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A DYNAMIC SOCIETY-ORIENTED TOTAL COST OF OWNERSHIP MODEL FOR ELECTRIC BUS DEPLOYMENT

Summary. This paper presents a new methodology for calculating the total cost of ownership (TCO) for the deployment of battery-electric buses in public transportation. The model considers multiple parameters and their dynamics, complementing the existing body of knowledge on TCO models. The model integrates internal and external cost categories, accounting for cost dynamics over time and the allocation of these costs among different stakeholders, including public transport operators and local authorities. Unlike static models, our dynamic framework captures the evolution of costs throughout the project lifecycle by incorporating forecasted values for variables such as operational expenditures, energy prices, maintenance, and environmental costs. Furthermore, the model includes externalities such as emissions and noise pollution costs, which are often overlooked in traditional TCO assessments. Based on data obtained from public transport operators, we applied the TCO model to a real-life long-term conversion scenario in southern Poland. The main research findings emphasize the importance of operating and external costs in the overall TCO structure, with the latter accounting for up to 30% of the total TCO. Their inclusion in the model is crucial because they are typically not considered in TCO models.

1. INTRODUCTION

One of the dimensions of reducing the environmental impact of human activity is environmentally friendly public transport. Cities and metropolitan areas aim to increase the proportion of buses that use alternative fuels, and the deployment of battery electric buses (BEBs) is one such option. BEBs are locally emission-free, which is beneficial for residents of densely populated areas [9]. However, their environmental impact is not negligible: the origin of the materials for electric vehicle batteries and the process of their extraction, as well as their subsequent disposal, are questionable [19]. However, the main challenge in their deployment is to overcome the problems caused by BEBs' limited range and the resulting need to recharge them [7]. This implies, among other things, choosing the correct type of bus with appropriate battery packs [3], estimating energy consumption along the route [2], determining the charging strategies [7], selecting optimal locations for chargers or battery swap stations [28] and scheduling charging [17].

The energy demand of the entire system is also an issue. In the analysis, the price difference between electric and diesel buses is important. The latter depends on the region of the world, the size of a single order batch, the equipment, the size of the battery, and, thus, the range, the design used, the warranty

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conditions, and other factors [14]. Analyses claim that presently, an electric bus is approximately twice as expensive as a conventional bus with a combustion engine, with external costs only taken into account to a small extent as evaluation criteria in the tender procedures for vehicle purchases [10]. Analysis of these problems requires consideration of the characteristics of the transportation network and local conditions, such as weather conditions and terrain [25]. The technical problems mentioned above lead to organizational challenges, including determining which bus routes to deploy BEBs on [30] and in what order to do so [11]. This issue can and should be examined by analyzing the life cycle of various vehicles and their environmental impact, as well as considering the country's energy mix [21].

The decision to convert a fleet to electric buses may be driven by the policies of public transport commissioning bodies (e.g., cities and metropolitan areas). However, the financing and purchasing of bus fleets in most cities is the responsibility of public transport operators, as they must ensure the necessary means of transport for providing services. Each entity has a distinct fleet structure, economic situation, and opportunities for securing external funding for the fleet conversion process. This results in each entity being able to generate many different strategies for the exchange process.

The aforementioned aspects entail economic consequences, one dimension of which is the total cost of ownership (TCO) study: a methodology that extends beyond the purchase price to incorporate other costs associated with ownership [4]. The TCO methodology is used extensively in transportation. A survey of the literature reveals that the majority of case studies are [1, 6, 25, 27]. Typically, TCO is one optimization criterion, for example, in charging infrastructure optimization. Some studies have calculated the total TCO of a system based on vehicle operational schedules, as the required number of buses and chargers, as well as mileage and driver time, are directly derived from the timetable [24]. The cost of purchasing electric buses (including determining the size and composition of the fleet), the investment in charging infrastructure, and operating costs (including energy and personnel) were included. Other TCO models developed for bus line electrification include operational data (e.g., line characteristics and scheduled operations), technological data (e.g., charging data and battery parameters), and costs (acquisition costs of vehicles and infrastructure, operating costs, and disposal costs). They determined individual financial ratios for bus line electrification over the service life of vehicles [15].

Many studies on the TCO of BEB deployment rely on generic route data and simplified assumptions, such as the failure to include certain cost components (e.g., drivers' wages and network connection costs) [12] or considering them as permanently static values. Some models operate on static schedules without considering operational delays and traffic disruptions. Another problem is the lack of consideration or a very simplistic approach to calculating external costs. In addition, TCO models that have been developed so far do not take into account the different models of investment financing (own funds, loans, subsidies), which reduces their applicability value for transport companies. Similarly, developments in the battery and electricity markets are also important and largely determine the high cost of an electric bus, as evidenced by the European Union (EU) and the United States of America [29].

