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Original Article

WELL-TO-WHEEL ANALYSIS OF THE EMISSIONS FROM THE ELECTRIC BUSES USED IN POLAND AND CZECHIA

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Highlights:
- various aspects of the development of electromobility have been discussed;
- a computational model has been designed for calculating CHG emissions from electric bus charging across the life cycle;
- the WTW analysis of electric buses has been performed;
- determinants of CHG emissions from EV battery charging have been identified;
- an electric bus and a bus with an internal combustion engine have been subject to a comparative analysis for CHG emissions.

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Abstract. Road transport is one of the major sources of pollution. To solve this problem, alternative fuels with a lower environmental impact are sought. Therefore, it is important to determine the impact of the life cycle of transport fuels in order to assess, which of them are more environment-friendly by taking into account the emissions generated during fuel production and vehicle operation. Electric Vehicles (EVs) are becoming increasingly popular. This article discusses a life cycle approach to the assessment of transport fuels intended for electric buses. It presents a comparative Well-To-Wheel (WTW) analysis of the emissions from the buses used in Poland and Czechia by analysing their life cycle, with particular consideration of the production of the electricity required to charge electric batteries. Furthermore, a comparative analysis of an electric bus and a conventional diesel bus has been performed. The results of the analysis are expressed as Greenhouse Gas (CHG) emission ratios across the life cycle of the buses operated in Poland and Czechia.

Keywords: electric bus, well-to-wheel analysis, life cycle assessment, Poland, Czechia.

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Notations

BEV – battery EV;
CF – carbon footprint;
CNG – compressed natural gas;
EC – European Commission;
EU – European Union;
EV – electric vehicle;
FU – functional unit;
GHG – Greenhouse Gas;
GWP – Global Warming Potentials;
IPCC – Intergovernmental Panel on Climate Change;
LCA – life cycle assessment;
LCI – life cycle inventory;
LCIA – life cycle impact assessment;
LNG – liquefied natural gas;
RES – renewable energy sources;
TCO – total cost of ownership;
TTW – tank-to-wheel;
WTT – well-to-tank;
WTW – well-to-wheel.

1. Introduction

The various efforts undertaken over the recent years across the EU are aimed at the problems of low-carbon economy of the Member States. Adverse climate changes are predominantly attributable to carbon dioxide emissions. This is precisely why Europe has made maximised reduction of CHG emissions one of its policy priorities. Based on a literature review, it has been established that the transport sector is the second largest source of pollution in the entire EU, with approximately 70% of the pollutants being emitted by road transport. The overall body of CHG emission problems is considered relevant to transport systems. It is all the more important when considering the EC's guidelines as well as the new challenges to the circular economy model. Public transport, including city buses in the first place, is an important element of the EU's strategy for reducing the negative environmental impact of transport. In line with the EC guidelines, what matters in particular is the development of electromobility in public transport. The EU's main document obliging the Member States to foster changes in the transport sector is the *White Paper*: *Roadmap to a Single European Transport Area – Towards a Competitive and Resource Efficient Transport System* (EC 2011). As specified in the *White Paper*, by 2030, there are to be half as many vehicles running on conventional fuels in cities, and by 2050, they are assumed to disappear completely and be replaced by low-emission vehicles. Directive 2009/33/EC of the European Parliament and of the Council requires state institutions and certain logistics operators to consider the environmental impact, CHG emissions, and energy consumption factors when purchasing new vehicles, which ultimately contributes to the promotion of alternative fuel vehicles to a considerable extent (EC 2009). The growing number of electric city buses is observed across the entire EU. So far, the literature has addressed the problems associated with the use of biofuels in the transport sector of the Member States in light of the EU regulations (Kupczyk *et al.* 2017) and the LCA analysis of the diverse fuels used in public transport (Nordelöf *et al.* 2019). Another problem subject to numerous analyses has also been the development of sustainable transport (Borucka, Załęski 2017). The environmental analyses of EVs performed to date have also considered batteries and the TCO modelling of electric buses (Thorne *et al.* 2021). They have shown that the TCO of electric city buses is actually rather high at the moment. Ellingsen *et al.* (2022) have discussed the environmental impact of diverse battery production technologies. In terms of environmental aspects, one can still observe considerable shortage of studies representing this scientific and research area, which pertain to the environmental assessment of public transport, especially with regard to alternative fuels, electromobility, and energy systems in individual countries.

In daily practice, transport-related entities, which are aware of the negative environmental impact of means of transport use various methods of analysis to study the environmental effect of vehicles. The most widespread analytical method is the WTW fuel life cycle analysis, enabling assessment of the CHG emissions generated throughout the production, transportation, distribution, and operation of a vehicle. The WTW analysis is a component of the more complex LCA analysis, which is most typically performed within the limits of a system referred to as cradle-to-grave, which means that it studies the environmental impact of the object in question starting from its manufacture until the time of its disposal. The LCA makes it possible to identify both direct and indirect environmental burdens triggered by the life cycle of a vehicle. The LCA's main elements are the identification and quantification of potential environmental burdens related to raw materials, energy consumption, and emissions released into the environment. Besides analysing the environmental impacts associated with fuel production and consumption, the LCA also takes such factors as vehicle production and assembly, maintenance, and ultimately disposal into account. With regard to EVs, also battery production is included in the analysis. As in the WTW method, so in the LCA, the environmental impact is expressed in the consumption of raw materials and energy as well as CHG emission (Szumska *et al.* 2018). An option of extending the boundaries of the life cycle analysis system according to the cradle-to-cradle concept is currently being considered on account of the new and preferred circular economy model in which every raw material should be recycled. The LCA analysis is performed in line with the ISO 14040:2006 standard, according to which, it should consist of the following steps: defining the purpose and scope of the analysis, defining a set of inputs and outputs, impact assessment, and interpretation of the results. The LCA analysis flowchart originally adopted for purposes of this study has been provided in Figure 1 (Folęga *et al.* 2022).

