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Total Cost of Ownership analysis and energy efficiency of electric, hybrid and conventional urban buses

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Highlights

- We have described a modelling framework for some urban bus routes in Kielce, Poland.
- We have defined assumptions for the conducted TCO analysis.
- We have presented some results of the TCO analysis for different types of urban buses.
- We have determined two factors that have a significant impact on TCO values.
- In our opinion, electric buses represent the highest TCO values among urban buses.

Abstract

From an economic perspective, the purchase cost of an electric bus is greater than that of a conventional one. This results from the additional components of the bus drivetrain and the costly charging infrastructure. However, it should be noted that electric bus ensures greener and more sustainable public transport. The presented study focuses on the economic and energy efficiency analysis of city buses with different types of driving system evaluated for selected urban and suburban routes. The routes differ in terms of the number of journeys per day, elevation, the daily distance travelled, and the daily operating time. The results demonstrate that driving conditions can affect economic efficiency. The Total Cost of Ownership (TCO) method used in the study shows that electric buses represent the highest TCO values among the vehicles taken into account. However, for the TCO calculated for electric and hybrid buses, fuel (energy) costs have a much lower share than for the TCO of conventional buses.

Keywords

public transport, electric bus, Total Cost of Ownership.

1. Introduction

Currently, the largest part of the fleet of Polish companies operating urban public transport have buses equipped with conventional diesel propulsion systems. Positive information is the growing year-by-year share of buses powered by alternative fuels or equipped with alternative drives.

The increase in the number of low-emission vehicles is associated with the increasing level of ecological awareness of the society. Lowering noise levels, environmental protection, and air quality are the main reasons why Polish cities are trying to replace conventional buses with low-emission vehicles. Adopted more than two years ago, the Responsible Development Strategy [20] assumes the dissemination of transport based on electric buses and other vehicles using electric drive trains. The Ministry of Development has assumed that by 2021 1,000 electric urban buses will be in operation on Polish roads. With the help of EU funds and Polish government programs, city carriers can count on cofinancing for the purchase of alternative powered vehicles.

Rising fuel prices are another issue. In the global economy, oil plays a key role in the economic system [13]. Transport is particularly dependent on oil. The fuel market is sensitive to any economic and political changes. Oil prices depend on political, economic, social, technical, climatic, and military factors. Large fluctuations in the fuel market occur during armed conflicts, especially in areas extracting crude oil [21, 29].

It is also worth emphasizing that vehicles with alternative drives show lower energy consumption, which significantly reduces operating costs. These factors make hybrid (HEV) and electric (EV) vehicles more and more competitive compared to conventional vehicles. One of the barriers to increasing the market share of this type of vehicles is still high purchase costs.

The diversity of alternative powertrain technologies increases the challenges in decision making, so it is necessary to study in detail the different configurations of city buses. This is especially important when estimating the profitability of city buses, taking into account operating schedules and route planning. Compared to passenger cars, the energy indicators that characterize the fuel consumption of city buses for the period of their operation are much higher.

The aim of this work was an analyse of the economic efficiency of city buses with different types of drive system for selected urban and suburban lines, using the Total Cost of Ownership (TCO) method. The

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value of owning and operating costs for city buses depends largely on the type of propulsion system. Electrically powered vehicles require batteries to be replaced during the lifetime of the bus. Operators who decide to purchase low-emission vehicles should take into account the costs of additional infrastructure, and this applies to electric buses. Often this involves adapting bus depots or bus stops to install battery charging devices. TCO makes it possible to estimate the total costs of a vehicle related to its purchase, use and decommissioning. The aim of this paper was to estimate the amount of the following costs: purchase cost of the vehicle, cost of fuel consumption, cost of repairs, cost of battery replacement, cost of charging infrastructure during the lifetime of the vehicle. In this study, an analysis of the costs associated with the ownership of urban buses with conventional, hybrid and electric drive systems was conducted.

The presented paper is organized as follows. Section 2 describes the general description of the Total Cost of Ownership concept. Section 3 illustrates the modelling framework, presenting the selected routes, vehicles, and simulation program. Section 4 provides the TCO model. Section 5 discusses the results. Section 6 concludes and highlights shortcomings of the study.

2. Total Cost of Ownership (TCO)

Total Cost of Ownership - TCO (Total Cost of Ownership) is the sum of all vehicle costs from its purchase phase, through usage, to its disposal. The TCO analysis allows for the assessment of direct and indirect purchase costs. It gives the opportunity to determine the amount of costs associated with the use and possession of the purchased means of transport. In the literature, the main cost categories that make up a vehicle's TCO are: purchase cost, fuel (energy) cost, repair, and maintenance costs.

