DOI 10.18.276/978-83-8419-053-1-37

28th European Conference on Artificial Intelligence (ECAI 2025)

STUDY OF EMISSIONS, ENERGY CONSUMPTION, AND OPERATING COSTS OF CITY BUS FLEET: EXPLORING THE ROLE OF AI AND TECHNOLOGICAL SOLUTIONS IN SUSTAINABLE URBAN TRANSIT.

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ABSTRACT

Purpose: *The purpose of this article is to conduct a comparative analysis of city buses included in the public transport fleet in Szczecin, with a focus on evaluating the economic and ecological performance of conventional, hybrid, and electric vehicles.*

Need for the study: *With growing environmental concerns and the increasing need for cost-effective urban mobility solutions, there is a strong demand to identify the most sustainable and economically viable types of buses for public transport systems. This study addresses this need by assessing actual operating data across different vehicle technologies.*

Methodology: *The analysis conducted in the article covers energy consumption and associated costs (fuel or electricity, depending on the vehicle type) for each month over the span of one year. The data accounts for seasonal variations in energy demand, driven by the use of additional vehicle systems such as heating and air conditioning. The study also includes a brief theoretical consideration of how artificial intelligence systems could enhance operational efficiency of city buses.*

Findings: *Electric buses demonstrated the most favorable outcomes from both ecological and economic perspectives, while conventional diesel buses showed the least advantageous performance. Hybrid vehicles ranked between the two. The study also identified specific operational areas where the integration of AI technologies could further optimize efficiency and reduce costs.*

Practical Implications: *The results offer valuable insights for municipal decision-makers and transport operators considering the transition to more sustainable fleets. Moreover, the potential of AI-based systems to support operational improvements highlights a possible strategic direction for future development in urban public transport.*

Keywords: Urban logistics; City buses; Energy consumption; Transport; AI; Sustainable development

Jel codes: L320; L910; Q550; R400

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1. INTRODUCTION

Social costs of transportation in the form of pollution (Grazieschi et al., 2023) or noise (Muralikrishna and Manickam, 2017) are increasingly being considered on a par with internal costs such as fuel consumption (Persyn et al., 2022). This is encouraged, among other things, by the EU's transport policy ("Clean and sustainable mobility," 2023) which is based on the assumption of achieving climate neutrality by the Member States. The most important document speaking on this matter is the European Green Deal presented by the European Commission in December 2019 (Communication From The Commission to The European Parliament, The European Council: European Economic and Social Committee and The Committee of The Regions - The European Green Deal, 2019), which sets the year 2050 as the date for achieving climate neutrality in Europe. At the same time, it assumes a net reduction in greenhouse gas emissions of at least 55% compared to 1990 by 2030. According to Eurostat data ("Statistics | Eurostat," n.d.), in the period 2010 to 2023, cumulative greenhouse gas emissions [Greenhouse gases (CO2, N2O in CO2 equivalent, CH4 in CO2 equivalent, HFC in CO2 equivalent, PFC in CO2 equivalent, SF6 in CO2 equivalent, NF3 in CO2 equivalent)] by the transport sector (category: Transportation and storage) fell by only ≈0.06% from 2010 to 2023. Despite the fact that transport in the first quarter of 2023 accounted for only ≈10% of total European greenhouse gas emissions, it is the only sector of the economy where progress in reduction is so insignificant. The above obliges to carry out intensifying actions aimed at reducing emissions in the transport sector, otherwise, with maintaining the current trend, it will not be possible to achieve the goals of the climate policy adopted by the EU. According to Eurostat data ("Statistics | Eurostat," n.d.), in 2010, Poland was responsible for approximately 10% of air pollutants and greenhouse gases (expressed as CO2 equivalent) of the total value for 27 EU member states. By 2021, Poland's percentage share in this category had already risen to 12%. It should be mentioned here that the above may be the result of many things, such as the fact that Polish transport companies are responsible (as of 2022) for approximately 26% of the total intra-EU road freight transport (255,798 thousand tons of goods compared to a total of 976,436 thousand tons of goods for 27 EU member states) ("Statistics | Eurostat," n.d.). However, the role of Polish transport companies in reducing total EU emissions is indisputable. Taking this into account, it was decided to conduct research and analysis on the example of this country.

One of the basic actions taken to achieve climate neutrality is to eliminate the acquisition of energy from non-renewable sources (like mining) in favor of renewable energy sources such as wind or solar energy. Two sectors of the economy seem to be the most important in this respect, namely: energy production and transport (McPherson et al., 2023; Upham et al., 2023; Zhang et al., 2024). In 2020, road transport was responsible for 78.4% of global CO2 emissions (Santos and Smith, 2023). Therefore, during the conducted research, it was decided to focus on this branch of transport. At the same time, due to the possibility of applying the conducted research and analysis in practice, it was decided to narrow the field of research to urban passenger transport and the replacement of current means of transport with electric vehicles. Electric buses are becoming an increasingly large percentage of the urban public transportation fleet in many cities. Based on the state of urban transportation in Poland, a drastic change in their quantity can be observed among the bus fleets of transport companies. In 2016, among newly purchased buses, those with electric drive accounted for 1%, while in 2021: 37% of newly purchased vehicles (Jagiełło et al., 2023), which emphasizes how significant electric buses have become in recent years. Given the sustainable development goals promoted by the European Union and the economic and ecological factors (Souza and Dantas, 2020), it can be stated that the number of electric buses used in public urban transportation will increase year by year. When conducting research and analysis on changes in the transport fleet, the differences between corresponding technological solutions are a necessary and often overlooked issue. Examples of such differences are presented in the next section and are included in the final summary and conclusions. A large part of the available publications (Dębowski et al., 2021; Sparber et al., 2023; Teoh et al., 2018) focuses on the transfer of telemetry and costs for individual specific cases of replacing conventional transport solutions with a modern electric vehicle in order to possibly further extrapolate the obtained data. This approach has the advantage of being able to focus on many elements related to one specific case, but the disadvantage is the method of extrapolating the results that does not take into account variables resulting from the operation of the entire fleet of vehicles (in particular, the accumulation of problems assuming a domino effect). It was therefore decided not to focus on an extensive description of one case, but rather to specify and average the authentic results of the entire fleet of vehicles in terms of energy demand and the resulting average operating cost and its change depending on the influence of the seasons. Such results can be used for a comparative assessment of the results obtained thanks to extrapolation models. After obtaining the final values and conducting field research, it was also possible to indicate areas of the company's and transport fleet's operation where the use of artificial intelligence-based solutions would increase the efficiency of the entire transport system.