Unfortunately, in most cases, car production data are made confidential by the manufacturers, which makes it often impossible to perform a reliable LCA analysis of a specific vehicle. Where this is the case, one typically uses the available data describing a vehicle of a similar design. However, considering how problematic it is to acquire data concerning the environmental impact attributable to the vehicle production and given the fact that most of the pollutants generated over the vehicle life cycle are released in the fuel production and vehicle use phases, it is the WTW method that one typically applies to determine the vehicle's environmental impact (Ercan, Tatari 2015).

The main purpose of the article is to analyse the emissions generated throughout the fuel life cycle of city buses in Poland and Czechia. The analysis in question covered the life cycle of an alternative fuel equivalent, namely electric drive. The studies focused on the electricity supplied from the power grid of the aforementioned countries, used to charge the batteries of electric buses. Another aspect taken into account was the changes assumed to affect the energy systems of these countries between 2020 and 2050.

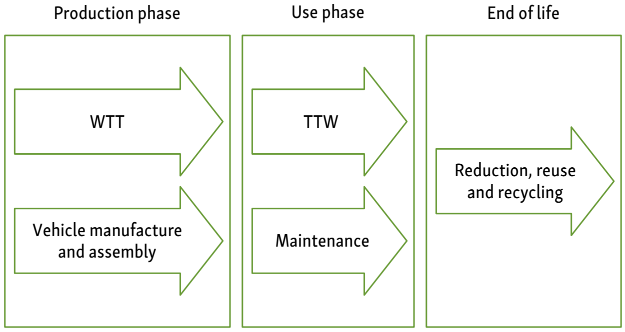

Figure 1. LCA flowchart (source: own elaboration of the authors)

2. Evolution of electrically driven buses

The evolution of electric buses is clearly evident in many countries of the EU. One can distinguish between the following propulsion systems used in public transport vehicles: conventional powertrain, electric drive, hybrid drive, gas-powered, and hydrogen-powered buses. Diesel-powered vehicles are the least environmentally friendly in terms of CHG emissions compared to other propulsion sources. In order to reduce the emission of toxic substances from internal combustion engines, the EC has established the EURO standards, imposing limits on the emissions of harmful compounds attributable to vehicles, laid down in a series of European Directives. The first standard entered into force in 1993, applicable to all vehicles sold across the EU, and each successive standard has gradually become more restrictive. In line with the *White Paper*, released in 2011, vehicles equipped with conventional internal combustion engines are expected to have been completely removed from urban transport by 2050 (EC 2011). This means that despite the unquestionable advantages of these buses, such as low price and relatively cheap operation, it is inevitable that they are eventually phased out (EC 2011). Therefore, being fully aware of the legal requirements in place, transport companies have already started investing in vehicles powered by alternative systems.

The hybrid powertrain system designed for buses involves cooperation of 2 engines: a diesel engine and an electric one. An indisputable advantage of this solution is the possibility of using only the electric motor when starting, which is when the combustion engine produces the largest amounts of harmful substances. The electric motor generates a full range of torque from the very ignition, which allows it to make the most of its parameters while the vehicle is starting. On longer routes, when the bus speed exceeds 50 km/h, the diesel engine is in use, performing better than the electric motor in this case. A hybrid bus can also use both engines at the same time or separately, as described above (Krawiec 2014).

Hydrogen-powered buses are electric buses. This type of vehicle is propelled by an electric motor, where hydrogen is only an energy carrier. Electrical energy is obtained from the oxidation of the hydrogen-based fuel (Folęga *et al.* 2022).

Among the available internal combustion engine alternatives, electric drive systems have recently been growing in popularity the most. Electric motor vehicles, both buses and passenger cars, are widely promoted across the EU, mainly through financial bonuses intended to stimulate their purchase. This kind of support also takes the form of diverse projects, the largest in Europe being Zero Emission Urban Bus System (ZeEUS, *https://zeeus.eu*), which focuses on supporting the development of electric urban transport. Witnessing the growing popularity of electric buses, leading bus manufacturers are becoming increasingly involved in the continuous development of this technology, willing to establish their competitive position in this emerging market. Electric buses are widely considered to be the future of environment-friendly public transport. Vehicles of this type are propelled by high power lithium-ion batteries. Their operating range reaches up to 300 km, which enables them to traverse the entire route, which a typical city bus covers on average. However, one should keep in mind that their energy consumption depends on a number of factors such as the bus load, weather conditions, terrain, and the operation of additional on-board equipment, which means that, in practice, the actual running range of such a vehicle is considerably smaller (Krawiec 2014). A solution to this problem may be frequent short-time battery charging, e.g., at bus stops. What one should definitely consider on its downside is the cost of the vehicle purchase and the insufficient, yet prerequisite, charging infrastructure. In order to comply with the EU requirements, local authorities should support transport companies through measures aimed at fleet upgrading, such as co-funding schemes and support for the infrastructure development. The main advantages of an electric bus include: low CHG emission, quiet engine operation, high powertrain efficiency, lower operating costs, and improved travelling comfort. With appropriate handling, total torque can be utilised already at the start, which is far superior to conventional drive systems, technology-wise. The fact that the electric drive system features neither a clutch nor a gearbox also translates into a fixed transmission ratio between the motor and the wheels. The powertrain is composed of a microprocessor-based control system, a motor, an inverter (a power electronic system), as well as batteries and supercapacitors responsible for energy storage.

3. Legal aspects of the development of electromobility in the bus fleets of Poland and Czechia

Electromobility development is one of the priorities of the economic policy currently implemented in Poland. Released in 2016, the *Electromobility Development Plan* (NFOŚGW 2023) has proved to be among its main instruments. Its original premise was to create conditions for the development of production and dissemination of EVs. The support offered under this scheme, including financial aids, has been aimed at a number of targets, including further development of electric buses. Their widespread use in public transport of Polish cities is expected to help in improving the quality of life by reducing air and noise pollution.