In the work [37] it was suggested that the total cost of vehicle use consists of: One-Time Cost (e.g. purchase cost, registration cost) and recurring costs (e.g. fuel, repair, insurance costs). According to the authors of [15], the TCO analysis of a vehicle can be carried out in two categories: consumer-oriented research and society-oriented research. The first group takes into account the costs distinguished by consumers and compares various technologies of vehicle propulsion systems. For society-oriented TCOs, consumer costs include the external costs of using a vehicle, such as air pollution, noise, accidents, congestion, climate change, and environmental impact.

In many analyses and studies, the total cost of using vehicles is extended to include factors relevant to the author. For example, in [37] it was shown that as many as 34 different factors influence the TCO level of a vehicle with an electric drive system. Among them there were identified the main groups of costs associated with the production of the vehicle and batteries, operating costs, costs associated with charging, taxes and fees. These costs were distinguished on the basis of available scientific articles and articles, opinions of specialists and employees of the automotive industry, and on the basis of the results of the consumer survey.

The article [10] presents the TCO analysis carried out for passenger cars with electric and conventional hybrid drives. The authors have shown that consumer preferences have a significant impact on the purchase of an electric vehicle. According to the results of the analysis, buyers (consumers) are mainly guided by the purchase price of the vehicle.

For example, work [1] presents a comprehensive TCO model, in which special attention has been paid to the costs of using a vehicle with a hybrid plug-in drive system. The maintenance cost of the vehicle includes the insurance cost, the annual cost of registration, the fuel cost, the repair cost, the value of the redemption and the cost of the loan. The authors emphasized that the value of TCO is significantly influenced by vehicle type, annual mileage, and changes in fuel prices. The authors of the articles [17, 3] drawn similar conclusions. A TCO analysis was carried out for various types of passenger car (small, medium, large) and three assumed annual mileage values. Furthermore, in the TCO cost analysis of hybrid and electric vehicles presented in [17], the resale value of the battery for its next use (so-called second life, for example, as an energy storage device) was taken into account.

The article [40] presents the TCO values for various types of passenger cars (small, medium and large). The Monte Carlo method was used to estimate the TCO in 2025. Based on the results obtained, it was found that "small" electric cars in 2025 will have a lower TCO level than conventional cars of the same class.

Owners of new vehicles usually use them for an average of 5 to 8 years. Then they resell the vehicle. According to [9], the vehicle's resale price is influenced, among others, by mechanical reliability, durability, user feedback, and social trends. In the works [28, 9], the costs of the total use of vehicles with conventional and alternative drives were compared. The analyses assume that the car has a lifetime of 5 years and the TCO includes the resale value of the vehicle. The authors developed a model on the basis of which it was found that the resale price of a vehicle depends on its mileage. On the basis of the results, hybrid and electric vehicles have higher resale prices than conventional vehicles, in addition to lower fuel costs.

Vehicle use conditions have a significant impact on the total cost of their use. The article [11] provides an analysis of the TCO level for light duty vehicles (LDV) with conventional and alternative drives. The results presented show that the values of the total cost of ownership values of electric and hybrid vehicles are lower in urban driving conditions and higher when the share of driving on highways is high.

The geographical region may also affect the TCO level. Fuel price level, average annual mileage, taxes and insurance prices, as well as climatic conditions, as well as road condition depend on the country or region [33]. The impact of the factors mentioned above on the TCO values of vehicles with various types of propulsion system was confirmed in the paper [2]. Based on the TCO analyzes carried out for 14 cities in the United States, electric vehicles have been shown to have the highest TCO levels. Government subsidies are a key factor in the increase in the number of electric and hybrid vehicles on the vehicle market. In the article [31], an analysis of the cost of using passenger cars was carried out for 11 Chinese cities.

In the paper [25], the TCO level for passenger cars with hybrid, electric, and plug-in hybrid cars was estimated in the years 2000-2015 for the UK, the US, and Japan. Using the regression model, the relationship between the TCO value and the market share of hybrid and electric vehicles was determined. The authors conclude that the increase in the market share of alternative powered vehicles is affected by a reduction in the TCO value through government subsidies (Japan). Similarly, the authors of the work [18] state how the cost of TCO for conventional and electric passenger cars is calculated in eight European countries. The authors analysed the impact of taxes and fees on the TCO level of a vehicle. As in previous publications, the authors emphasize that government subsidies can increase the number of electric vehicles.

