EVALUATION OF THE LIFE CYCLE COSTS FOR URBAN BUSES EQUIPPED WITH CONVENTIONAL AND HYBRID DRIVE TRAINS

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Abstract

The life cycle cost (LCC) methodology provides understanding of economic aspects of urban buses equipped with different types of propulsion. The LCC analysis delivers the sum of costs related to the acquisition, operation, repair and maintenance disposal as well as the costs for the each bus power train technology. The method allows to take into account all costs for the whole vehicle's life cycle and creates a precondition for precise information database for decision making. In addition to the economic factors LCC can be extended to environmental aspects such as greenhouse gases emissions.
The environmental impacts of the vehicle lifetime may be presented in monetary values.
The paper presents the Life Cycle Cost analysis undertaken for urban buses fitted with conventional, series hybrid and parallel hybrid drives. Provided LCC analysis includes the economic and environmental aspects. The paper also delivers the evaluation of the total air pollutant emissions for all stages of lifetime of the each analysed urban bus. The results show that the hybrids have slightly lower life cycle cost than conventional bus. Moreover, hybrid buses were found to have lower life cycle environmental impacts.

Keywords: Life Cycle Cost, hybrid electric vehicle, Life Cycle Assessment, air pollutant, urban bus

1. Introduction

The urban transportation companies have taken actions to replace the diesel-powered buses by alternative fuelled or alternative powered buses, such as: compressed natural gas (CNG) fuelled or liquefied natural gas (LNG) fuelled, biodiesel fuelled, battery electric drive system, hybrid electric (diesel-electric drive system) and fuel cell or hydrogen powered. The decision to choose and purchase a particular vehicle's drive option is not easy to make. Therefore, determining of the LCC can be a useful tool to compare costs associated

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with the production and operation of vehicles equipped with different types of propulsion systems. The LCC – Life Cycle Cost method allows to estimate costs ranging from the phase of vehicle production through every day use and operation to disposal phase as waste. The life cycle cost estimation includes a detailed economic analysis, including investment costs (i.e. purchase, registration, additional necessary infrastructure), costs of use (fuel, electrical energy, repairs and maintenance costs, insurance) as well as decommissioning costs (recycling) [20].

Level of LCC is strictly associated with fuel price, duty cycle, driving conditions (e.g. operation in city centre, suburbs, or on highways) as well as annual mileage. Some studies [10, 11] have been performed for the evaluation of Life Cycle Cost for electric buses in urban conditions.

The LCC value is also relates to a vehicle type. Alternative powered vehicles require the specific type of materials, components and manufacturing process. Many works have been devoted to analyse the life cycle cost of city buses with various types of propulsion systems. The paper [18] shows the LCC calculated for 21 different urban bus technologies. Presented results demonstrate the highest LCC level for hybrid buses. In works [1, 4] LCCs of buses equipped with hydrogen cells, conventional, hybrid and electric drives were compared. These analyses show that the hydrogen cells bus can be characterized by the highest lifecycle cost among the analysed vehicles. The reason is the expensive hydrogen fuelling infrastructure.

In reports [17, 23] the life cycle cost method was used to provide an overview of the current state of the fleet in public transport companies. The presented analysis summarized the costs and potential greenhouse gas reductions, and delivered the benefits of investment in alternative fuelled drive systems. In order to assess the vehicle's life cycle the ecological aspect only, the LCA method can be used. The Life Cycle Assessment (LCA) is focused on the estimation and assessment of environmental consequences that individual stages of the vehicle life cycle exert, including the consumption of raw materials, energy or emission of harmful gases and substances, beginning from the vehicle production phase, through the production of materials and assembly phase, the vehicle usage, with the necessity of production of fuel or electrical energy and the level of fuel consumption until the end of the life cycle including the costs of recycling and utilization. It should be noted that the economic criteria are not taken into account in the LCA method [8].