Electromobility is one of the most crucial spheres in which various measures are implemented in Poland. The development of this sector is driven not only by environmental and climatic conditions, but also by innovative solutions, which change the competitiveness of industries as well as the global map of dependence on raw materials.

In an attempt to face up to the high expectations towards the transport sector in Poland, a package of dedicated legal regulations has been created at the Ministry of Energy to support the development of electromobility and the use of alternative fuels in transport. The documents pertaining to this subject envisage a number of incentives for drivers and businesses, as well as further expansion of EV charging and CNG/LNG refuelling infrastructure. Among these measures, the *Electromobility Development Plan* is considered crucial, being a flagship project of the governmental *Strategy for Responsible Development*. The pursuit of the objectives of the *Strategy for Responsible Development* as well as of the *Electromobility Development Plan* had paved the way towards establishing the *Electromobility Development Plan* entitled *Energy for the Future*, adopted by the Council of Ministers on 16 March 2017 (ME 2017), defining the benefits associated with the widespread use of EVs across the country and identifying the economic and industrial potential of this area. According to the *Electromobility Development Plan*, electromobility development should proceed in 3 phases:

- phase I was preparatory in nature, and it was completed in 2018, as the preconditions for the development of electromobility in regulatory terms as well as targeted public funding schemes had been created;
- in the phase II (2019–2020), EV charging infrastructure was developed in selected metropolitan areas, and incentives for purchasing EVs were intensified;
- phase III (2020–2025) is based on an assumption that the electromobility market will have reached maturity, making it possible to gradually phase out the support instruments.

The *Electromobility Development Plan* has become an important factor in the development of a new market with long-term growth potential in Poland, built on long-standing traditions of bus production, and using innovative technologies (Dyr, Abramowicz 2016). In order to meet the requirements, set out in the *White Paper* and the relevant European directives, Poland is creating its own documents. An extension of the *Electromobility Development Plan* has been the *Act on Electromobility and Alternative Fuels* of 11 January 2018 (KS 2018). It mainly addresses problems related to the sale of electricity at charging points and the legal relationships connected with the identification of the parties involved in EV charging (Szumska *et al.* 2018; Walendzik *et al.* 2016). It is not the legal constraints that have been slowing down the development of electromobility, but the financial barriers associated with the high costs of purchase of EVs, their short running range compared to internal combustion vehicles, and the insufficiently developed EV charging infrastructure. Poland can and should follow in the footsteps of other countries, which have taken responsibility for organising the charging infrastructure by nominating specific entities in charge of this process. And these entities have indeed been identified in the *Act on Electromobility and Alternative Fuels*. They are the charging service provider and the infrastructure operator. The document stipulates that the infrastructure operator is to be held responsible for the construction and operation of charging points. The service provider will be appointed by municipalities on a competition basis. If the event that there are no parties interested in this activity, the local energy distributor will be obliged to assume responsibility for the installation of charging points within the municipality. In summary, the *Act on Electromobility and Alternative Fuels* is predominantly focused on the legal conditions of the supply of energy to EVs, and it is based on the assumption that infrastructure development will be provided by both the state and the entities designated by the former (Burchart-Korol, Folęga 2019). The latest data extracted from the e-bus counter of the Polish Chamber of Electromobility Development show that 707 electric buses are currently in operation in Polish cities. The Polish Chamber of Electromobility Development projects that, between 2022 and 2024, there will be more than 1350 electric buses on Polish roads (Transport Publiczny 2025).

Electromobility has also been developing intensively in Czechia. The Czech government has also adopted the European initiatives for clean mobility. In November 2015, it approved the *National Action Plan for Clean Mobility* to support e-mobility in Czechia (MPO 2014, 2024; Euroenergy 2021). The problem of clean mobility is addressed in all the fundamental strategic materials of the Czech government pertaining to the spheres of energy, transport, and environment. One of the state's sub-priority directly linked with clean mobility include increase in the use of alternative fuels – electromobility (MPO 2014, 2024; Euroenergy 2021). Based on data available on the website of the Transport Research Centre (CDZ 2025), 144 electric buses are registered in Czechia. The highest increase in the registration rates of electric buses occurred in 2017, 2018, and 2022. It was then that 22 (2017), 50 (2018), and 40 (2022) BEV buses were registered, respectively. Most electric buses (35%) are operated in the Moravian–Silesian region, which is the Czech–Polish border region and the most industrial part of Czechia with steel mills and coal mines still in operation. The development of electromobility in this region is supported by efforts to improve the environment and reduce air emissions. Compared to other alternative fuel buses, including the 144 BEV buses currently in service, there are 1777 vehicles running on CNG and 2 on LNG (CDZ 2025). The optimistic scenario for the development of electromobility in Czechia assumes that 2672 BEV buses will have been registered by 2045 (MPO 2014, 2024; Euroenergy 2021).

4. Goal and scope of analysis

The in-house studies conducted by the authors involved application of the LCA analysis specifically dedicated to vehicles, i.e., the WTW method, to assess the potential environmental impact of electric bus battery charging. 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 CHG gas emissions. The WTW method, developed by the Joint Research Centre and endorsed by the EU, is recommended for the analyses of GHG emissions from the transport sector (Hass *et al.* 2014).

The WTW analysis can be basically broken down into 2 phases: WTT, where the environmental impact associated with fuel production, transportation, and storage is studied, and TTW, where the environmental impact associated with the vehicle's fuel combustion is taken into consideration. In this respect, it should be noted that, from the perspective of the WTW analysis, EVs do not emit pollutants in their use phase, since they are assumed to be carbon neutral. When studying the energy consumption and CHG emissions attributable to an EV, one should mainly focus on the WTT phase, which, in this particular case, means the GHG emissions related to electricity production (Ercan, Tatari 2015), which is precisely the kind of analyses discussed in this study.

The purpose of the study addressed in this article was to perform an environmental WTW analysis for the city buses used in Poland and Czechia.