We can divide TCO models into static and dynamic [12]. Static models are based on the assumption of a constant time value of money, while dynamic models account for changes over time by incorporating net present value (NPV). In most cases, dynamic models also consider projected future expenditures. We can also identify two approaches for TCO calculations: consumer-oriented and society-oriented. Consumer-oriented TCO analysis only includes the costs perceived and borne by consumers. They include the purchase price, as well as all costs associated with the actual receipt and use of the item that are borne by the consumer [4, 19]. A society-oriented TCO analysis adopts a significantly broader perspective, incorporating not only capital and operating expenditures but also external costs, such as carbon emissions [16].

In Chapter 2, we describe our dynamic society-oriented TCO model for electric bus deployment.

2. METHODOLOGY

The TCO model is designed to facilitate the ex-ante evaluation of long-term costs associated with planned investments. The model is dynamic, as it incorporates changes in various cost categories over time, and society-oriented, as it accounts for external costs. It covers long-term planning, including the life cycle and actual use of vehicles and infrastructure. It is intended for transport operators, transport organizers, and policymakers at various levels and includes the possibility of assigning different TCO components to different stakeholders and beneficiaries of the investment. Additionally, the model considers various financing mechanisms, including co-financing from external funds. It encompasses all major cost categories related to the acquisition of an electric bus fleet and the associated infrastructure, with particular emphasis on depreciation, which constitutes one of the largest components of transport-related expenses. Figure 1 presents the general elements of the dynamic society-oriented TCO model. As input, the TCO model includes information on subsequent bus batches, infrastructure batches, and spare battery batches, along with information about economic analysis parameters. The number of batches of buses and infrastructure may not be equal, and they may not start at the same time.