2. LITERATURE REVIEW

For the purposes of the classic basic literature review, the Scopus database was used to select relevant publications. The basic keyword was "bus" in combination with "electric", then the search was limited to the keywords: "buses", "costs", "electric bus", "bus systems", "energy efficiency", "hybrid vehicles" and "electric power utilization". After defining the basic search, 10,666 results were obtained. The search was then narrowed by limiting the results to: Article, Conference paper and final version in English, which reduced the results to 9,557. It was limited to articles from 2020 (3,543 results), then the subject area was limited to: "Energy", "Environmental Science", "Social Sciences", "Business, Management and Accounting", "Economics, Econometrics and Finance" and "Multidisciplinary" (2,176 results). At the above stage, the articles were assessed. First, after evaluating the titles and keywords, 2094 items were eliminated, then the abstracts were analyzed, which led to the elimination of another 44 papers and leaving 38 for analysis of the possibility of accessing the content and reviewing the full texts. Finally, 18 papers were selected for the literature review presented in Table 1.

Table 1. Literature review of electric bus exploitation costs in current studies

No.	References	Approach	Description	Average Cost per km
1	(McCluskey et al., 2025)	Model, Literature review	The article examines the economic aspects of introducing electric buses in the UK. The authors point out that the total cost of electric buses is generally similar to diesel buses. An important argument in the discussion is the size of the batteries, which are often smaller than would be justified, due to the lower cost of the initial purchase.	EV - £1.739 Diesel - £1.744
2	(Moradi et al., 2024)	Model	The article presents a study on the optimization of charging infrastructure and strategies for an electrified public transport system. Dynamic programming (DP) was used to optimize costs, battery degradation and system efficiency. In addition to standard elements (such as route length, number of trips, etc.), the model used assumes, among others, battery wear and the forecasted number of years of operation of the vehicle charging infrastructure. The obtained result shows that with good optimization, the possible reduction of the total cost is 35%.	n.d.
3	(Wagner and Walther, 2024)	Model, Case Study	The analysis was carried out on the example of a bus network in Northern Italy with a diverse terrain (urban/rural and mountain routes). The authors indicate that the combination of BEB and FCEB bus technologies in mixed fleets can meet various operational needs. The above combination will be most profitable when the purchase cost of FCEB buses drops below 625 thousand euros. Or the price of hydrogen drops below 4.33 euros/kg.	n.d.

No.	References	Approach	Description	Average Cost per km
4	(Chamier-Gliszczynski et al., 2024)	Literature review, Mathematical analysis, Case Study	The article focuses on the process of changing from conventional city bus technologies to more advanced technological solutions in order to reduce pollutant and noise emissions generated by public transport. The paradigm shift assumes replacing combustion buses with electric, hydrogen or trolleybuses. An analysis of the costs associated with fleet replacement and infrastructure construction was conducted.	n.d.
5	(Batóg et al., 2024)	Literature review, Mathematical analysis	The article discusses the electrification of public urban transport in Poland, focusing on financing options, forecasts for the electric bus fleet and demand for electricity. The authors indicate low efficiency of the batteries used, lack of charging infrastructure and high energy demand as significant barriers in the above process.	n.d.
6	(Avenali et al., 2024)	Model, Real Options analysis	The article describes an analysis based mainly on the Real Options method to support decision-making on replacing bus fleets with more ecological technologies. The authors show that the costs per mile using their method taking into account uncertainties in the case of electric buses (BEB) can be lower than in the case of other solutions, but the differences between max. and min. are also the largest in this case.	Urban enviroment BEB – 2,63 (+/- 0,71) $/mil DF – 2,97 (+/- 0,23) $/mil CNG – 3,17 (+/- 0,16) $/mil
7	(Ginting et al., 2024)	Literature review, Life Cycle Assessment analysis	The article discusses the environmental impact of electrification of public buses in Jakarta, Indonesia, using life cycle analysis (LCA). The authors point out the short battery life and the life cycle of electric buses, which should be over 32 years for the best effect. It is indicated that BEBs have a greater environmental impact than diesel buses in Indonesia's current energy mix, which is mainly based on fossil fuels, and that changes in this area should be made.	n.d.
8	(Siddiqui et al., 2024)	Mathematical analysis (economic)	The main assumption of the article is to compare four types of buses: solar, electric, hydrogen and diesel, in terms of social, environmental, and economic costs and benefits. The authors indicate that solar buses have the highest net value (NPV per seating capacity) at the level of PKR 79.46 million (approximately EUR 260,500), which means the greatest benefits in relation to costs, while the lowest value (-PKR 5.87 million, approximately -19,242 EUR) was obtained by hydrogen buses. Electric buses in this study obtained a result of PKR 57,154, which due to the lack of need to build solar infrastructure places them as a desirable alternative to other technologies.	n.d.
9	(Kügemann and Polatidis, 2024)	Multi-criteria analysis, Case Study	In this paper, a multi-criteria analysis (MCDA) methodology including Life Cycle Sustainability Analysis (LCSA) was used to evaluate alternative fuel buses, taking into account their application in the public transport system on the island of Gotland (Sweden). Evaluations were performed on bioethanol, biodiesel, biogas, hybrid (biodiesel and biogas), battery electric and hydrogen fuel cell hybrid buses. For the presented Case study, biogas and biogas hybrid buses were the most preferred (which is related to local biogas production).	n.d.

No.	References	Approach	Description	Average Cost per km
10	(Chung and Chiou, 2024)	Mathematical analysis (economic)	The article discusses the economic aspects of city bus operations for a mixed fleet (different technological solutions operating in parallel), especially taking into account the impact of electric buses. The comparison and calculations are based on the data of entire companies. As one of the main results, it can be indicated that when the number of electric buses in the fleet reached a certain level, the operating cost decreased, which indicates the possibility of achieving savings by increasing the share of these vehicles. The authors also talk about the economies of scale and the increase in costs in the case of small operators in contrast to large ones where they were reduced.	n.d.
11	(Åslund and Pettersson-Löfstedt, 2023)	Case Study, Semi-structured interviews	The article focuses on the transition of Swedish public transport to electric buses, analyzing the positive aspects, expectations and interests of different groups involved in this process, such as public transport authorities (PTA), transport operators (PTO) and local governments. The authors present the advantages and disadvantages of electric buses in the context of the discussed case study. One of the most important conclusions is the need for cooperation between entities and their effective communication. It is indicated that Sweden has already made great progress in the electrification of rolling stock and intends to continue on this path.	n.d.
12	(Topal, 2023)	Model, Mathematical analysis	This paper focuses on the financial analysis of the use of hybrid fuel cell, electric and conventional (diesel) buses in the metrobus system in Istanbul (Turkey). It discusses the importance of these technologies for the development of sustainable urban mobility, potential implementation challenges and environmental benefits of individual solutions.	EV (BOB) – 0,31 eur/km (fuel) and 0,11 eur/km (maintance) Diesel – 0,62 eur/km (fuel) and 0,24 eur/km (maintance)
13	(Liu et al., 2023)	Model, Mathematical analysis	The article discusses the study of drivers' behavior in the context of savings in driving electric buses, the analysis was based on large data sets. The CRITIC (Criteria Importance Through Intercriteria Correlation) model was used to assess drivers' behavior. The proportion of low economic efficiency on weekends was 4.5 times higher than on weekdays, which is associated with the greater "aggressiveness" of drivers' driving on these days. A new method of constructing driving cycles for weekdays and weekends was shown, using Principal component analysis (PCA) and k-means clustering method.	n.d.