In addition to economic factors, in the analysis of the total cost of ownership, many studies also consider the ecological aspects of various types of propulsion systems in vehicles. For example, the analysis of operating costs presented in [12] takes into account the emission costs of 44 vehicles available on the market with 6 different hybrid propulsion configurations. Based on the results, driving conditions have a significant impact on the level of total cost of ownership. Hybrids tested show the lowest costs in urban driving conditions, while the highest on highways. The paper [35] presents the analysis of TCO costs, including emission costs for passenger cars with conventional (gasoline, diesel) and alternative (HEV, HEV, plug-in HEV, EV, LPG) cars.

The paper [14] presents the analysis of operating costs, including the cost of emissions of conventional and alternative heavy-duty vehicles (HEV, EV, CNG). Fuel consumption, energy, and emissions values were estimated for six routes in the British Columbia (Canada) region.

In the literature, one work can be found in which the value of the total cost of use includes social costs. Among the factors that influence social costs, the following are mainly distinguished: emissions costs, costs of climate change, costs of accidents, costs of noise, and costs of congestion. The article [9] presents the analysis of total cost of use, taking into account the social costs of passenger cars with conventional propulsion (Diesel, gasoline) and equipped with engines fueled with natural gas (LPG, CNG). Social costs include the cost of the harmful effects of air pollution and greenhouse gas emissions on the human body. In [30], the TCO values were estimated taking into account the social costs of 66 passenger cars with conventional and alternative drives. As a result of the analyses, the average TCO value was estimated for each of the types of propulsion system available on the market. The total cost of ownership values presented in [5] include the social costs of using the vehicle. The authors also examined the impact of driving behavior on the TCO level. Based on the results of the aforementioned works, electric vehicles are characterized by the lowest social costs. They show the lowest emission values and have the lowest noise level.

In many works, the level of TCO cost was considered as the one taking into account technical aspects, such as the capacity of the fuel tank and the distance that the vehicle runs using only an electric motor, among other [24, 38]. The paper [16] presents the TCO analysis of LDV category vehicles with different types of propulsion system (ICE, BEV, HEV, FCEV and FC-R) taking into account the impact of range of electric vehicles. Electric vehicles and vehicles equipped with fuel cells show significantly higher TCO values. The authors predict that this may change only after 2030, when the cost of lithium ion cell and battery production decreases and the range of this type of vehicle increases.

In the literature, TCO cost analyses can be found mainly for passenger cars. The authors focus on comparing vehicles equipped with conventional and alternative drives. Few publications on the evaluation of economic benefits and the TCO estimate for city buses are available. These works as a rule present a comparison of the TCO cost level for buses with different types of propulsion system, including [23, 36, 8].

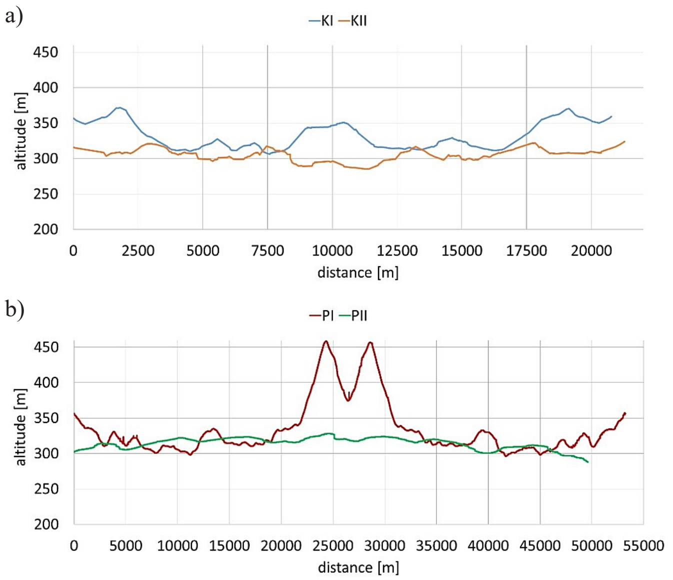

Fig.1. Vertical shape of terrain for a) urban and b) suburban routes

Table 1. Driving cycle parameters

cycle		time [h]	length [km]	average speed [km / h]	average acceleration [m / s^2]
urban	KI	1,35	21,90	15,95	0,55
	KII	1,27	20.81	16,44	0,54
suburban	PI	2,19	49.61	26,62	0,58
	PII	2,08	53.19	23,64	0,4

3. Modelling framework

3.1. Routes

Routes regularly served by public transport vehicles in Kielce, Poland, have been used for analyses. The routes run through the city centre. The route chosen as the first cycle (KI) reflects the bus route 13, which runs more or less latitudinal, from the east to the west of the city, in a relatively flat area. For the second urban cycle (KII), the bus route No. 30 was used, which runs longitudinally from the northern to the southern part of the city in the highland area. The maximum gradient of the route is 4%.