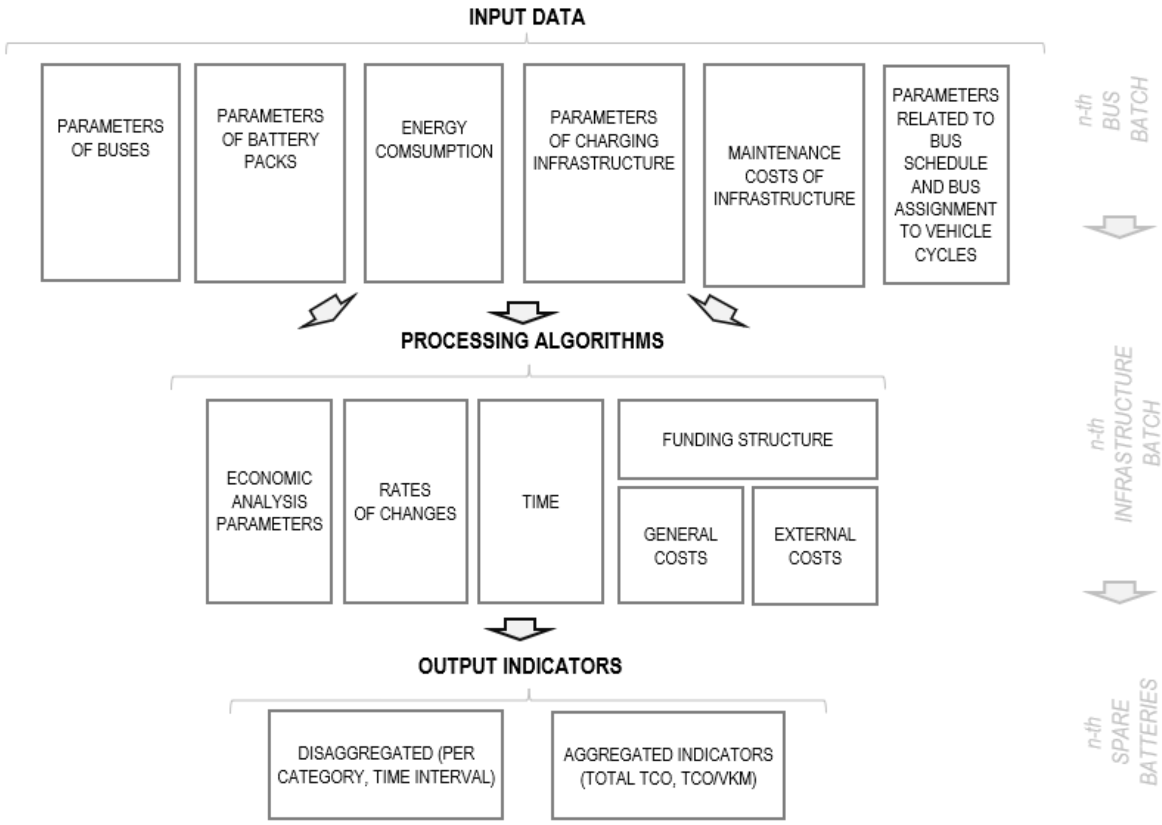

Fig. 1. Key elements of the dynamic society-oriented TCO model

The presented framework of the TCO model is a multi-stage process comprising three primary components: input data, processing algorithms, and output indicators. The input layer comprises technical and financial data on the number and timing of bus purchases, infrastructure deployment plans, and spare battery replacement schedules. The transformation layer comprises modules for cost estimation (both capital and operational), present value discounting, external cost computation, financing structure simulation, and economic analysis parameters. These modules process the inputs using time-dependent algorithms, enabling dynamic updates based on cost trends and investment phasing. Finally, the output layer delivers the TCO results in disaggregated form (per cost category, time interval, and stakeholder), along with aggregated indicators such as EUR/vkm or total investment cost over the defined project horizon. Each module is interconnected to simulate the feedback mechanisms typical of dynamic modeling, such as how subsidy availability or energy price trajectories influence long-term cost structures.

In this model, the term "batches" refers to the segmented procurement or investment phases for electric buses, infrastructure, and spare batteries. For example, a bus batch typically denotes a group of 10 buses acquired in a five-year interval, reflecting a phased investment strategy aligned with financial and operational planning. Similarly, infrastructure batches refer to grouped installations of charging equipment—such as depot chargers or pantographs—corresponding to the number of buses introduced in a given period. Spare battery batches follow the same periodic approach, with battery replacements scheduled every five years to ensure fleet reliability and performance throughout the analysis horizon. This segmentation reflects the common real-world procurement practice of gradual fleet electrification and staged capital investment, often dictated by public budget cycles, procurement laws, or the availability of funding mechanisms, such as EU subsidies.

Economic analysis parameters are essential variables used to compute the present value of future costs and benefits in the TCO model. These include, but are not limited to, the discount rate (financial and social), inflation assumptions, tax relief factors, the rate of change in energy costs, labor costs, maintenance cost growth rates, insurance cost growth, and assumptions on the future evolution of external costs such as emissions and noise. In line with European Commission (EC) recommendations, the model allows users to input country-specific or project-specific values for these parameters, enhancing the precision and contextual relevance of the economic evaluation. Users can either adopt default values or adjust them to reflect local macroeconomic conditions and sectoral trends.

The subsequent steps of the algorithm require data on the model's validity period, the planned BEB purchases, and the required infrastructure. It is essential to enter the acquisition costs of the selected charging technologies and the number of installations. It is also necessary to determine the financing structure and other economic analysis parameters. It is necessary to enter the value of the discount rate for buses with batteries and infrastructure. We can use the default values recommended by the European Commission or adapt them as needed. In the rates of change section, we need to enter the energy supply cost rate, the personnel cost rate, the energy cost rate, the tax relief, the annual insurance cost change rate, and other costs if a single cost rate is used. It is also essential to enter the energy cost rate for both low-voltage and medium-voltage networks, as well as the tax relief for each if a medium-low-voltage network rate is used. In the final step, we need to specify the rate of change of air pollution and GHG emissions, the cost of noise emissions, and the cost of pollutant emissions.

The estimation of present value (PV) is a financial method for analyzing cash flows occurring at different time intervals. This method determines the current value of future cash flows through discounting. In general, the present value is lower than or equal to the future value [16, 22]. The TCO is calculated using the following formula:

$$\boldsymbol{TCO = (PV_{bus} - PVL_{liq\_bus}) + PVOC_{bus} + PV_{infr} + PVE_{exter},} \tag{1}$$

where PV_{bus} represents the present value of the acquisition costs of electric buses, PVL_{liq_bus} represents the present value of the proceeds of liquidation, $PVOC_{bus}$ represents the present value of bus operating costs, PV_{infr} represents the PV of the infrastructure, and PVE_{exter} represents PV of the external costs. The PV is calculated as follows [13, 23]:

$$\boldsymbol{PV = FV \times \frac{1}{(1-i)^t},} \tag{2}$$

where FV represents the future value of costs, i represents the discount rate, and t represents the period.