No.	References	Approach	Description	Average Cost per km
15	(Muñoz et al., 2022)	Mathematical analysis	The authors of the article compare different city bus technologies in terms of costs, energy consumption and environmental impact (Case Study: Argentina). The basic method used was the "Well-to-Tank" (WTT) analysis, where the processes related to the production, transport, and distribution of energy carriers (e.g., diesel, hydrogen, electricity) are analyzed. In the next stage, the focus is on the "Tank-to-Wheel" (TTW) analysis, where energy consumption and greenhouse gas emissions were calculated during the vehicle use stage, using different drive configurations and dynamic simulations for two driving cycles. In terms of data, historical data were adopted along with a forecast until 2030. The best results were achieved by CNGV (Compressed natural gas vehicle) vehicles.	n.d.
16	(Stec, 2021)	Literature review, Mathematical analysis (statistics)	The article assesses the economic efficiency of using low-emission and zero-emission vehicles in public transport in the Visegrad Group (V4) countries. The author devotes much attention to the issue of sustainable mobility and points out that one of the strategic goals of the EU is to reduce transport emissions. Among the analyzed vehicles, the cheapest to operate in the perspective of 15 years are electric buses, and the most expensive are hydrogen buses (due to high purchase costs). The year 2035 was indicated, in which the development of technology should reduce the costs associated with hydrogen technologies to a level that will increase their use for economic reasons..	Chechia: Diesel – 1,56 eur/km Electric – 1,51 eur/km Hybrid (electric) – 1,47 eur/km Hydrogen – 1,82 eur/km Hungary: Diesel – 1,62 eur/km Electric – 1,53 eur/km Hybrid (electric) – 1,49 eur/km Hydrogen – 1,85 eur/km Poland: Diesel – 1,65 eur/km Electric – 1,60 eur/km Hybrid (electric) – 1,53 eur/km Hydrogen – 1,85 eur/km Slovakia: Diesel – 1,57 eur/km Electric – 1,53 eur/km Hybrid (electric) – 1,48 eur/km Hydrogen – 1,82 eur/km

No.	References	Approach	Description	Average Cost per km
17	(López-Ibarra et al., 2020)	Model, Mathematical analysis	The paper focuses on the issue of transport network optimization, focusing on the total cost of ownership of the fleet, while ensuring that certain basic established values are not exceeded. For the purposes of the applied model, a Case Study of a fleet of 10 Plug-In Hybrid Electric Buses was used.	n.d.
18	(Borén, 2020)	Literature review, Case Study, Mathematical analysis	This article addresses the topic of sustainable transport, focusing on electric buses in the context of the Swedish public transport system. It discusses the costs in financial and social terms compared to other types of propulsion such as diesel or biogas. It is found that the energy efficiency of electric buses in the use phase is three times higher than that fossil fuel buses.	n.d.

Source: own elaboration.

3. METHODOLOGY

3.1. Overview of the Study Area

Firstly, when researching the change of conventional fleets to electric vehicles, it is necessary to take into account the differences between the models of electric buses in use and the solutions used in them, as well as how they affect carbon dioxide emissions or energy consumption. One of the available solutions are lithium-ion batteries, which are used by companies such as Solaris ("Urbino electric," n.d.). Unfortunately, the manufacturer does not specify exactly what type of lithium-ion batteries are used. A different approach can be seen with company Yutong, which uses lithium-ion batteries, specifically lithium-iron-phosphate cells. (U12 E-bus YUTONG, n.d.). The most common solutions (in terms of battery technology selection) used in electric vehicles are three-component lithium batteries and lithium-iron-phosphate (LFP) batteries. The first one is characterized by higher energy density, higher charge, and better performance, but this type of battery is susceptible to thermal runaway in the event of battery damage and has low resistance to high temperatures. The LFP battery, on the other hand, is cheaper, safer due to its high temperature resistance, and has a better lifespan, but it also has low energy density and charging efficiency. In addition, its performance at low temperatures is worse than that of a three-component lithium-ion battery (Liu et al., 2022; Su, 2022). In the case of LFP batteries, the advantages are much more important than the disadvantages, which is why these batteries are becoming more and more often chosen solutions in the automotive industry. (Yang et al., 2021).

One of the key factors when purchasing an electric bus for a company is choosing the appropriate battery capacity. Depending on the dimensions of the vehicle, engine power, or maximum number of passengers, the battery capacity should be selected accordingly so that the vehicle can be used in an optimal way. However, it is important to calculate or estimate the required maximum capacity, as the weight of the battery increases with its capacity, which translates into increased electricity consumption (Pielecha and Pielecha, 2020). Another significant difference between individual electric buses is their adaptation to various battery charging methods, which include: charging in depots using plug-in chargers, fast charging (e.g., via pantograph), wireless charging or replacing batteries after they are discharged. (Alamatsaz et al., 2022). It is also worth noting that some electric buses are actually low-emission vehicles, not zero-emission vehicles, due to the central heating system which is not powered by electricity, but by diesel fuel (Čulík et al., 2021). Opting for such solutions leads to greater environmental pollution than in the case of vehicles using entirely electricity, especially in winter, when the demand for heating in the bus is the highest.