Many works have been devoted to the Life Cycle Assessment for city buses with various types of propulsion systems. Studies [3, 14, 24] present comparison analysis of greenhouse gases emission of conventional and alternative powered urban buses. Paper [9] provides LCA analysis of urban buses equipped with a classic internal combustion engine and alternative powered drives. The authors examined the impacts of type of the vehicle's drive system on the emission of the greenhouse gases for the manufacture, use, maintenance and infrastructure phases of diesel and battery electric buses.

The LCA method can be used to assess the environmental impact of specific vehicle's component life cycle. For example, the paper [12] presents the analysis of greenhouse gas emissions of every stage of lithium-ion batteries life-cycle. Studies [26, 27] present the estimation of the environmental impacts of recycling during the end of vehicle life.

To assess the economic and environmental aspects of the life cycle at each stage of the vehicle life, the EIO-LCA (Economic Input-Output Life Cycle Assessment) method can be used. This method estimates economic factors related to the vehicle's production and use of the vehicle. Impact on the natural environment, manifesting in the emission of related harmful substances during the phase of production and distribution of fuels, production of car parts and subassemblies, assembly of parts and subassemblies, operation and use of the vehicle and withdrawal out of exploitation, were expressed in monetary units and presented in the form of costs [20]. Examples of the application of the EIO-LCA method for the analysis of the life cycle costs of urban buses equipped with classic and alternative drives can be found, among others, in the works [19, 25].

The analysis of the vehicle life cycle can be carried out for specific road and geographic conditions. Study [28] presents the life cycle cost estimated for urban buses equipped with conventional and alternative drives operating on selected routes in Pittsburgh (USA). Presented results show that electric buses fitted with rapid charging system indicate the five time lower emission cost than conventional bus. Paper [9] provides the evaluation of life cycle cost for conventional bus and electric buses equipped with different energy storage technology: NMC – lithium nickel-cobalt-manganese, LFP – lithium-iron phosphate, LTO – lithium-titanate. Regardless the type of battery pack, electric bus displayed higher life cycle cost than conventional bus.

To estimate the tailpipe emission the vehicles simulation programs can be used. Studies [6, 16, 22, 29] provide the life cycle cost analysis involving both economic and environmental aspects of conventional and alternative powered buses. The emission was obtained through the simulation programs for the driving cycles developed using the real-world condition data.

To evaluate alternative powered bus and fuel technologies, a variety of interactive modelling tools were developed to facilitate such assessments. Many of them have been developed to examine the total life cycle cost, which includes both the economic and environmental aspects of alternative fuel and advanced vehicles. The most popular tools are AFLEET (Alternative Fuel Life-Cycle Environmental and Economic in Transportation) and EIO-LCA (Economic Input Output Life Cycle Assessment).

The AFLEET estimates the petroleum use, greenhouse gas emissions, air pollutant emissions, and cost of ownership of light-duty and heavy-duty vehicles. The tool provides a model dedicated for calculating on the basis of the input values (e.g. vehicle type, vehicle fuel type, purchase price, annual mileage, lifetime, fuel economy) the annual operating costs as well as average annual petroleum consumption, greenhouse gas emissions, and air pollutant emissions. In the study [5] the AFLEET program was used to compare the life-cycle social costs of air pollution and climate change for some vehicles equipped with the alternative drive trains.

The EIO-LCA tool has mathematically defined procedure using economic and environmental data to estimate the effect of changing output of a vehicle's life. The tool provides the analysis of environmental impact from mining, extraction, and processing the metal ores, making electronic parts, forming windows and many other processes that are needed for parts to build the complete vehicle. In the study [7] the EIO-LCA tool was used to analyse the life cycle cost of diesel-powered urban bus and five types of alternative fuel-powered urban buses.

There are also some programs dedicated only for estimation of the vehicle's life environmental impacts. These programs contain extensive databases with values enabling estimation of energy demand, raw materials consumption and greenhouse gas emissions during production of diesel oil, gasoline and alternative fuels, as well as during production of parts and subassemblies, in the assembly stage and in the operation and use phase of vehicles with various types of systems drive. The most popular of them are: GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation), MOVES (Motor Vehicles Emissions Simulator), and GaBi Software.