Lines No. 41 (PI) and No. 43 (PII) were used to develop suburban cycles. These lines are characterized by similar length and similar travel time, while they differ in vertical profile. Differences in the height of the terrain along bus route No. 41 reach 160 meters, while for route No. 43 - only 60 m.

The urban KI cycle lasts 4568 s, its length is 20.25 km, and the average speed is 15.95 km / h. The KII cycle is about 700 m shorter and has a higher average speed of 16.44 km / h. The PI suburban cycle is about 4 km shorter than the PII and has a higher average speed. The duration of both cycles is similar. Selected driving cycle parameters are presented in Table 1.

The speed profiles of the selected driving cycles are presented in Fig. 2.

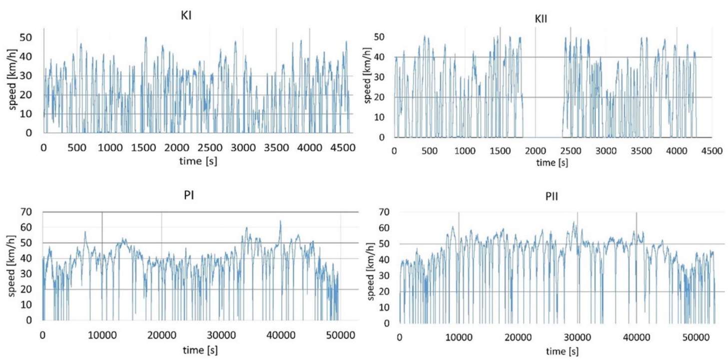

Fig. 2. Speed profiles of driving cycles

3.2. Vehicles

A city bus with a length of 12 meters, a frontal area equal to 7.24 m2, a rolling resistance coefficient equal to 0.001, and an aerodynamic drag coefficient of 0.6 was chosen for the simulation tests. Simulations were carried out for the following propulsion system options: conventional, series hybrid (SHEV), parallel hybrid (PHEV) and electric with a battery of 200 kWh (EV 200 kWh) and 300 kWh (EV 200 kWh) energy capacity. Other vehicle technical specifications are presented in Table 2.

Lithium ion batteries were assumed to be used in vehicles. The initial battery state of charge (SoC) in hybrids was 70% and in electric buses was 100%.

3.3. Ways to charge electric vehicles

Buses with an electric drive system have a limited range, usually 100-150 km. This determines the need for the appropriate selection of

Table 2. Data describing the configuration of bus propulsion systems

	Diesel	EV 200 kWh	EV 200 kWh	SHEV	PHEV
combustion engine power [kW]	205	-	-	140	190
electric motor power [kW]	-	200	170	150	40
battery energy capacity [kWh]	-	300	200	9,4	1,8

the strategy and the battery charging method so that the vehicle can properly implement the assumed timetable. The energy charging of electric buses can be performed in the depot or using fast charging devices at stops or bus termini. Currently, the following methods for charging electric bus batteries are distinguished:

- charging via plug connector,
- charging using a pantograph,
- wireless (inductive) charging.

Two of the above-mentioned methods are widely used in Poland: charging with a plug connector and with a pantograph. The battery charging system using a plug connector (similar to obvious plug-in) is similar to charging systems for electric passenger cars. It is about supplying electricity using a cable with a plug, DC or AC. When charging with alternating current, it is necessary to use a rectifier installed in the vehicle, which results in an increase in the weight of the bus and a reduction in the passenger space. The charging method using a plug-in connector is carried out mainly in depots during a night stopover due to the long charging time.

Charging electric bus batteries using a pantograph is currently the most popular method. Unlike the previous charging method, the use of a pantograph allows the battery to be recharged at bus stops and loops (bus termini). Depending on the configuration of the system, the pantograph can be pulled out of the charging station ('Off-board Top-down Pantograph') or from the vehicle ('Off-board Bottom-up Pantograph'). After stopping at a designated place, the bus is connected to the charging station using a pantograph. Charging is carried out with a direct voltage of up to 750V at a current of up to 1000A. The pantograph charging method allows for quick charging of the bus battery; however, it requires appropriate and expensive infrastructure [6, 32].