3.2. Subject of the study

As a basis for the calculations and research aimed at obtaining real values of operational data for the bus fleet, the Polish city of Szczecin located in the northwestern part of the country was chosen. This city was chosen because it is the only one in Poland that has zero emission buses and at the same time conducts continuous tests of new technological solutions, hence it was possible to obtain data on both diesel buses and hybrids or electric buses. Another argument for choosing this city to conduct the research is the fact that hybrid buses such as the Solaris Urbino 18 Hybrid (the first mass-produced hybrid bus in Europe) are used in Poland (this model) only in eight cities. Moreover, due to many years of Polish, German and Scandinavian influences, the city of Szczecin has an extensive spatial structure based on the concentric model, during many modernizations and reconstructions changing towards a star corridor model (city center with a complex of squares in various shapes and radially intersecting streets) often found in the case of European agglomerations of strategic or commercial importance. The terrain is lowland, hilly with a large number of elevations and the Odra River flows through the center of the city. The average temperatures are shown in Figure 1 in the section showing the condensed results of annual energy consumption measurements of the tested vehicles. The city has one main urban transport administrator, which is a separate organizational unit of the Municipal Office. The above-mentioned budgetary unit was established in 2002 and is called the „Road and Urban Transport Administration in Szczecin (pol. Zarząd Dróg i Transportu Miejskiego w Szczecinie)". The Road and Urban Transport Administration in Szczecin is responsible for planning and organizing public transport in Szczecin and neighboring municipalities, while the transport process itself is the responsibility of dependent entities in the form of operators serving a given type of transport. The data obtained and the research carried out were conducted at one of the above operators, which has the highest qualifications in the subject of this research, the company „Szczecińskie Przedsiębiorstwo Autobusowe "Klonowica" Spółka z o.o." (SPAK). The company has been operating since 1999, providing passenger bus transport services in the area mentioned above. The company uses vehicles from Man and Solaris, with 14 electric buses from the latter manufacturer in its fleet. Their electric bus fleet includes vehicles with a length of 12 and 18 meters, which, depending on the model, use batteries (Solaris High Power) with a capacity of 60 or 90 kW. Most often, two 60 kW batteries are used per bus, which allows them to be charged simultaneously using the available 120 kWh charging stations (plug-in) built in the city, at the end stops and bus depots. ("Sześć nowych elektrobusów już w Szczecinie," n.d.). The design of the units also allows for charging buses using a pantograph using the wires of the existing extensive tram network in the city. With an average (defined for the purposes of this study) route length of approximately 15 km (full route, in both directions), assuming increased road traffic, a bus with two 60 kW batteries is able to make 4 trips until the battery is discharged. During practical tests, a driving format assuming 3 trips per 1 charge was estimated and started to be used. The company purchases several electric buses annually with the aim of a complete fleet replacement. The number of units purchased depends on the amount of funding under local government, national and EU programs aimed at reducing transport pollution. The buses currently in use were co-financed, among others, by the „GEPARD - Zero-emission public transport (eng. CHEETAH - Emission-free public transport)" program ("GEPARD - Bezemisyjny transport publiczny - Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej - Portal Gov.pl," n.d.) as well as from the funds of the National Fund for Environmental Protection and Water Management under the priority program „Green public transport" ("Autobusy elektryczne dla Szczecina. Miasto otrzyma ponad 6 mln zł dotacji z NFOŚiGW na rozwój elektromobilności - Agencja Restrukturyzacji i Modernizacji Rolnictwa - Portal Gov.pl," n.d.). Current and future investments focus on the use of funds from the "Green Public Transport" program, however, the amount of funding has been reduced in recent years, which, with the current settlement, only allowed for the purchase of 2 of planned 8 new vehicles. According to tender data, the new vehicles will be low-floor and air-conditioned, adapted to the needs of people with physical disabilities, buses with a power of 145 kW (category M3 - BEV: Battery Electric Vehicle). Both vehicles are designed to accommodate at least 120 passengers (minimum 35 seated). It should be noted that Szczecin, as the only city in Poland, has a fleet of fully emission-free electric buses in which both heating and air conditioning are battery-powered. This should be taken into account when making comparisons, as the difference in energy efficiency and power consumption of individual vehicle models can often result from an incorrect combination of unsuitable variants, which is difficult to verify when using literary sources.

3.3. Research Methodology

The emission and energy consumption studies were conducted based on data (telematics data and actual operating costs available to the operator) obtained in cooperation with and from the urban public transport operator in Szczecin - SPA Klonowica. Table 2 shows the fleet of vehicles owned by the company and key information about these vehicles that directly affect carbon dioxide emissions and energy consumption of buses. It is noteworthy that the average age of the vehicles in the fleet is provided. A noticeable change in the company's approach to ecological solutions can be observed, as it initially decided to purchase low-emission vehicles and later switched to zero-emission buses.

Table 2. The status of SPA Klonowica's bus fleet as of 24.02.2025 (Spak.pl, 2025; Mkm.szczecin.pl, 2019; Solarisbus.com; n.d.)

Vehicle type	Engine type	Engine power	Dimensions (length x width)	Maximum number of passengers (including seats)	Number of vehicles in the company's fleet	Average age of vehicles
MAN A21	Diesel	235 kW (320 KM)	11,95m x 2,5m	107 (30-39)	1	18,00
MAN A23	Diesel	228 kW (310 KM)	17,95m x 2,5m	175 (45)	3	18,00
Solaris Urbino 10	Diesel	176 kW (239 KM)	9,94m x 2,55m	81 (19-23)	4	14,00
Solaris Urbino 12	Diesel	188 kW (256 KM)	12m x 2,55m	86-94 (28-39)	26	15,46
Solaris Urbino 12 Electric	Electric	200 kW	12m x 2,55m	99 (39)	6	3,00
Solaris Urbino 12 Hybrid	Hybrid	151 kW	12m x 2,55m	94 (30)	8	7,00
Solaris Urbino 18	Diesel	231 kW (314 KM)	18m x 2,55m	136-168 (41-47)	36	14,03
Solaris Urbino 18 Electric	Electric	240 kW	18m x 2,55m	123 (41)	10	3,40
Solaris Urbino 18 Hybrid	Hybrid	220 kW	18m x 2,55m	147 (42)	8	7,00

Source: own elaboration.

In scientific literature, various approaches can be found regarding the study of energy consumption, fuel combustion, and cost-effectiveness of operating vehicles with specific types of engines. In one of the analyzed publications, authored by G. Zając and S. Jurga (Zając and Jurga, 2017), energy consumption studies of public transport vehicles were conducted, and megajoules per passenger-kilometer [MJ/pas.km] were used as the unit for conventional vehicles, while kilowatt-hours per passenger-kilometer [kWh/pas.km] were used for electric buses. However, among others, authors such as W. Gis, S. Kruczyński, S. Taubert and A. Wierzejski (Gis et al., 2017) conducted a standardized road test for urban traffic (SORT-2) using buses powered by compressed natural gas, diesel, and electric power. To show the final results of the study, the authors used the unit of fuel/electricity consumption per kilometer [kWh/km]. After taking into account the prices for the appropriate sources of energy, authors obtained the cost of driving one kilometer for each type of vehicle. After analyzing the obtained results, a possible theoretical application of AI-based systems to increase the efficiency of urban transport in the studied context was also proposed.

4. RESULTS

Due to the potential universality of the obtained results, in the further part of the article, where the analysis of energy consumption results of vehicles belonging to SPA Klonowica was carried out, the results are presented in kilowatt-hours per kilometer [kWh/km], and the cost of fuel/energy (and AdBlue solution for buses powered by diesel) per 1 vehicle-kilometer [vkm] is presented. The use of these two units will allow for obtaining uniform results for vehicles with different types of engines, which will facilitate their comparison. On the other hand, the cost of fueling a vehicle per 1 vkm will allow for taking into account all additional factors (current energy prices, amount of used AdBlue solution), and as a result, will enable obtaining a clear answer to the question of which type of buses is the most efficient in terms of operating costs. The study used the actual heating value, which is 10,7 kWh per liter for diesel (MacKay, 2008). Due to the previously indicated differences in energy consumption related to periods of variable temperatures, the data from each month is shown.