The WTW analysis was conducted in accordance with the ISO 14040:2006 and ISO 14044:2006 standards, and using the *SimaPro v.9* software (*https://support.simapro.com/s/article/What-s-new-in-SimaPro-9-0*) with the *Ecoinvent v.3* database (*https://support.ecoinvent.org/ecoinvent-version-3.0*). The *SimaPro v.9* is software that is used to analyse the life cycle of various products and processes. The analyses used the *Ecoinvent v.3* database, which enabled a detailed analysis of the electricity life cycle

In this study the CHG emissions were analysed for electricity. We focus on the WTT phase which, in this particular case of electric buses, means the GHG emissions related to electricity production and energy use in relation to a unit of consumption in the electric bus per 100 km

Following the guidelines of ISO 14040:2006, the goal and scope of the study, including the FU applied, the system boundary, and the basic analytical assumptions were defined (phase I). The phase II consisted in analysing the input and output datasets, i.e., the LCI, comprising a list of all data items required for the WTW analysis. Phase III was the 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 IV was the interpretation of the results thus obtained.

The study included an analysis of the structure of electrical energy generation in Poland and Czechia, both at present (i.e., in 2020) and in the future (in 2030 and 2050), as well as an assessment of the impact of the energy mix structure in the power grid on the CHG emission index. Energy production is heavily diversified across Europe in terms of the energy sources in use, which translates into a wide variety of impacts these sources exert on environmental indicators. The studies addressed in this article focused on the environmental impact of the production of electricity for charging of electric bus batteries in 2 countries. The main sources of electricity production in the countries in question were also identified. For comparative purposes, the FU was defined as 100 km. The system boundaries comprised the electricity production in Poland and Czechia as well as the electric bus battery charging while the buses were in service. Such an approach is commonly referred to as cradle-to-gate.

5. Assumptions and method

The literature reviews conducted to date have implied that, with regard to EVs, electricity constitutes the main determinant of the impact on GHG emissions (Ercan, Tatari 2015). For the purposes of this study, it was assumed that the bus subject to analysis was powered entirely by rechargeable batteries. Assuming that the vehicle operation does not cause any harmful atmospheric emissions, its environmental impact was established solely on account of the energy consumption related to battery charging. The charging process relies on the public power grid, and consequently, the environmental impact of the electric bus is affected by how the electricity consumed to charge the bus batteries is generated. The object of the study addressed in this article was a 12 m bus. This choice was due to the fact that 12 m vehicles represent the most common bus type in operation across the EU. The relevant technical data of the bus subject to the analyses performed under this study have been provided in Table 1. The energy consumption of an electric bus depends on many factors and various driving conditions. For purposes of this study, it was assumed that the bus consumed an average of 175 kW·h / 100 km of distance covered. The overall energy consumption value of up to 175 kW·h / 100 km was adopted with reference to the literature review for 12 m electric buses in use under real-life operating conditions, with passengers on-board and additional systems, such as air conditioning, active (Zhou *et al.* 2016). The study comprised an analysis of the current and projected structure of electrical energy sources as well as an environmental analysis taking CHG emissions into account. For the sake of comparison, all the analyses referred to the same FU of 100 km.

Table 1. Technical data of the bus assumed for the analyses (Solaris Bus 2025)

Parameter	Technical data
Model	12 Electric
Length	12 m
Total passenger capacity	70
Number of seats	25
Batteries	200 kW·h, lithium-ion
Charging system	plug-in
Operating range	300 km
Electricity consumption for battery charging	175 kW·h / 100 km

The main source of data used for the analyses concerning the current and projected structure of electrical energy production in Poland and Czechia was the documentation released by the EC. The data concerning the energy systems used for charging of the electric bus batteries were processed with reference to country-specific data (Capros *et al.* 2016). The electricity production structure of a given power grid is one of the most important parameters taken into account when analysing EVs. Therefore, it was assumed that the most important factor determining the environmental impact of electric buses was the structure of generation of the electrical energy consumed when charging their batteries. Based on the available data (Capros *et al.* 2016; European Data 2025), the 2020 status and the projections for 2030 and 2050 were analysed.

The environmental impact analyses were conducted by considering the assessment of the CHG emissions associated with the life cycle of electrical energy, meaning that all data concerning the electricity production in the respective countries subject to analysis were taken into account. Both the basic assumptions and the set of input and output energy production data were extracted from the *Ecoinvent v.3* databases.

The WTW–GHG environmental life cycle assessment was performed using the LCIA method, designed and released by the Intergovernmental Panel on Climate Change (IPCC 2014). The application of the IPCC's method made it possible to calculate the CHG emission factor based on the GWP benchmark, which represents the radiative forcing of CHGs released into the environment, converted into kilograms of carbon dioxide equivalent. The IPCC addresses various climate change factors in a timeframe of 100 years. Total CHG emission is a component of the bus's CF.

6. Results and discussion

6.1. Assessment of energy generation sources

The GHG emission related to the bus operation is predominantly attributable to battery charging, and that mainly depends on a given country's energy mix. Electrical energy can be obtained from diverse sources, such as coal, crude oil, gas, nuclear power, biomass, hydropower, wind power, and solar power. The last 3 of the aforementioned sources are considered to be renewable, and as such they are preferable in terms of their share in the energy mixes of the EU countries. For the purposes of the environmental WTW analysis of electric buses, a detailed life cycle assessment of the Polish and Czech energy systems was performed. Table 2 specifies the percentage share of individual energy sources used for electricity production in 2020–2050.

Having analysed the structure of the electrical energy production in the EU, the authors identified a significant decline in the share of coal (both hard coal and lignite) as well as a moderate decrease in the share of nuclear power.