Plug-in chargers usually allow buses to charge with a power of 100-150 kW. It takes several hours to fully charge the battery. For pantograph chargers, it is possible to charge at night with a power of 50-150 kW, as well as to recharge the battery at stops and loops with a power of 150-600 kW. High charging power allows batteries to be recharged in a short time [34].

3.4. Vehicle Modelling and Simulation Software - ADVISOR

ADVISOR software (ADvanced Vehicle SImulatOR) software was used for simulations. Their results have been presented in the paper. The software is an overlay on the Matlab / Simulink environment. ADVISOR is a popular tool for simulating vehicles with various drive configurations. It was developed by the American National Renewable Energy Laboratory (NREL). The software contains embedded vehicle models (LDV, HDV) with conventional, serial, and parallel hybrid drives, electric vehicles, and vehicles equipped with hydrogen cells. Using extensive libraries, the user develops the vehicle model using drop-down menus in the dialog box. In the first step, the type of vehicle, the type of drive, and the individual elements of the drive system can be selected. The user can specify the parameters of the power train, its efficiency, and mass. In the next step, the driving cycle can be chosen. With the assumed propulsion configuration and the specified driving cycle, the program enables the evaluation of the drive characteristics and execution of the energy flow analysis for the developed vehicle. The program also allows modification of models by entering files with vehicle data, characteristics and parameters of the propulsion system modules and the storage tank, or design and implementation of the user's own model. It is also possible to modify the built-in or add developed by the user driving cycle by implementing files with data describing speed as a function of time, road gradient as a function of road distance covered, etc. [19, 39].

ADVISOR is a widely used tool for assessing the energy of vehicles equipped with an alternative drive train. Examples of using the ADVISOR program in city bus modeling and simulation tests can be found, eg, in works [22, 4, 26].

4. Cost analysis

4.1. TCO model

The total cost of ownership in relation to the route covered by the vehicle can be described in the following form:

$$C_{TCO} = \sum_{n=1}^{N} \left(C_p + \sum_{i=1}^{I} \left(C_f + C_m \right) + C_b + C_i \right) \quad (1)$$

where: C_{TCO} - the total cost of ownership, C_p - the cost of vehicle purchase, C_f - the cost of fuel consumption, Cm - the cost of maintenance and operation, C_b - the cost of battery replacement, Ci - the cost of infrastructure, i (1,2,..., I) - vehicle age, n (1,2,..., N) - number of vehicles.

The first component of the TCO is the cost of vehicle purchase (C_P). Companies providing public transport services decide on the selection of the transport means supplier based on the tender results. Therefore, city bus manufacturers always adapt the offer to the individual buyer's expectations. The cost of purchasing C_p can be calculated as follows:

$$C_P = \sum_{n=1}^{N} P_a \quad (2)$$

where: P_a - purchase price of the bus.

The TCO cost includes the fuel costs (C_f) for conventional or hybrid buses and, in the case of an electric vehicle, the electric energy purchase costs. The fuel cost (C_f) can be calculated using the formula:

$$C_f = \sum_{n=1}^{N} \left(\frac{f_c}{100} \cdot P_f \cdot D \right) \quad (3)$$

where: f_c - average fuel consumption (energy) [dm^3 / 100km, kWh / 100km], P_f - price per unit of measure [euro / dm^3, PLN / kWh], D - annual mileage [km].

Another component of the total cost of ownership (TCO) is the cost of vehicle maintenance and operation (Cm), which includes insurance costs, periodic inspection costs, costs of replacement of tires and working fluids, as well as the costs of repairs required and costs of removing defects.

Current operational experience shows that the energy storage device has a much shorter service life than the bus life. It was assumed that the battery pack should be replaced every 6 years; therefore, the battery will need to be replaced twice during the life of the bus. The cost of the battery replacement C_b is as follows:

$$C_b = \sum_{n=1}^{N}\sum_{j=1}^{J}(P_b \cdot B) \quad (4)$$

where:
P_b – is the battery replacement price [euro / kWh], B - battery capacity [kWh], j (1,2,..., J) - the number of battery replacements during vehicle life.

Buses equipped with an electric drive system require special infrastructure to be launched. It is a set of battery charging stations. The cost of the infrastructure - C_i can be calculated as follows:

$$C_i = L \cdot P_C \quad (5)$$

where: L - number of charging stations on a given bus line, P_C – total cost of installation of the charging station [euro].