The GREET provides a comprehensive life cycle analyses to compare the energy use and emissions for conventional and advanced vehicles. The tool evaluates environmental impacts of advanced and new transportation fuels the fuel cycle from well to wheel and the vehicle cycle through material recovery to vehicle disposal. The paper [15] presents the life cycle assessment for bio-ethanol powered vehicles. The study performed a comprehensive life cycle analysis according to two modes Well-to-Pump and Pump-to-Vehicle simulated using GREET tool.

The MOVES estimates the pump-to-wheel greenhouse gas emissions and total energy consumption for light and heavy duty vehicles under a wide range of user-defined conditions. The tool estimates the emissions and fuel consumption based on vehicle's operation activities and the corresponding engine operating modes. Unfortunately, the MOVES does not provide the assessment of emissions for vehicles equipped with hybrid or electric drive systems. In the study [30] the MOVES tool project level sensitivity tests on running emissions were conducted thru the analysis of vehicle specific power, scaled tractive power, and emission rates versus speed curves.

The GaBi Software provides the comprehensive environmental impacts analysis associated with all stages of the vehicle's life from the phase of the raw material extraction through materials processing, manufacture, distribution, operation, repair and maintenance, and disposal or recycling. In the paper [13] GaBi software was used to evaluate the life cycle assessment of a car body parts consisting of steel and aluminium die cast in a process chain.

The aim of this paper was to evaluate the costs and environmental impacts analysis of conventional and alternative powered city buses. In the study the Life Cycle Cost method was used to provide comparison of conventional and hybrids urban buses. Presented analysis includes economic aspects, such as purchase cost, costs of repairs and maintenance, costs of fuel, costs of hybrid buses battery pack replacement and environmental aspects estimation for the life cycle assessment (LCA). The fuel economy values was estimated based on simulation under driving cycle developed for Kielce (Poland).

2. Assumptions for the LCC analysis

The life-cycle cost analysis (LCC) was carried out for city buses with three types of drive systems: parallel hybrid, series hybrid and conventional. The LCC includes: purchase cost, costs of repairs and maintenance, costs of fuel, costs of hybrid buses battery pack replacement and costs of emissions. In order to estimate the costs associated with the emission of harmful substances, an environmental estimation of the life cycle assessment (LCA) was conducted. The GREET program was used for this purpose.

According to the Plan on Urban Mobility for City Kielce [31] average annual millage amounts 60 000 km. It has been assumed that the service life of the analysed vehicles is 15 years. Average values of fuel consumption has been taken from the study [21]. The fuel efficiency values, taken into accounts in this paper were obtained from simulation of urban buses powered by conventional diesel engine, parallel and series hybrid electric drive under the driving cycles developed for city Kielce (Poland). The calculations were conducted with assumption that the fuel cost is 4.5 PLN / dm^3 (cost of diesel on the day of the analysis) [34]. The data chosen for the LCC estimation are presented in Table 1. The costs have been calculated in PLN (1 PLN = 1 Polish zloty = 0.23 EUR = 0.27 USD).

Tab. 1. Assumptions made for the analysis of the life cycle of city buses

	Conventional bus	Series hybrid bus (SHEV)	Parallel hybrid bus (PHEV)
Average fuel consumption [dm^3/100 km] [21]	60,3	49,7	52,0
Cost of purchase [PLN] [32]	850 000	1 400 000	1 400 000
The cost of repairs and maintenance [PLN/year] [32]	68 000	77 000	77 000
The battery cost [PLN]	-	15 120	2 520
The battery capacity [kWh]	-	10,8	1,8
1 kWh cost [PLN] [35]	-	700	700
Number of the battery exchanges during operation period	-	2	2

The urban transportation companies negotiate bus purchase prices directly with producers or select the supplier by public tender. The purchase price mostly depend on equipment of the bus and quantities of purchased or ordered vehicles. The cost of city buses purchasing includes prices of production components and subassemblies costs as well as assembly costs. The processes of mining, production of materials and vehicle components require high energy expenditure and are a source of emission of harmful substances. Electric and hybrid buses require additional components of electric drive, including a set of batteries, which significantly affects the production costs. The estimates of purchase costs of conventional and hybrid buses have been taken from report [32].