In 2020, the coal fraction in the energy mix was 80% in Poland and 53% in Czechia. In subsequent years, coal's share in the energy mix will continue to fall. In 2030, it will account for 65% in Poland and 45% in Czechia. The share of nuclear energy is expected to increase in some EU countries, including Czechia (54%), while the share of coal will decrease significantly, but will still remain a part of the energy mix in Poland (26%) and Czechia (18%). Following an analysis of the projections for the development of the power industry in the years to come, it was concluded that energy based on fossil fuels would be gradually replaced by renewable sources. Another important fact to note is that, in the countries without nuclear power plants, such as Poland, it is precisely the nuclear power plants that are considered to be the best and fastest alternative, allowing the fraction of coal in the energy mix to be reduced. The related changes will involve further development of RES-based power systems, mainly wind power plants, along with the growth of the nuclear power sector.

6.2. Environmental assessment of electric bus battery charging – the model used to calculate CHG emissions over the life cycle of electric bus charging

Under the study addressed in this article, a model was developed to assess the GHG emission indicators for the life cycle of the electrical energy consumed for electric bus battery charging. The GHG emissions were analysed

Table 2. Percentage [%] share of energy sources in electrical energy production (source: own elaboration of the authors)

	Nuclear power	Coal	Crude oil	Gas	Biomass	Hydro power	Wind power	Solar power
2020								
Czechia	35	53	0	5	1	3	1	3
Poland	0	80	0	5	6	1	6	0
EU	23	23	1	17	6	11	14	5
2030								
Czechia	32	45	0	12	4	3	1	3
Poland	0	65	0	15	8	1	11	0
EU	22	16	1	19	8	11	17	7
2050								
Czechia	54	18	0	12	8	4	2	3
Poland	28	26	0	17	8	2	18	0
EU	18	6	0	21	10	10	24	11

against individual sources of electricity by taking the power grid projections into account, i.e., the expected changes in the energy mix of Poland and Czechia. For purposes of the study, 8 major energy sources used for electrical energy production were considered. 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* software. The LCA analysis of the production from the electricity sources in question was conducted in line with the ISO 14000 series standards (ISO 14040:2006; ISO 14044:2006). The results of the analysis have been provided in Figure 2.

Following the analyses of the percentage share of individual energy sources used for electricity production and of the GHG emissions for each of these sources, the study involved the WTW analysis of electric buses. In order to calculate the GHG emissions attributable to an electric bus on the WTW basis, a WTW emission model was developed

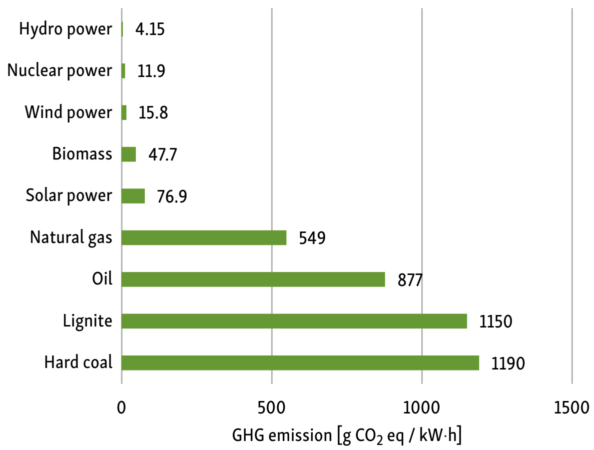

Figure 2. GHG emission analysis for individual sources of electrical energy (source: own elaboration of the authors)

for electric buses (see Equation). The data required for the GHG emission calculations to be conducted for the electric bus (the results expressed in g CO_2 eq / 100 km) were as follows: percentage share of individual energy sources, GHG emission from each source, and energy consumption for bus battery charging per 100 km.

$$WTW_{EB} = \left(GHG_{ES\,1-8} \cdot S_{ES\,1-8}\right) \cdot E_{EB},$$

where: WTW_{EB} – GHG emissions attributable to the electric bus [g CO_2 eq / 100 km]; GHG_{ES1-8} – GHG emissions from the generation of 1 kW·h of energy from individual sources [g CO_2 eq / kW·h] (values calculated as part of the study); S_{ES1-8} – percentage share of the energy source (where: *S* – share; *ES* – energy sources) in the energy mix of the given country; E_{EB} – electricity consumption for bus battery charging [kW·h / 100 km] (the energy consumption by the electric bus was assumed to equal 175 kW·h / 100 km).

Based on the WTW_{EB} model developed by the authors (Relation 1) and with reference to the GHG emissions calculated for individual energy sources (GHG_{ES1-8}), the GHG emissions were analysed specifically for bus battery charging in Poland and Czechia. The study also comprised an analysis of the electrical energy structure in the Polish and Czech power grids, both now and in the future.

6.3. Analysis of GHG emissions for electric buses and

The WTW model developed by the authors made it possible to analyse GHG emissions throughout the life cycle of the fuel of the electric buses used in Poland and Czechia by taking into account each country's energy mix against electricity production. The results obtained for the present state (2020) and the projections for 2030 and 2050 have been illustrated in Figure 3.

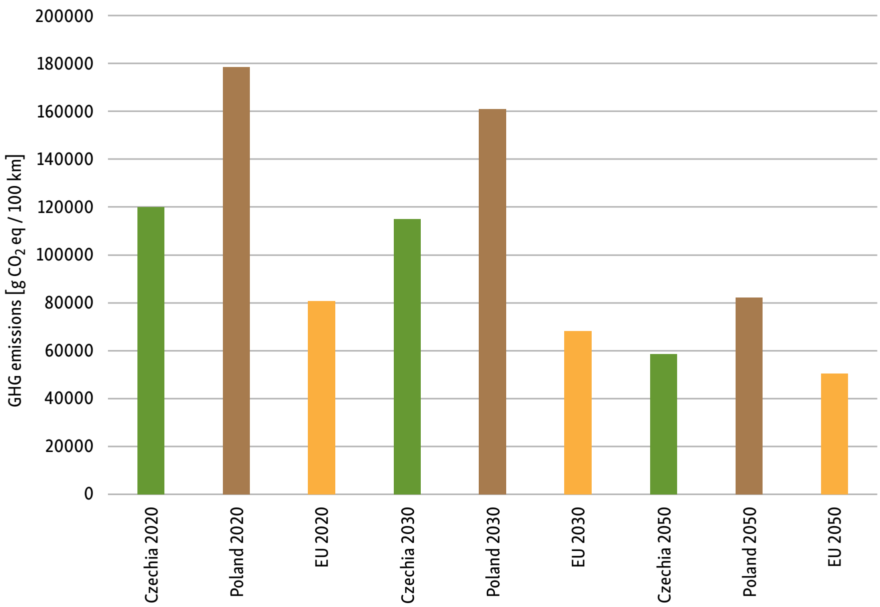

Figure 3. GHG emissions from an electric bus, calculated in the WTW cycle (source: own elaboration of the authors)