4.2. Data used for cost analysis

The analysis has assumed that the useful life of the bus is 15 years, the price of diesel oil is 1.17 euros / dm^3, and the price of electricity is 0.15 euros / kWh (Polish Chamber of Liquid Fuels, 2020). The prices of fuels, electric energy and the cost of replacing batteries in EV and HEV vehicles mentioned above were treated as fixed. In Table 3 data from vehicles taken for analysis are presented. Repair and operating costs are based on [41]. The battery replacement cost was taken from [7].

In the paper, two main methods of charging electric bus batteries were considered: fast charging using a pantograph located on the loops and slow charging using a plug-in, used mainly in depots. Table 4 presents the prices of the chargers taken from [41].

Table 3. Vehicle data for TCO analysis

	Diesel	EV	SHEV (9,4 kWh)	PHEV (1,8 kWh)
purchase cost [euro]	214 300	595 300	357 100	357 100
maintenance and operation costs [euro/year]	3 500	3 000	3 600	3 600
cost of battery replacement [euro]	-	215 000	6 700	13 000

The driving cycles presented in the previous section reflect the currently implemented public transport routes in Kielce (Poland). Table 5 shows the daily parameters of selected urban and suburban bus routes. Data were taken from the Urban Mobility Plan for City Kielce [27].

Table. 4. Prices of pantograph chargers used for calculations

	charging power [kW]	cost [PLN]
Plug-in charger	150	12 000
Pantograph charger	150	72 000
	300	85 000
	450	95 000
	600	120 000

5. Results

5.1. Energy consumption

Fig. 3 shows the energy consumption values obtained for the analyzed vehicles after completing the routes once.

Table. 5. Daily operation parameters on selected bus route

cycle	daily work time [h]	weekly distance [km]	number of trips per week	number of buses on the route per day
KI	21.15	951.75	87	3
KII	15.56	956.97	82	4
PI	10.95	256.9	6	1
PII	18.72	500.13	9	1

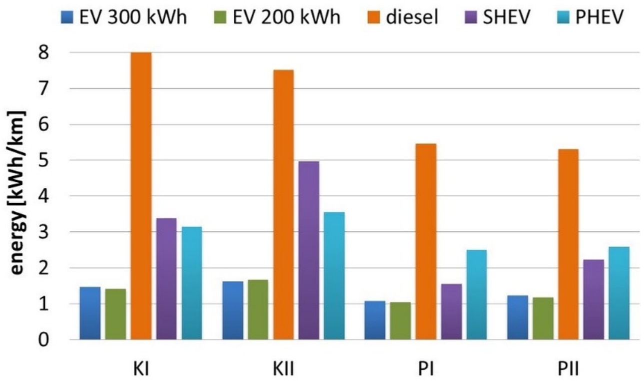

Fig. 3. Energy consumption

The highest energy consumption values obtained for the vehicles analyzed were observed for urban cycles. This is especially evident for buses with conventional and hybrid propulsion systems. For the KI urban cycle, the vehicle with a classic powertrain recorded about 35% lower energy consumption in suburban cycles. Compared to the KI cycle, electric buses showed a 27% lower energy consumption in the PI suburban cycle and a 16% lower energy consumption in the PII cycle. The bus with parallel hybrid drive compared to the KI cycle noted a lower energy consumption by about 20% in suburban cycles. In relation to the KI cycle, a vehicle with a serial hybrid drive recorded a lower energy consumption of 54% in the PI cycle and 34% in the PII cycle, respectively.

For cycles with a varied route profile (KII and PII), the electric and hybrid buses that were analyzed, the higher level of energy consumption was obtained. Vehicles with electric and hybrid powertrains can recover some of the kinetic energy during braking. Fig.4 presents the energy regenerated in the cycle per 1 km of the route.

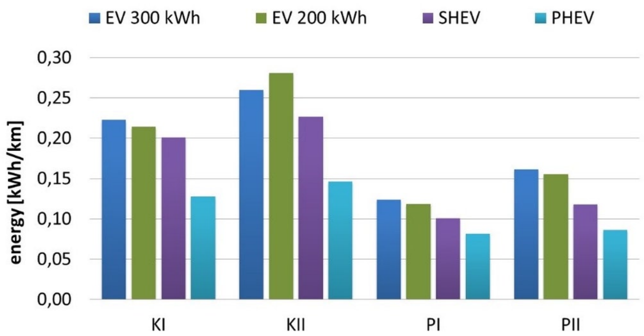

Fig. 4. Regenerated energy level

The highest values of recovered energy were obtained for urban cycles. It can be explained by short driving distances and, thus, the need for frequent accelerations and braking. Higher levels of recovered energy were achieved on routes with a varied route profile.

