissions established for the individual electricity sources shown in Figure 2 and for nuclear energy have been summarised in Table 4.

As determined by the LCA method, the total GHG emissions from the production of 1 litre of diesel oil, which amounts to 3.15 [kg CO₂ eq./l], has been illustrated in Figure 6 and compiled in Table 5 in a breakdown into production-related emission and that associated with the consumption of 1 litre of diesel oil.

Table 4. Greenhouse gas emissions from the generation of 1 kWh of energy calculated for individual sources of electricity. Source: author's own compilation.

Item	Source of electricity	Greenhouse gas (GHG) emissions [kg CO ₂ eq./kWh]
1	Hard coal	1.19
2	Lignite	1.15
3	Natural gas	0.547
4	Hydropower	0.00415
5	Solar power	0.0769
6	Wind power	0.0158
7	Biogas	0.228
8	Biomass	0.0477
9	Pumped storage power plants	1.34
10	Biomass co-firing	0.054
11	Other industrial power plants	1.6
12	Nuclear energy	0.0119

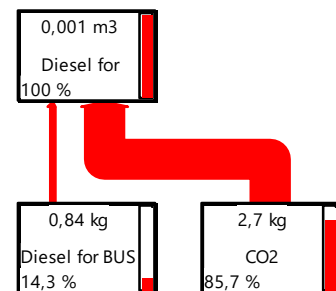


Figure 6. GHG emission determinants for 1 litre of diesel fuel.

Source: author's own compilation.

Table 5. GHG emissions calculated for 1 litre of diesel fuel. Source: author's own compilation.

Indirect GHG emissions from the production of 1 litre of diesel fuel [kg CO ₂ eq./l]	Direct GHG emissions from the combustion of 1 litre of diesel fuel [kg CO ₂ eq./l]	Total greenhouse gas emissions GHG_{DIESEL} [kg CO ₂ eq./l]
0.45	2.7	3.15
14.3%	85.7%	100%

Following the analyses of the percentage share of individual energy sources used for electricity production and of the GHG emissions established for each of these sources, the study involved an analysis of the electric energy consumed for charging of electric bus batteries.

The author's original calculation model developed to determine the greenhouse gas emissions over the life cycle of fuels for an electric bus is described by Equation 1:

$$GHG_{E-BUS} = [(\sum_{i=1}^n GHG_{ENERGY\ i} \cdot U_{ENERGY\ i}) \cdot E_{E-BUS}] + (GHG_{DIESEL} \cdot E_{DIESEL-BUS}) \quad (1)$$

where:

GHG_{E-BUS} – greenhouse gas emissions attributable to an electric bus [kg CO₂ eq./100 km];

$GHG_{ENERGY\ i}$ – greenhouse gas emissions calculated for 1 kWh generated from individual energy sources [kg CO₂ eq./kWh] (Table 4);

$U_{ENERGY\ i}$ – percentage share of the energy source in a given country's energy mix [%] (Table 2);

E_{E-BUS} – average electricity consumption by a bus [kWh/100 km];

GHG_{DIESEL} – greenhouse gas emissions calculated for the production of 1 litre of diesel oil [kg CO₂ eq./l] (Table 5);

$E_{DIESEL-BUS}$ – average diesel oil consumption for electric bus heating [l/100 km];

In order to verify the author's original model (Equation 1), an electric bus was analysed using the real-life data provided in Table 1. The calculations performed for this purpose were based on the computational greenhouse gas emissions established for the production of 1 kWh of electricity derived from individual energy sources (Table 4). Table 6 contains the greenhouse gas emissions calculated by the LCA method (Table 3) and collated with the emission value obtained using the author's original model (Equation 1) with reference to the data provided in Tables 4 and 5.

Table 6. Greenhouse gas emissions in 2022 for a single electric bus. Source: author's own compilation.

Greenhouse gas emissions [kg CO ₂ /100 km]		Relative error
LCA	Model	[%]
156.31	156.1	0.13

Following an analysis of the calculation results obtained using the original model prepared by the author and summarised in Table 6, one can conclude that the greenhouse gas emissions [kg CO₂/100 km] established by application of the LCA method and in line with Equation 1 are consistent, which confirms the usefulness and accuracy of the proposed model for determining greenhouse gas emissions from electric buses.

6. Summary and conclusions

With regard to the environmental impact assessment of the greenhouse gas emissions attributable to public bus transport, it

is prerequisite that one should apply the LCA method in its comprehensive format, i.e. covering the well-to-wheel (WTW) scope. As part of the studies and analyses performed by the author, the greenhouse gas emissions from electric buses were assessed using the real-life data obtained from the chosen municipal transport company operating in Poland. The GHG emissions attributable to electric buses were studied by considering changes to the energy production projections using the WTW approach in line with document [23]. Based on the calculations and analyses concerning the greenhouse gas emissions identified in public bus transport, the author proposed an original computational model enabling the greenhouse gas emission values to be determined over the life cycle of the fuels intended for an electric bus. The model proposed by the author can be used to analyse electric buses in terms of the cost-benefit relationship as well as their operating costs. With reference to the calculations and studies discussed in this article, the following conclusions can be formulated:

1. The relevant changes to the energy mix, assumed in line with the electricity generation projections for Poland [23], have caused a drop in the average greenhouse gas emissions from electric buses in the consecutive years of the analysis compared to 2022. For the energy mix envisaged for the years 2025, 2030, 2035, and 2040, being the source of the electricity consumed to charge batteries of electric buses, a decline in the mean emissions by 5%, 13.5%, 30%, and 39%, respectively, can be observed in comparison with the 2022 energy mix.
2. On account of Poland's current energy mix, using electric buses in transport is not enough to effectively reduce the greenhouse effect, since the reduced GHG emissions from the operation of these buses still entail high CO₂ emissions from coal-fired power plants.
3. It is possible to achieve some additional benefits associated with the reduction of the greenhouse gas emissions attributable to electric buses under the condition that diesel-powered heating systems are not used in the electric buses operated in Poland.
4. When used to determine the greenhouse gas emissions

from electric buses, the original model proposed by the author enables the GHG emissions to be assessed with diverse sources of electric energy in mind. This makes it a universal model which can be successfully applied

when assessing GHG emissions over the life cycle of fuels in different countries, but also when analysing costs against benefits as well as total ownership costs of electric buses.

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