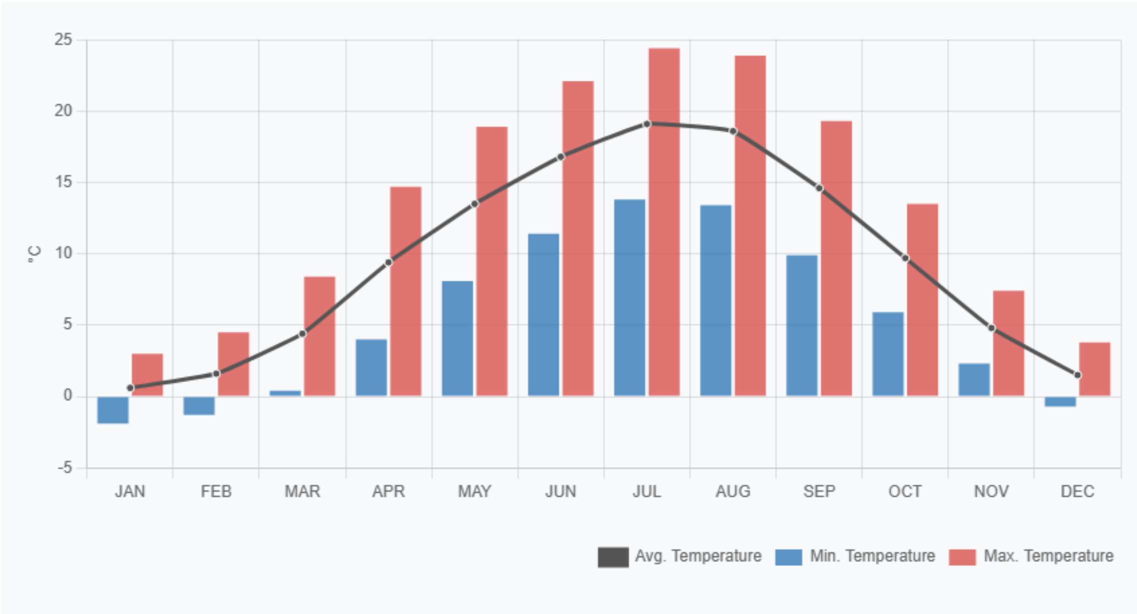

Figure 1. Temperature chart for the city of Szczecin from January 1 to December 31, 2024
Source: based on: https://meteostat.net/en/place/pl/szczecin?s=12205&t=2024-01-01/2024-12-31

Figure 1 presents the average, minimum and maximum temperatures for the city of Szczecin in year 2024. Temperatures are crucial for fuel or electricity consumption due to the use of heating or air conditioning systems. Extremely high or low temperatures can also negatively affect battery capacity, which in the case of electric buses affects their operational capabilities.

In the study, data presenting the energy consumption of vehicles with different types of engines (diesel, hybrid, electric) based on data from invoices provided by SPAK, which included the following values (all monetary values shown below are converted to the European common currency using the exchange rate from March 12, 2025 (4.20 PLN = 1 EUR):

- for diesel buses: fuel consumption and consumption of the water-based AdBlue solution, which is required in this type of vehicle
- for hybrid buses: fuel consumption (the hybrid vehicles in question do not have a charging function, the electricity is obtained in them through recuperation, which means that the invoices do not include the consumption of electricity)
- for electric buses: electricity consumption

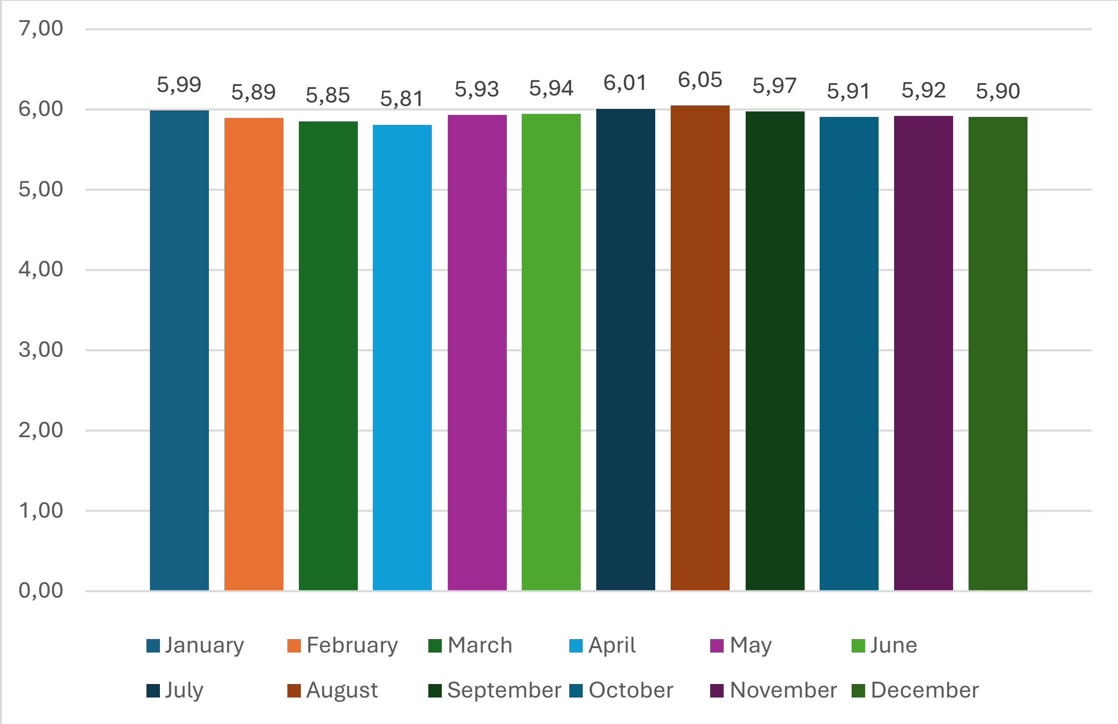

Figure 2. Energy consumption of diesel vehicles per 1 vkm in the studied periods (kWh)
Source: own elaboration.