For example, in the EU, for projects co-financed by European funds for the period from 2014–2020, the European Commission recommended a 4% financial discount rate for long-term analyses in financial calculations. In contrast, a 5.0% social discount rate (SDR) was used for economic analyses. According to the cost-benefit analysis (CBA) methodology employed by the European Commission, the social discount rate represents the societal valuation of future benefits and costs in comparison to their current value. The discount rate can also vary depending on the country, its macroeconomic situation, and the sector in which the investment is made. The real discount rate for TCO calculations for electric vehicles is determined as follows [20]:

$$\boldsymbol{real\ discount\ rate\ i = \frac{(1+nominal\ rate)}{(1+inflation\ rate)} - 1.} \tag{3}$$

When the analysis is carried out at constant prices, the real discount rate should be used. In our model, it is sufficient to use the nominal discount rate, as the analysis accounts for the dynamics of price changes of individual components, and thus, the analysis is more accurate than adjusting for inflation, as a macroeconomic quantity will not reflect the forecasts of price changes for such innovative components as batteries.

The total nominal cost of bus acquisition is calculated as the sum of the nominal costs of batteries, vehicles, and double-layer capacitors. The dynamic TCO economic model incorporates several investment financing strategies, allowing for different combinations of self-financing, bank loans, subsidies, and leasing, which are represented as follows:

$$\boldsymbol{AC_{bus\_nom_i} = AC_{bus\_cred\_i} + Bus_{self_i} + Bus_{sub_i} + Vbus\_init_i}, \tag{4}$$

where $AC_{bus\_nom_i}$ – the nominal acquisition costs of buses [EUR], $AC_{bus\_cred_i}$ – the amount of credit for bus purchase [EUR], Bus_{self_i} – the costs of bus acquisition (self-financing) [EUR], Bus_{sub_i} – subsidies for bus purchase [EUR], and $Vbus\_init_i$ – the value of the leased bus without initial fees.

Thus, the model includes various combinations of financing sources for vehicle purchases. Moreover, according to the developed model, different batches of buses may be financed using different methods. The model also considers that cash flows associated with the purchase of a bus fleet may occur at different points in time—for example, when the fleet is acquired in batches over multiple years or periods, which is a common scenario given the specific procedures governing such investments under public procurement law. Subsidies may also be granted in different periods and disbursed in tranches—a frequent situation, particularly in EU-funded projects, where payments are often delayed until the submission of appropriate accounting documentation. The developed TCO model includes two types of bank loans: loans with equal installments (annuities) and loans with decreasing installments (for which each installment includes a fixed principal component).

The nominal annual value of operating costs of electric buses include energy costs, maintenance costs, insurance, energy supply, and other costs (such as vehicle tax) and are calculated as follows:

$$\boldsymbol{OC_{bus} = OC_{ener} + OC_{maint} + OC_{insur} + OC_{ener\_supp} + OC_{other}}, \tag{5}$$

where OC_{bus} – annual operating costs of the bus fleet, OC_{ener} – annual energy costs, OC_{maint} – annual maintenance costs, OC_{insur} – annual insurance cost, OC_{ener_supp} – annual costs of daily energy supply, and $\mathrm{OC_{other}}$ – other annual costs (e.g., vehicle tax).

The annual cost of daily energy supply is determined using the following equation:

$$\boldsymbol{OC_{ener\_supp} = Bus_{oper\_ann} \cdot Ener_{supp\_cost\_r}}, \tag{6}$$

where OC_{ener_supp} – annual costs of the daily energy supply, Bus_{oper_ann} – annual transport work [vkm/year], and $Ener_{supp\_cost\_r}$ – energy supply cost rate [EUR/vkm].

The annual energy cost is calculated using the following formula:

$$\boldsymbol{OC_{ener} = Bus_{oper\_ann} \cdot [Ener_{cons} \cdot (Ener_{cost} - Tax_{relief})]}, \tag{7}$$

where OC_{ener} – annual energy costs [EUR], Bus_{oper_ann} – annual transport work [vkm/year], $Ener_{cons}$ – energy consumption [kWh/vkm], $Ener_{cost}$ – cost rate of energy [EUR/kWh], and Tax_{relief} – tax relief [EUR/kWh].