Fig. 5 shows the percentage share of energy taken from the electric bus battery after one cycle. The initial battery state of charge (SoC) has been assumed to be 100%.

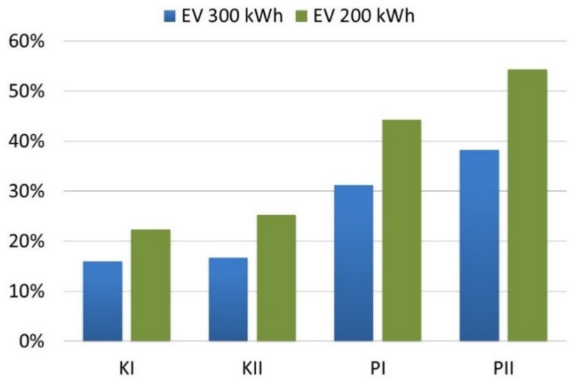

Fig. 5. Percentage share of energy taken from the battery

An electric bus equipped with a 300 kWh onboard battery consumes 16% of the energy available during a city cycle. For suburban cycles, the level of energy spent from the battery is 31% for the PI cycle and 38% of the energy stored in the battery pack for the PII cycle.

For the electric bus with the 200 kWh battery, for a single KI cycle about 22% of the stored energy must be used and for the KII cycle - 25%, respectively. This bus consumes about half of the energy available in the battery to perform one suburban cycle.

For the routes analyzed, electric buses are not able to meet the assumed daily working time (Table 5) without recharging the battery. The possible solution may be installation of the pantograph chargers with high charging power: 150, 300, 450, or 600 kW at the termini. In the presented study, the percentage of energy that can be stored when charging during 5 min 10 min, and 15 min stops between courses has been estimated (Fig. 6).

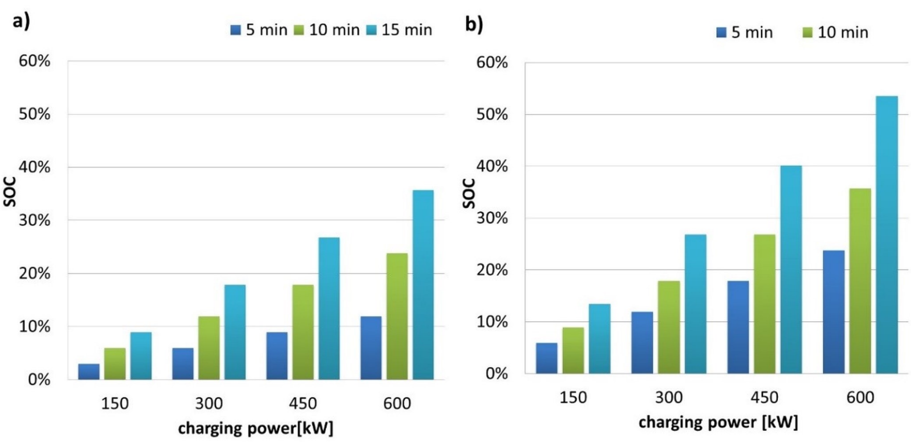

Fig. 6. Percentage of energy stored in the battery during charging of the battery with an energy capacity of a) 300 kWh, b) 200 kWh

The selection of the appropriate charging power depends on the range of the vehicle, the daily schedule, and the length of the routes. It can be seen in the figure above that using the 150 kW charger during 15 minutes of bus inactivity can charge 9% of the 300 kWh battery and 13% of the 200 kWh battery. This is not sufficient for the considered driving cycles.

For the KI and KII urban cycle routes, usage of the 450 kW charger is to be used, which should allow 300 kWh battery charge by 18% and a 200 kWh battery charge by 27% within 10 minutes. For the PI suburban route, the daily number of routes is small and the average sum of break time is 30 minutes. On this route, it is possible to use a 300 kW charger. For the PII route, three courses are scheduled in the morning and three at the traffic peak in the afternoon. This requires the installation of a 600 kW charger.

5.2. TCO analysis

The total cost of ownership (TCO) values for vehicles taken into account for urban and suburban cycles are presented in Fig. 7.