The conclusion, which can be drawn having analysed the data provided in Figure 3 is that, in each successive year of the analysis, the GHG emissions attributable to electric buses are higher in Poland than in Czechia. In the first year of the analysis, i.e., 2020, the GHG emissions in Poland came to 178405 g CO_2 eq / 100 km, while they amounted to 120040 g CO_2 eq / 100 km in Czechia. The environmental indicators of electric buses established for Poland and Czechia are higher than those of all EU countries, whose average 2020 GHG emission index for electric buses was 80785 g CO_2 eq / 100 km. This is due to the higher share of the energy sources with a negative environmental impact in the power grids of both Poland and Czechia. In the subsequent years of the analysis, the GHG emissions are expected to drop in Poland and Czechia, which is primarily related to the reduced share of fossil fuels and the increased share of both nuclear energy and RES. The next step in the analysis consisted in calculating the GHG emissions for individual electrical energy sources by taking into account their fractions in the energy mix of the given country. The relevant results have been provided in Tables 3 through 5.

Based on the previous analyses, it was proved that CHG emissions from the electrical energy production for the Polish power grid are much higher than in Czechia. The foregoing is due to the share of the coal-based power generation in Poland considerably exceeding that of Czechia. It should also be noted that, although there are plans to significantly increase the share of nuclear power in Czechia, this exerts no adverse effect on the GHG emissions from power generation. The analysis also evidenced a steady decline in the GHG emissions in successive years in both Poland and Czechia. The data provided in Tables 3–5 imply that the largest impact on GHG emissions is attributable to the use of coal (both hard coal and lignite) and natural gas in the production of electrical energy. Despite the increase in the RES share, these sources have no impact on GHG emissions (the impact of RES on GHG emission is negligible). Furthermore, in spite of the large fraction of nuclear power in the electrical energy mix, this has no impact on GHG emissions. The GHG emission rates in Poland, where power generation used to rely predominantly on coal-fired power plants, are projected to drop significantly in 2050. By that time, nuclear power plants are expected to have been commissioned in Poland, and further development of the wind power sector is also expected.

The study addressed in the article additionally included a comparative analysis of the GHG emissions generated by electric city buses and by a conventionally powered bus featuring a diesel engine.

In the case of the internal combustion engine bus from the study (Pielecha *et al.* 2016), the subject of that study was a city bus equipped with a conventional drive, characterized by the following parameters:

- 12 m diesel engine bus;
- internal combustion engine meeting the EURO 5 exhaust emission standard;

Table 3. GHG emissions calculated for individual energy sources, considering the percentage share of a given source in the energy mix of a given country in 2020 [g CO_2 eq / 100 km] (source: own elaboration of the authors)

2020	Nuclear power	Coal	Crude oil	Gas	Biomass	Hydropower	Wind power	Solar power	WTW GHG
Czechia	726	111067	0	6,561	130	1115	30	413	120041
Poland	0	169118	0	7982	613	481	205	5	178406
EU	483	48227	1216	25225	600	3915	434	686	80785

Table 4. GHG emissions calculated for individual energy sources, considering the percentage share of a given source in the energy mix of a given country. Projection for the year 2030 [g CO_2 eq / 100 km] (source: own elaboration of the authors)

2030	Nuclear power	Coal	Crude oil	Gas	Biomass	Hydropower	Wind power	Solar power	WTW GHG
Czechia	676	95328	0	17077	404	1045	32	396	114958
Poland	0	137200	434	21679	739	476	336	7	160871
EU	464	33668	1026	27066	760	3761	543	978	68264

Table 5. GHG emissions calculated for individual energy sources, considering the percentage share of a given source in the energy mix of a given country. Projection for the year 2050 [g CO_2 eq / 100 km] (source: own elaboration of the authors)

2050	Nuclear power	Coal	Crude oil	Gas	Biomass	Hydropower	Wind power	Solar power	WTW GHG
Czechia	1138	37693	0	17175	716	1351	56	439	58567
Poland	593	54677	222	24782	803	628	578	19	82303
EU	380	13064	222	29972	910	3626	760	1568	50505

- exhaust gas treatment system with a particulate filter installed;
- vehicle with a mileage of approximately 200000 km.

Exhaust emissions and fuel consumption tests included tests of exhaust emissions and fuel consumption of the vehicle in its operating condition, without any intervention in the vehicle.

Pollutant emissions and fuel consumption were measured in urban traffic conditions in a selected city in Poland.

The conclusions from the tests carried out in real road traffic conditions were as follows:

- mileage fuel consumption: 35.98 dm^3 / 100 km;
- road carbon dioxide emissions: 954 g/km.

As indicated in the literature on the subject, the GHG emission from a 12 m diesel engine bus approximately comes to 954 g CO_2 eq / 100 km (Pielecha *et al.* 2016). With reference to the results of the analysis, where the GHG emission value pre-assumed for a conventionally-powered bus with a diesel engine of the EURO 5 emission class and the GHG emission values established for the electric city buses used in Poland and Czechia were taken into account, it has been determined that, both for the year 2020 and in the 2030 projection, the GHG emissions from electric buses are higher compared to the bus featuring an internal combustion engine. Not until the year 2050 are the GHG emissions calculated for the electric bus expected to be lower than those of the internal combustion engine bus, which can be attributed to the high contribution of nuclear power and RES to the power system used for charging the electric bus batteries in both Poland and Czechia.