The correct calculation of the operation and maintenance components is important in the TCO model (i.e., for the assessment of the investment costs over the entire life cycle). For example, the experience of participating transport companies shows that the labor intensity of bus maintenance is at least 20% higher than for diesel vehicles. The nominal infrastructure acquisition costs incurred in a given year encompass all types of charging infrastructure, including depot-based conductive plug-in charging, battery swapping/charging systems, pantograph charging, bus-stop charging, and in-motion inductive charging. Moreover, the financing structure for the acquisition or construction of the required infrastructure may mirror that of the bus fleet, involving various combinations of own funds, bank credit, subsidies, and leasing. The components used depend on the technological and financial model adopted.

External costs are also incorporated into the TCO analysis. The annual external costs are estimated using the following formula:

$$\boldsymbol{EC_{exter} = Bus_{oper\_ann} \cdot (Noise_{cost_r} + EPoll_{cost_r}) + Bus_{oper_{ann_h}} \cdot HPoll_{cost_{er}}}, \tag{8}$$

where EC_{exter} – annual external costs of the bus fleet, Bus_{oper_ann} – annual transport work [vkm/year], $Noise_{cost\_r}$ – cost rate of noise emission per vehicle-km [EUR/vkm], $EPoll_{cost\_er}$ – cost rate of air pollutant and GHG emission per vehicle-km [EUR/vkm], $Bus_{oper\_ann\_h}$- annual transport work of bus fleet with oil heating [vkm/year], and $HPoll_{cost\_er}$ – cost rate of pollutant emission per vkm (bus heating with oil) [EUR/vkm],

The model considers traditional combustion heating because this is a necessity for electric buses in countries where winter temperatures fall below 0. Traditional combustion heating refers to auxiliary diesel-powered heating systems, commonly known as Webasto or similar combustion heaters. These systems are frequently installed in electric buses operating in cold climates, particularly in Central and Eastern Europe, to ensure sufficient cabin heating when ambient temperatures fall significantly below freezing. Due to the limited efficiency of battery-powered thermal systems in such conditions, internal combustion heaters remain a necessary supplementary solution. The energy consumption of the vehicle and battery usage efficiency are mainly influenced by the vehicle's heating and the number of passengers carried. The experience of participating operators shows that in countries such as Poland, approximately 30% of operational work is carried out using diesel-powered heating systems. In this case, the external cost rates for diesel should be applied, which are included in the model. Although electric buses significantly reduce noise pollution, the model assumes the application of a cost rate for noise emissions at 50% of the values for diesel buses.

The rates of external costs are averaged values calculated from marginal cost estimates for representative reference cases in the EU [5]. Of note, the user can choose values for well-to-tank costs related to air pollution and climate change. Well-to-tank external costs encompass all costs throughout the entire fuel life cycle, including externalities that arise not only during fuel combustion in various applications such as energy and transportation but also from fuel extraction, processing, transportation, and distribution [8]. The model is available online [31].

3. RESULTS ANALYSIS AND CASE STUDY

The following demonstration illustrates the functionality of the model using the Silesian Voivodeship as a case study. It is a highly industrialized region in southern Poland and the second-largest metropolitan area in Poland, with a population of 4.5 million people. The central part of this area comprises 42 municipalities, which vary significantly in terms of population and level of urbanization. Public transport in this area is organized by three entities: the Metropolitan Transport Authority (ZTM) in Katowice, MZUiM in Jaworzno, and the Marshal's Office of the Silesian Voivodeship. The public transport system encompasses buses, trams, trolleybuses, and trains. The central part of the Silesian Voivodeship features a well-developed, integrated, and relatively efficient public transport network. Nevertheless, this area faces challenges similar to those observed in other urban and metropolitan regions worldwide, such as increasing traffic congestion due to the rising number of private vehicles, a decline in the modal share of public transport, and a deterioration in the quality of life associated with air pollution and the external costs of transportation. Most operators are planning investments related to the electrification of their bus fleets, and some are already operating electric buses, though they still represent a small share of the total fleet. The conversion of the vehicle fleet to electric, combined with extensive infrastructure investments, is also currently planned at the level of transport policy actors: local public transport organizers in the central part of the Silesia Voivodship. A strategy is being developed in this respect, and investments will be co-financed with EU funds.

The practical applicability of the developed model was verified in collaboration with public transport operators. The proposed methodology was tested using a realistic operational scenario. The analysis was conducted based on one of the fleet conversion scenarios considered by an operator providing services in Central Silesia Voivodship. We obtained the data from this operator.