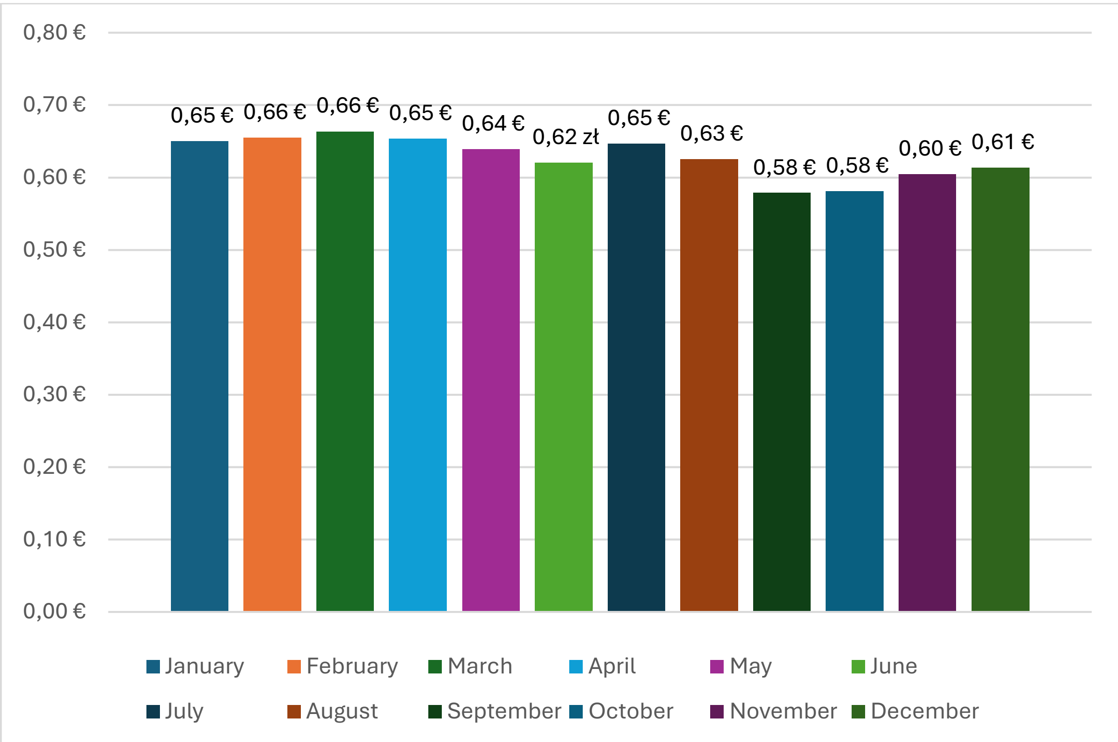

Figure 3. Fuel cost of diesel vehicles per 1vkm in the studied period
Source: own elaboration.

Figure 2 and 3 show the energy consumption and cost per 1 vkm for diesel vehicles. It can be seen that in the case of this type of bus, the differences between months are insignificant and there is no clear trend of changes depending on the studied periods.

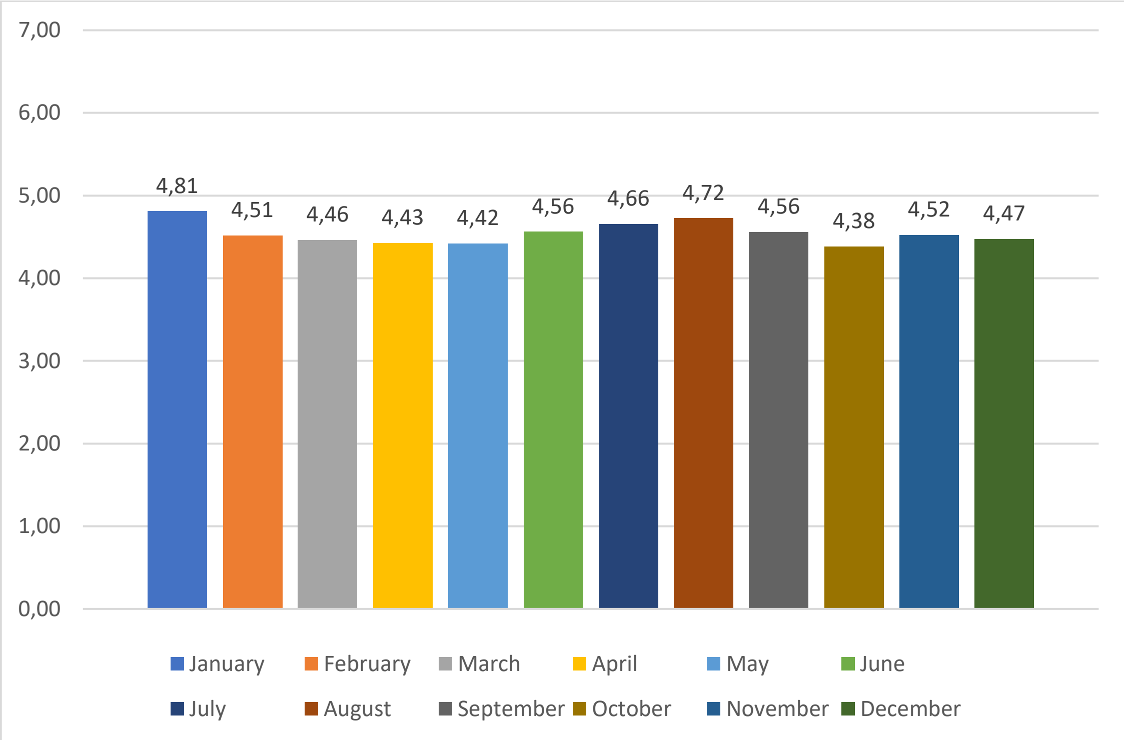

Figure 4. Energy consumption of hybrid vehicles per 1 vkm in the studied periods (kWh)
Source: own elaboration.