7. Conclusions

The purpose of the analyses and calculations conducted under the study discussed in the article was to assess the environmental impact of electric bus charging on GHG emission. The analyses were based on the IPCC's method, while their scope covered the life cycle of the alternative fuel used in buses. The study also comprised a review of the legal requirements applicable in Poland and Czechia, relevant to the development of alternative electric powertrain systems. On account of the progressing depletion of crude oil deposits, various alternative propulsion solutions are sought for road transport. The one, which has been gaining the utmost popularity is electric powertrain. The most dynamic development of this drive system can be observed in the urban bus transport sector. The incentives proposed by the EC have been making a significant contribution in terms of improving the environmental performance of transport across the EU and the development of alternative power sources used in road transport, but there are also solutions intended to discourage investing in conventional drives.

This article discusses the results of an analysis of CHG emissions by application of the WTW method. The research part was mainly focused on analysing the energy mix involved in the production of the electricity used to charge the batteries of electric buses. Not only was the current state of matters analysed, but also prospects reaching as far as to the year 2050 were made in an attempt to determine the CHG emissions generated in the operation of electric buses in Poland and Czechia. The results thus obtained have highlighted the great importance of the type of the energy sources used for electricity generation in the respective countries.

With reference to these analyses, it has been established that, in Czechia, where the power industry is becoming increasingly based on nuclear energy, battery charging in electric city buses is characterised by lower CHG emission rates than in Poland.

The comparative CHG emission analyses conducted by the authors by taking the present state of matters into consideration have shown that using an electric bus is currently more harmful to the environment than using a conventional bus featuring an internal combustion engine. The foregoing is due to the fact that the energy supplied to the battery charging process comes from a power grid whose main energy source is coal. On the other hand, however, the progressing shift from internal combustion vehicle engine fleets to electric ones is expected to yield significant environmental benefits in the future. The 2050 projection shows that, compared to internal combustion engine buses, the operation of electric buses will exert a much smaller negative environmental impact related to CHG emissions. Following the analysis, it has also been concluded that maintaining a high share of nuclear energy and RES in the energy mix used for electric bus battery charging in Poland and Czechia is expected to reduce the CHG emission rates of electric buses compared to those powered by an internal combustion engine.

The analyses performed by the authors have provided new knowledge, which can be utilised under further research on the development of electromobility in the sector of city buses and on the environmental impact of alternative fuels, such as electrical energy. The changes to the energy sector observed in the countries subject to analysis imply that electric city buses will become the future of sustainable public transport

Further research will seek to study various aspects of the sustainable development of transport, including integrated environmental, economic, and social analyses of public transport systems.

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Author contributions

Piotr Folęga was responsible for the concept and development of the results of the bus life cycle analysis.

Simona Jursová and *Dorota Burchart* were responsible for data collection, life cycle analysis, and drawing conclusions.

Pavlína Pustejovská was responsible for data interpretation and article editing.

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Authors declare that they have no competing financial, professional, or personal interests from other parties that might have influenced the performance or presentation of the work described in this manuscript.

References

Borucka, A.; Załęski, Ł. 2017. Car-pooling w aspekcie zrównoważonego rozwoju transportu, *Gospodarka materiałowa i logistyka* 5: 51–64. (in Polish).

Burchart-Korol, D.; Folęga, P. 2019. Impact of road transport means on climate change and human health in Poland, *Promet – Traffic & Transportation* 31(2): 195–204. https://doi.org/10.7307/ptt.v31i2.3074

Capros, P.; De Vita, A.; Tasios, N.; Siskos, P.; Kannavou, M.; Petropoulos, A.; Evangelopoulou, S.; Zampara, M.; Papadopoulos, D.; Nakos, Ch.; Paroussos, L.; Fragiadakis, K.; Tsani, S.; Karkatsoulis, P.; Fragkos, P.; Kouvaritakis, N.; Höglund-Isaksson, L.; Winiwarter, W.; Purohit, P.; Gomez-Sanabria, A.; Frank, S.; Forsell, N.; Gusti, M.; Havlík, P.; Obersteiner, M.; Witzke, H. P.; Kesting, M. 2016. *EU Reference Scenario 2016 – Energy, Transport and GHG Emissions – Trends to 2050*. Luxembourg: Publications Office of the European Union. 220 p. https://doi.org/10.2833/001137

CDZ. 2025. *Registrace nových autobusů v EU*. Centrum dopravního výzkumu (CDV), Brno, Česká republika. Available from Internet: https://www.cistadoprava.cz/registrace-novych-autobusu-v-eu/ (in Czech).

Dyr, T.; Abramowicz, A. 2016. Projekt eBus jako instrument rozwoju transportu publicznego, *Autobusy: technika, eksploatacja, systemy transportowe* 17(7–8): 22–25. (in Polish).

EC. 2009. *Directive 2009/33/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of Clean and Energy-Efficient Road Transport Vehicles*. 8 p. Available from Internet: http://data.europa.eu/eli/dir/2009/33/oj

EC. 2011. *White Paper: Roadmap to a Single European Transport Area – Towards a Competitive and Resource Efficient Transport System*. COM(2011) 144 final. 28.3.2011, European Commission (EC) Brussels, Belgium. 31 p. Available from Internet: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52011DC0144

Ellingsen, L. A.-W.; Thorne, R. J.; Wind, J.; Figenbaum, E.; Romare, M.; Nordelöf, A. 2022. Life cycle assessment of battery electric buses, *Transportation Research Part D: Transport and Environment* 112: 103498. https://doi.org/10.1016/j.trd.2022.103498

Ercan, T.; Tatari, O. 2015. A hybrid life cycle assessment of public transportation buses with alternative fuel options, *The International Journal of Life Cycle Assessment* 20(9): 1213–1231. https://doi.org/10.1007/s11367-015-0927-2

Euroenergy. 2021. *Aktualizace predikce vývoje elektromobility v ČR do roku 2045: pracovní tým ZL 17 aktualizovaného NAP SG*. Euroenergy, spol. s r. o., Praha, Česká republika. 99 s. Available from Internet: https://mpo.gov.cz/assets/cz/energetika/strategicke-a-koncepcni-dokumenty/narodni-akcni-plan-pro-chytre-site/2022/2/Elektromobilita_predikce-do-2045.pdf (in Czech).