The electric fleet conversion scenarios assumed the purchase of four different batches of 10 new electric buses every five years, with each batch of 10 buses having a distinct financing model. Two scenarios were analyzed. In the first scenario, the first batch of buses and charging infrastructure is 100% self-financed by the operator. Moreover, in both scenarios, the investment in charging infrastructure will not be phased but will be accumulated in one year. In the second scenario, the first batch of buses and charging infrastructure is assumed to receive an 85% non-refundable EU grant. In both scenarios, the second and fourth batches are 90% loan-financed, and the third batch is 70% lease-financed. Infrastructure investment includes a plug-in depot charger and a pantograph charger located at each bus stop, one for each bus. The analysis is long-term, and infrastructure maintenance costs are incurred over a 30-year period. We assumed the costs to be constant throughout the analysis period (Table 1). In addition, we also assume that every five years, 10 new replacement batteries are bought, and every seven years, the cost of battery disposal is incurred (EUR 1,000 for every 10 batteries).

Table 1

Values of the main variables in the adopted scenario

	Batch 1	**Batch 2**	**Batch 3**	**Batch 4**
Analysis period in years	**1–5**	**6–10**	**11–15**	**16–31**
Number of buses in operation	10	20	30	40
Annual operational work	4 197 500	8 395 000	12 592 500	20 148 000
Number of service personnel hours	21900	43800	65700	87600
Annual energy costs	906 660	1 813 320	2 719 980	4 351 968
Annual maintenance costs	109 500	219 000	328 500	438 000
Annual insurance costs	100 000	200 000	300 000	400 000
Annual costs of daily energy supply	839 50	1 679 000	2 518 500	4 029 600
Other cost per year	10 000	20 000	30 000	40 000
Annual operating expenses	1 965 660	3 931 320	5 896 980	9 259 568
Annual operation with oil heating	1 399 166.7	2 798 333.3	4 197 500	6 716 000
External costs per year	965 425	1 930 850	2 898 275	4 634 040

Figs. 2 and 3 present the TCO for the planned investment annually within two scenarios without subsidies (Scenario 1) and with subsidies (Scenario 2).