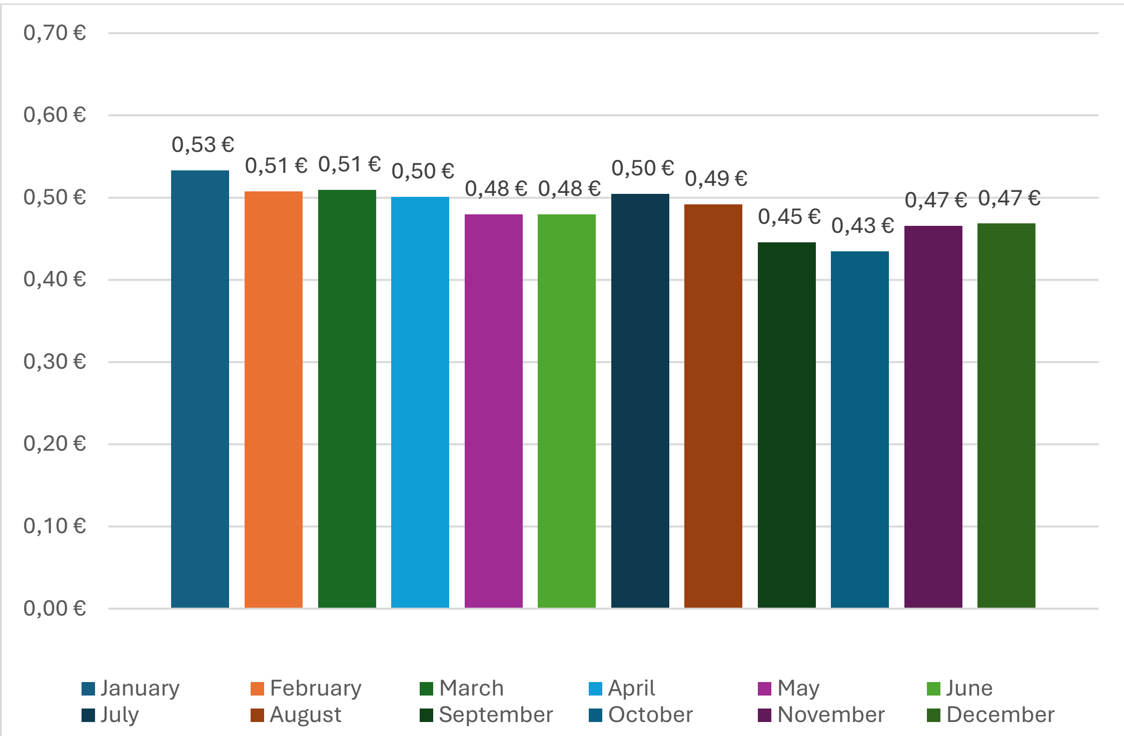

Figure 5. Fuel cost of hybrid vehicles per 1vkm in the studied periods
Source: own elaboration.

Figure 4 and 5 show energy consumption and cost per 1 vkm for hybrid engine vehicles. As in the case of diesel buses, monthly differences in energy consumption and costs are not significant and do not show clear trends. However, both energy consumption and cost are much lower compared to a conventional engine. Such dependencies may result from the fact that in a hybrid bus, the main engine is also a diesel engine, which is why monthly dependencies may be similar to the previous case. On the other hand, the use of an electric engine as a supporting system, obtaining energy through recuperation, allows for a significant reduction in fuel consumption, and thus a reduction in operating costs and energy consumption.

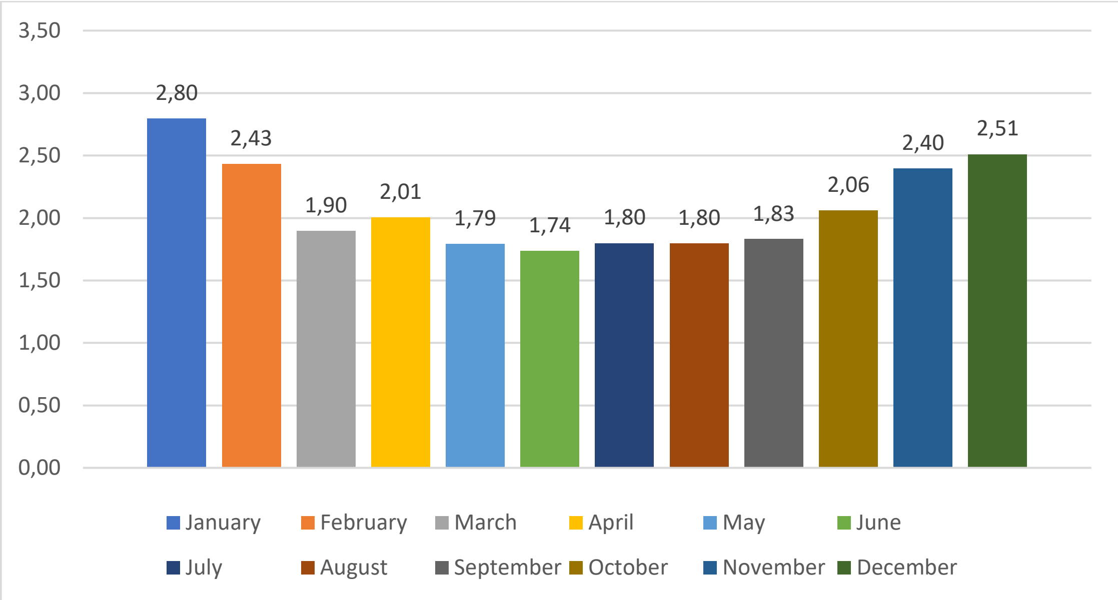

Figure 6. Energy consumption of electric vehicles per 1 vkm in the studied periods (kWh)
Source: own elaboration.

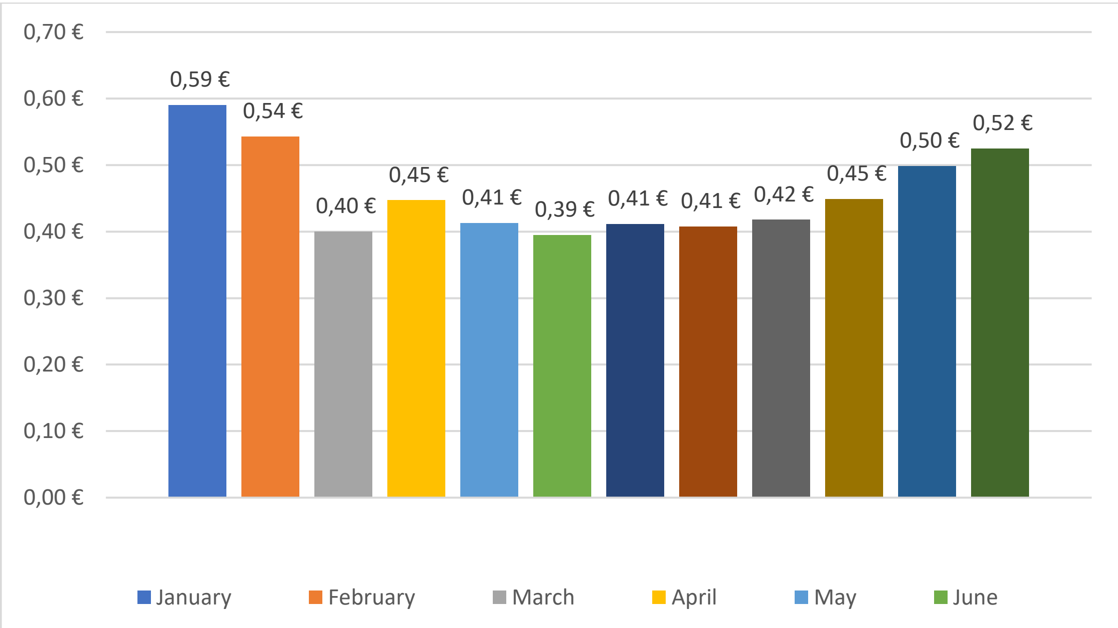

Figure 7. Fuel cost of electric vehicles per 1vkm in the studied periods
Source: own elaboration.

Figure 6 and 7 show energy consumption and cost per 1vkm for electric vehicles. The presented graphs show that both operating costs and energy consumption are the lowest in months with moderate and warm temperatures, while in winter months, when temperatures are relatively low, there is a clear increase in costs and energy consumption. This is consistent with common knowledge about batteries and research conducted in this area (Torbus et al., 2017).