European Data. 2025. *Emisje gazów cieplarnianych na mieszkańca*. Oficjalny portal europejskich danych. Available from Internet: https://data.europa.eu/data/datasets/rc2elcdetgfxdpe27gyzow?locale=pl (in Polish).

Folęga, P.; Burchart, D.; Marzec, P.; Jursova, S.; Pustejovska, P. 2022. Potential environmental life cycle impacts of fuel cell electric vehicles powered by hydrogen produced from Polish coke oven gas, *Transport Problems* 17(1): 151–161. https://doi.org/10.20858/tp.2022.17.1.13

Hass, H.; Huss, A.; Maas, H. 2014. *Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context*. Tank-to-Wheels Report (TTW). Version 4a. European Commission, Joint Research Centre, Institute for Energy and Transport. 62 p. https://doi.org/10.2790/95839

IPCC. 2014. *AR5 Synthesis Report: Climate Change 2014*. Intergovernmental Panel on Climate Change (IPCC). Available from Internet: https://www.ipcc.ch/report/ar5/syr/

ISO 14040:2006. *Environmental Management – Life Cycle Assessment – Principles and Framework*.

ISO 14044:2006. *Environmental Management – Life Cycle Assessment – Requirements and Guidelines*.

Krawiec, K. 2014. Alternatywne napędy autobusów w publicznym transporcie zbiorowym, *Logistyka* 4: 2040–2049. (in Polish).

KS. 2018. *Ustawa z dnia 11 stycznia 2018 r. o elektromobilności i paliwach alternatywnych*. Kancelaria Sejmu (KS), Warszawa, Polska. Available from Internet: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20180000317 (in Polish).

Kupczyk, A.; Mączyńska, J.; Sikora, M.; Gawron, J.; Tucki, K. 2017. Stan obecny i przyszłość biopaliw wykorzystywanych w transporcie państw członkowskich w świetle regulacji prawnych UE, *Gospodarka materiałowa i logistyka* 10: 16–22. (in Polish).

ME. 2017. *Plan rozwoju elektromobilności w Polsce: Energia do przyszłości*. Ministerstwo energii (ME), Warszawa, Polska. 40 s. (in Polish).

MPO. 2024. *Clean and Sustainable Transport. Government Approves the Update to the National Action Plan for Clean Mobility*. Ministerstvo průmyslu a obchodu (MPO), Praha, Česká republika. Available from Internet: https://mpo.gov.cz/en/guidepost/for-the-media/press-releases/clean-and-sustainable-transport--government-approves-the-update-to-the-national-action-plan-for-clean-mobility---282798/

MPO. 2014. *Státní energetická koncepce České republiky*. Ministerstvo průmyslu a obchodu (MPO), Praha, Česká republika. 145 s. Available from Internet: https://mpo.gov.cz/assets/cz/energetika/statni-energeticka-politika/2016/12/Statni-energeticka-koncepce-_2015_.pdf (in Czech).

NFOŚGW. 2023. *Elektromobilność*. Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej (NFOŚGW), Warszawa, Polska. Available from Internet: https://www.gov.pl/web/elektromobilnosc (in Polish).

Nordelöf, A.; Romare, M.; Tivander, J. 2019. Life cycle assessment of city buses powered by electricity, hydrogenated vegetable oil or diesel, *Transportation Research Part D: Transport and Environment* 75: 211–222 https://doi.org/10.1016/j.trd.2019.08.019

Pielecha, J.; Magdziak, A.; Markowski, J.; Jasiński, R. 2016. Ekologiczna ocena eksploatacyjna autobusów miejskich z zastosowaniem wybranych stabilizatorów do paliw, *Autobusy: technika, eksploatacja, systemy transportowe* 17(12): 1289–1296. (in Polish).

Solaris Bus. 2025. *Urbino Electric*. Solaris Bus & Coach sp. z o.o., Owińska, Polska. Available from Internet: https://www.solaris-bus.com/pl/pojazdy/napedy-zeroemisyjne/grupa-urbino-electric (in Polish).

Szumska, E.; Sentek-Matysiak, E.; Pawełczyk, M. 2018. Porównanie kosztów cyklu życia autobusów miejskich z napędami konwencjonalnym i alternatywnymi, *Prace Naukowe Politechniki Warszawskiej*. *Transport* 120: 395–404. (in Polish).

Thorne, R. J.; Hovi, I. B.; Figenbaum, E.; Pinchasik, D. R.; Amundsen, A. H.; Hagman, R. 2021. Facilitating adoption of electric buses through policy: learnings from a trial in Norway, *Energy Policy* 155: 112310.
https://doi.org/10.1016/j.enpol.2021.112310

Transport Publiczny. 2025. *Ponad 700 elektrycznych autobusów w Polsce*. Available from Internet: https://www.transport-publiczny.pl/wiadomosci/ponad-700-elektrycznych-autobusow-w-polsce-73582.html (in Polish).

Walendzik, M.; Łepkowski, M.; Nowacki, G. 2016. Wpływ transportu drogowego na środowisko naturalne człowieka i zagrożenia występujące w transporcie drogowym rzeczy, *Autobusy*: *technika*, *eksploatacja*, *systemy transportowe* 17(6): 459–464. (in Polish).

Zhou, Bo.; Wu, Y.; Zhou, Bi.; Wang, R.; Ke, W.; Zhang, S.; Hao, J. 2016. Real-world performance of battery electric buses and their life-cycle benefits with respect to energy consumption and carbon dioxide emissions, *Energy* 96: 603–613.
https://doi.org/10.1016/j.energy.2015.12.041