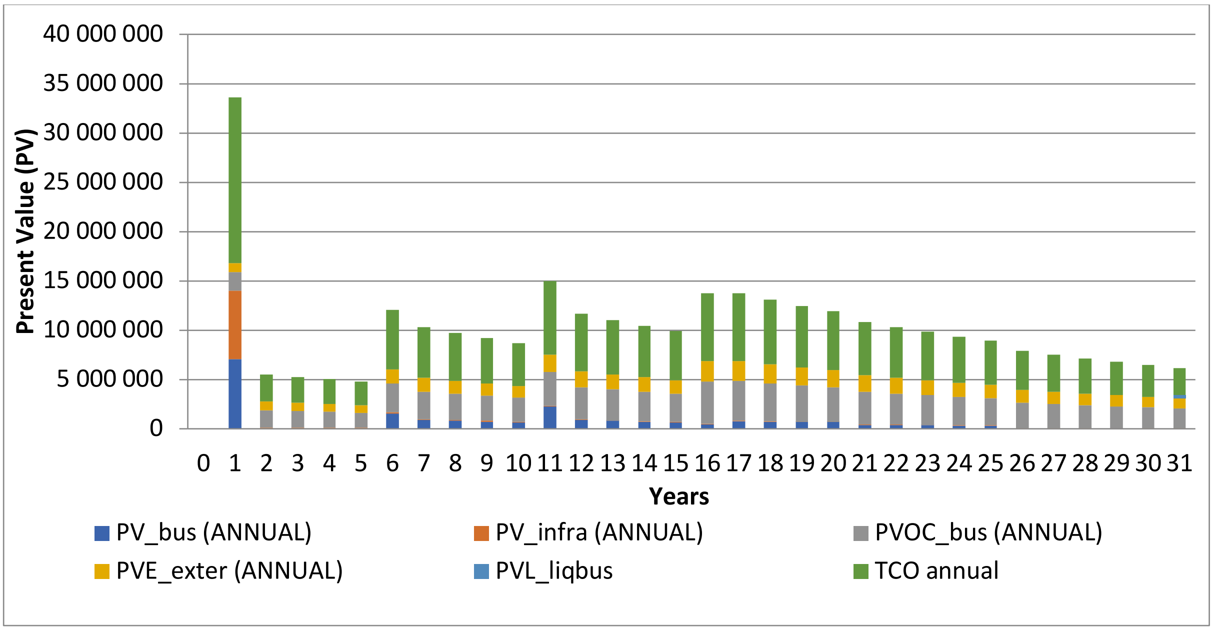

Fig. 2. TCO per year for Scenario 1 without subsidies

The final TCO value is expressed in EUR/vkm based on the total mileage over the operational period. The values of each TCO component for both scenarios are presented in Table 2. The only difference between the two analyzed scenarios is the subsidy received during the first five years of the planned investment. The negative values in the first five years of Scenario 2 are related to the subsidy (an 85% non-refundable EU grant) received for the purchase of buses and infrastructure. This subsidy significantly impacts the TCO of the investment. In Scenario 1, it is assumed that the first batch of buses and charging infrastructure is entirely self-financed by the operator, resulting in positive present values during the initial period. The conditions for the subsequent periods are identical in both scenarios; therefore, the values of individual components remain consistent across both cases.

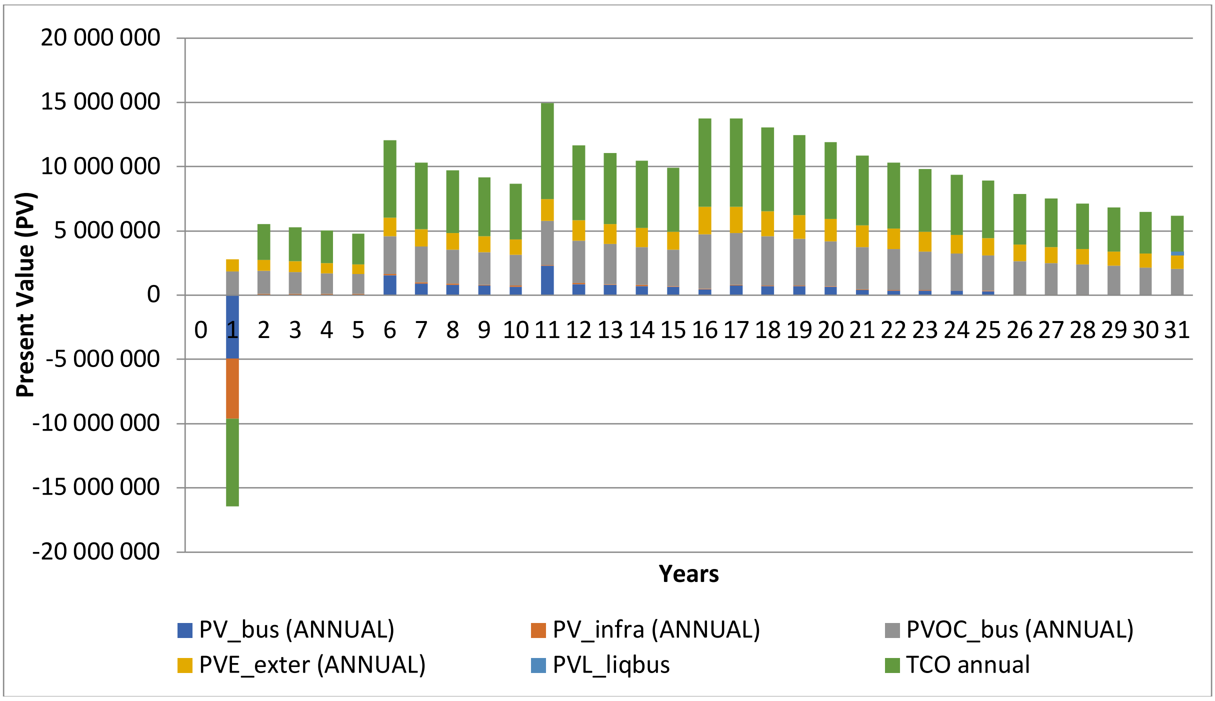

Fig. 3. TCO per year for Scenario 2 with subsidies

The final TCO value for the adopted scenario is 135.2 million EUR, which translates to 0.55 EUR/vkm in this case based on the total mileage over the operational period (246.8 million vkm). If the operator were to receive no external support for the investment, the TCO over the entire 30-year analysis period would increase to 0.64 EUR/vkm.

The case presented demonstrates the possibility of a detailed analysis of all cost components over any period. The results enable the assessment of the planned conversion with a high degree of accuracy, as well as the comparison of multiple variants of planned activities.