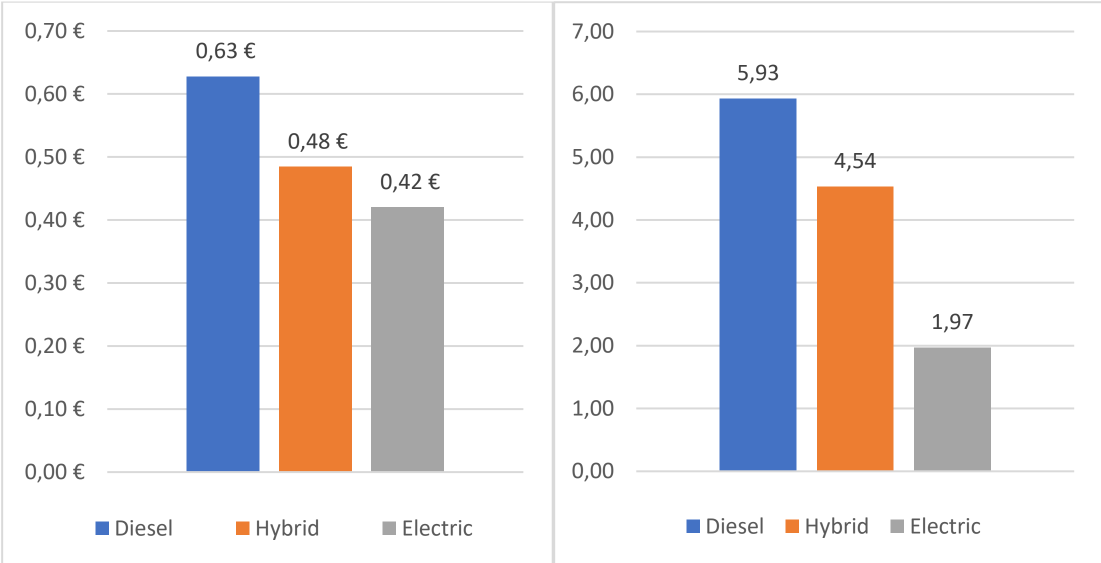

Figure 8. Energy consumption (kWh) and fuel cost of studied vehicles per 1vkm in 2024
Source: own elaboration.

Shown results clearly indicate the advantage of modern, ecological transport technologies over conventional solutions. In the case of the conducted study, it can be concluded that the cost of fuel/energy for hybrid buses is approximately 24% lower than for analogous vehicles using conventional combustion technologies, and for fully electric vehicles, the cost is approximately 33% lower.

It is obvious that in the scope of fleet operation, the cost of energy/fuel consumption is not the only operating cost of the company. However, other costs such as depreciation, repairs or service are similar in the case of any selected buses from those used in Szczecin and examined for the purposes of this article. In the case of electric vehicles, a drop in performance or the possible need to replace the battery after a certain period of time must be taken into account, however, in this case the operational buses did not experience any significant reduction in performance up to the time of the research and the form of management and organization adopted at SPAK (including not using the full capacity of the batteries) provides sufficient margin for this reduction in performance to occur without any impact on the operation of the fleet. For a company starting its business, in contrast to the case under study, there are also costs associated with building plug-in chargers or charging lines. In Szczecin, the charging infrastructure is already well-developed and plug-in chargers are located at the end stops of bus routes. There is also, as previously indicated, an extensive tram network, the power supply of which has been made available to electric buses. Buses can be and are recharged during mandatory stops related to the regulations on drivers' working hours and waiting time in accordance with the timetable. The design of the units used and the stations built in accordance with all safety procedures allows the batteries to be charged when passengers are present in the vehicle. Taking into account the above, the costs of energy/fuel itself and their consumption in selected periods were presented, taking into account the adopted variables and the fact that the electric units used are zero-emission vehicles in the full sense, which is not true in the case of a large number of publications (usually low-emission solutions are studied because the indicated units use diesel generators to provide heating and/or air conditioning). Additionally, the presented data concern the entire network of connections and the full fleet used by the company, which is also rare and the results of published studies are being often extrapolated from individual cases on single lines.

There are few publications proposing the use of AI solutions in fleet management and improving the efficiency of public transport buses. There are individual applications in the field of energy optimization management of used batteries (Jondhle et al., 2023), but there are issues where models using AI, whether as transformers or expert models, could have some application. In the opinion of the authors of this article, it would be possible to distinguish 3 basic groups where current systems could bring the greatest benefits:

- Route optimization: Application of AI to analyze traffic data, predict travel patterns and optimize routes, which leads to lower energy consumption and emissions.
- Energy management: AI can monitor energy consumption in real time and introduce recommendations for energy efficiency.
- Failure prediction: Application of AI algorithms in diagnostics of the technical condition of vehicles, which reduces repair costs (by quickly detecting faults) and increases operational efficiency, sometimes also reducing the cost of repairs.

At the same time, in the area of urban intelligent logistics systems, the same tool that could theoretically deal with route optimization in the area of public transport companies, when integrated with urban systems, could be responsible for demand prediction. Which would mean predicting by the AI expert system increases or decreases in transport demand depending on the time of day, level of road traffic, weather, road condition or accidents or other types of traffic flow obstructions. This would allow for adjusting the operating time of traffic lights or informing transport companies according to current needs in real time and overall reducing the environmental and energy costs of the entire system.

5. CONCLUSION

The results presented in the article indicate that choosing a fleet of electric vehicles, in addition to reducing greenhouse gas emissions, especially carbon dioxide, is also the most cost-effective solution for transport companies (and municipal companies) in terms of operating costs. This means that there are more arguments for introducing electric vehicles to the fleets of transport companies than just aspects related to environmental protection. The presented comprehensive results containing practical information and based on a network of connections instead of one line can encourage companies to use solutions consistent with the EU transport policy, which in turn will accelerate the process of achieving climate neutrality in Europe. The presented data can also serve further research in the field of urban transport and sustainable development. At the same time, the theoretical directions of development of supporting the operations of urban bus fleets with the help of systems using artificial intelligence, proposed in the article, may serve as an inspiration for further research and development of this type of systems.

Funding: Co-financed by the Minister of Science under the “Regional Excellence Initiative”.

Regionalna Inicjatywa Doskonałości

Ministry of Science and Higher Education
Republic of Poland

Acknowledgments:

This article was created thanks to substantive support and using the necessary data provided by Szczecińskie Przedsiębiorstwo Autobusowe Klonowica Sp. z o. o. In particular, we would like to thank the President of the Company's Management Board: Mr. Krzysztof Putiatycki, the Operations Manager: Mr. Jacek Remiszewski and the Technical Manager: Mr. Andrzej Lachowicz, without whom this article would not have been possible.

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