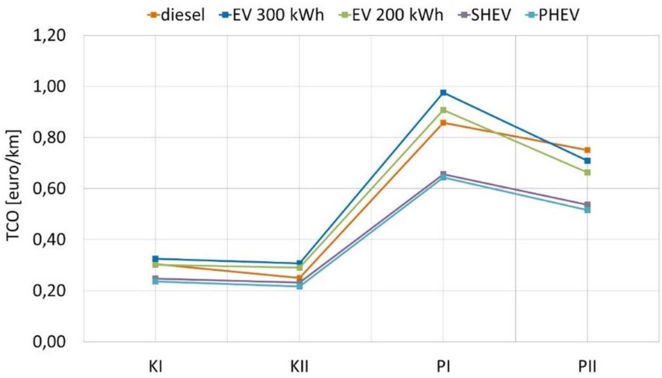

Fig. 7. Summary of Total Cost of Ownership (TCO) on selected bus routes

The total cost of ownership significantly depends on the route (R). For urban routes, the TCO values obtained for hybrid and conventional vehicles are similar. In urban cycles, the TCO values calculated for electric buses are nearly 50% higher compared to buses with standard power trains.

The vertical profile of the route is also an important issue. For the urban KII and suburban PI cycles, the route profile was varied, which significantly influenced the fuel (energy) consumption, and thus the TCO values of the analyzed vehicles increased. For hybrid buses, lower fuel consumption values were obtained compared to conventional vehicles. Therefore, hybrids work well on routes with varying terrain. For the urban cycle KI, the TCO values obtained for hybrids were similar to the TCO level of conventional vehicles, and in the PII cycle, the TCO was lower for hybrids by approximately 25%.

Furthermore, the number of courses performed during the week has a significant impact on the value of TCO. The purchase costs and infrastructure installation costs are incurred on a one-off basis and therefore they are not dependent on mileage. The more courses, the lower the influence of the fixed costs listed above is. This is especially visible in the case of the PI route, which is operated by only one vehicle and runs only six courses a week.

Purchase costs represent the highest share in the TCO of buses with electric and hybrid drives (Fig.8). Depending on the route, its share is 50-74% TCO. However, for electric and hybrid buses, fuel (energy) costs have a much lower share. For electric buses, this share is 4-18% TCO, and for hybrids, 15-40% TCO, respectively. Fuel costs have the largest share of the TCO of conventional vehicles.

6. Conclusions

The purpose of this study was to analyze the total ownership cost of city buses with different types of propulsion system and for selected urban and suburban cycles. On the basis of the results, it can be seen that the route and the daily courses have a significant impact on the TCO values. These two factors significantly affect the total cost of

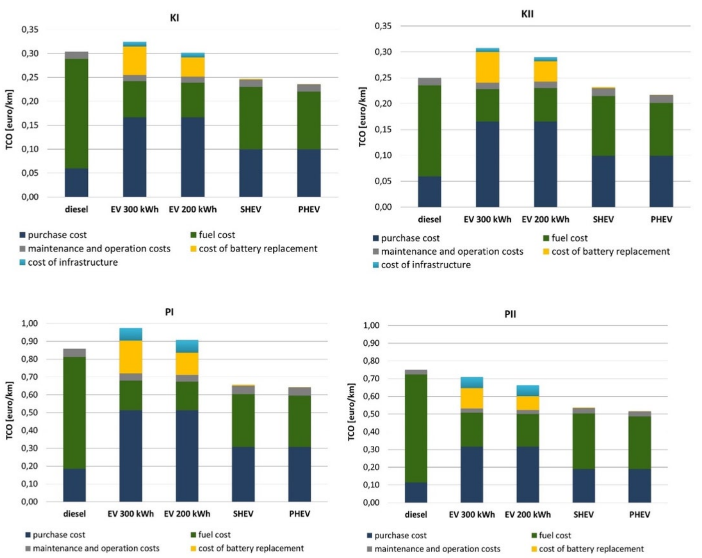

Fig. 8. TCO structure for the analyzed bus routes

ownership of the vehicle regardless of the type of propulsion system.

In addition, it was shown that the costs of owning and operating a city bus depend on the type of drive train. The TCO method allowed the assessment of the values of the individual cost components comprising vehicle purchase and operating costs. The test results show that electric buses represent the highest TCO values among the vehicles taken into account. Compared to standard buses, the TCO values obtained for electric buses in urban cycles are about twice as high. Currently, only hybrid buses can compete with conventional buses. They are characterized by a lower level of fuel consumption and similar values of the total cost of ownership.

Many authors of the works mentioned in the first part of the paper expect that vehicles equipped with electric propulsion systems will become competitive for vehicles with standard buses in a few years. This will be the result of the lower prices of lithium-ion batteries and the rising fuel prices. Currently, the only chance to increase the share of electric buses in the fleets of Polish municipal public transport companies is the total or partial financing of their purchase using government or local government subsidies.

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