4. CONCLUSIONS

This paper presents a new methodology for calculating the TCO of electric buses in public transport. The model is based on the ex-ante economic evaluation of the conversion process of a conventional or mixed fleet of urban buses, aiming to obtain the broadest possible deployment of BEB in public transport (referred to hereafter as the conversion process). This process involves putting a specified number of electric buses into service, either one at a time or in batches (thus gradually reducing the share of conventional buses). Primarily for economic reasons, this process is a multiphase one for most actors and is often spread over many years. Therefore, it is important to plan the conversion process rationally. This is all the more relevant given that transport operators are keen to invest in innovative technologies in cases where the financial risk is low, as suggested in [26]. The methodology of our model takes into account important long-term issues for these entities that have not been addressed in previous models or current financial calculations, such as the inclusion of external (including climate-related) costs, the allocation of costs to stakeholders, the dynamics of cost changes, and different financing models.

Table 2

Results for two simulated scenarios analyzed with the public transport operator

TCO components	Total (EUR) 30 years	Batch 1	Batch 2	Batch 3	Batch 4
Scenario 1 (without subsidies)					
PV_bus	22 094 014.18	7 047 619.05	4 659 447.67	5 332 094.67	5 054 852.80
PVOC_bus	85 791 591.00	7 376 680.06	407 070.99	318 950.77	625 578.30
PV_infr	8 728 280.12	8 510 279.11	13 336 052.74	15 673 719.42	48 271 539.73
PVE_exter	42 585 760.17	4 179 785.01	6 549 941.86	7 698 076.25	24 157 957.04
PVL_liqbus	326 132.02	0.00	0.00	0.00	326 132.02
TCO 30 years	158 873 513.02	27 114 363.23	24 952 513.26	29 022 841.11	77 783 795.84
TCO EUR/vkm	**0.6437**	**1.2919**	**0.5945**	**0.4610**	**0.6434**
Scenario 2 (with subsidies)					
PV_bus	10 113 061.80	-4 933 333.33	4 659 447.67	5 332 094.67	5 054 852.80
PVOC_bus	85 791 591.00	-4 280 462.80	407 070.99	318 950.77	625 578.30
PV_infr	-2 928 862.74	8 510 279.11	13 336 052.74	15 673 719.42	48 271 539.73
PVE_exter	42 585 760.17	4 179 785.01	6 549 941.86	7 698 076.25	24 157 957.04
PVL_liqbus	326 132.02	0.00	0.00	0.00	326 132.02
TCO 30 years	135 235 418.20	3 476 267.99	24 952 513.26	29 022 841.11	77 783 795.84
TCO EUR/vkm	**0.5479**	**0.1656**	**0.5945**	**0.4610**	**0.6434**

The analysis of the TCO results for a fleet conversion scenario based on the actual assumptions of the public transport operator allows important conclusions to be drawn. The investment under study assumes a long-term, phased conversion of the fleet to an electric fleet. In the case of the investment studied, the TCO structure is dominated by operation and maintenance costs (more than 60%) and external costs (more than 30%). The investment in infrastructure has the smallest share in the TCO structure. The application of the model in business practice highlights the importance of operating costs and external costs in the overall structure of TCO. Previous research and TCO models in this area have not considered costs, and the application of the model to a realistic scenario shows just how important external costs are as a component of TCO. Given this fact and climate-neutral policies, the question arises as to whether they should be a major element in TCO analyses and also a permanent element in public procurement, such as in the form of public contracts and tenders.

It is also worth noting that the model considers the possibility of assigning different components of TCO to various stakeholders/beneficiaries of the investment. This is particularly important when considering different funding mechanisms, as one possible option is a model in which operators purchase the buses and charging infrastructure at depots, while the charging infrastructure outside the depots is funded by the relevant transport policy actors, typically the local authorities that contract transport services. Such a model enables the standardization of infrastructure and technological solutions used throughout the area, as well as the integration of various operators. Separating bus battery charging infrastructure outside depots from operators also provides greater cost transparency, allowing for the specification of infrastructure costs and fleet operating costs.

Moreover, the developed TCO model provides the opportunity to make a detailed sensitivity analysis of cost parameters, taking into account individual cost components, including external costs, as well as changes in forecasts of the dynamics of these costs over time. Sensitivity analyses of the cost parameters in TCO models for electric buses have not yet been conducted.

Our methodology makes a significant contribution to the literature in two key areas. First, it complements the existing theoretical achievements with a new, detailed TCO model of great application value for public transport operators, as well as for local governments that shape sustainable transport development strategies. Second, it takes into account the dynamics of changes in micro- and macroeconomic factors that influence TCO in the long term. Its application value has been confirmed by public transport service providers, who have tested the model and are formulating their new rolling stock purchasing policies with its help. These entities operate in different economic and organizational settings.

In addition, our research enables the creation of public policy solutions for subsidies and procurement in the context of financing electrified public transportation.

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