The energy storage devices have a shorter operation period than the bus's operating time. It was assumed that the battery pack should be replaced every 6 years, therefore during the bus operation it will be necessary to replace the energy storage device twice. The prices of the lithium-ion battery packs have been still decreasing for the latest years. It has been assumed that the cost of lithium-ion battery is 700 PLN per kilowatt-hour [35]. In this calculation the additional cost of the pack enclosure, module housings, wiring, circuitry, and plumbing has been not included in the cost of battery replacement.

Repair and maintenance costs include also costs of insurance and periodic inspections, costs of tires and operating fluids replacements as well as costs of required repairs and removal of defects. The level of repair and maintenance cost of conventional and hybrid urban bus has been sourced from report [32].

Evaluation of the environmental Life Cycle Assessment (LCA) was carried out using the GREET program (Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model), developed by the Argonne National Laboratory (ANL) as part of a project run by the US Department of Energy. The GREET program enables estimating the impact of individual phases of the life cycle of vehicles equipped with conventional and alternative propulsion systems on the natural environment. The program uses data provided by the EPA (Environmental Protection Agency) -US agency dealing with the protection of human health and the environmental studies [33]. GREET provides the opportunity to estimate energy consumption and emissions of harmful compounds caused by the production and distribution of fuel and by all phases of the vehicle's life cycle. The program scheme is presented in Fig. 1.

Fig. 1. Scheme of the GREET software tool [33]

In the GREET program, production and distribution of fuel is called "the fuel cycle". The following stages have been identified: raw material extraction, raw material transport, refining and purification, distribution and fuel consumption during vehicle operation. GREET also includes "the vehicle cycle" model, containing: sourcing of raw materials, production and processing of raw materials, production of components, assembly of the vehicle, operation of the vehicle and decommissioning. The parameters of 80 vehicles of various classes:

passenger cars, light heavy goods vehicles (LDV) and heavy goods vehicles (HDV) have been defined in GREET's database. The following drive system options are available [36]:

- conventional with a spark-ignition engine,
- conventional with self-ignition engine,
- hybrid with a spark-ignition engine,
- hybrid with self-ignition engine,
- plug-in hybrid with spark-ignition engine,
- plug-in hybrid with self-ignition engine,
- full electric vehicle,
- fuel cells vehicle.

There are approximately 100 fuel options available in the program, including petroleum-derived fuels, gaseous fuels, biofuels, hydrogen and electricity generated from various energy sources and raw materials [36].

Thanks to the interactive interface and graphical tools the simulation can be carried out easily. The dialog box consists of two areas. On the left there are types of car fuel available to be chosen. Clicking on the selected option enables choice of the vehicles available on the screen to be displayed. On the right side of the dialog box the energy output and emission level of harmful compounds for the particular stages of the life cycle of the selected vehicle is displayed. The user can modify the vehicle parameters and develop its own one. The period of analysis, the annual millage, the driving condition, and the vehicle load must be entered before starting calculations [33]. The results of the calculations are:

- the amount of energy coming from the combustion of the fossil fuels (oil, gasoline, gas, coal) or from renewable sources (biomass, wind, solar rays, water);
- the level of greenhouse gas emissions (CO_2, CH_4, N_2O) of harmful compounds contained in the exhaust gases (CO, NO_x, PM_x, SO_x, aliphatic and aromatic hydrocarbons);
- water creation.

The life cycle of the buses selected for investigations was divided into the following phases: fuel production (petroleum extraction and refining, production of fuel, distribution and storage), the production of the vehicle (production of parts and components and vehicle assembly) and the vehicle operation and use.

3. Results of the analysis

Levels of emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter (PM_x) and volatile organic compounds (VOC) per one kilometre of total mileage were analysed for the environmental life cycle assessment of city buses. The GREET program does not specify the emission values for the parallel and series hybrid configurations, therefore the emission level was generally presented for the hybrid drives. Fig. 2 shows the emission level of the above mentioned compounds for the life cycle of buses with conventional and hybrid drives.

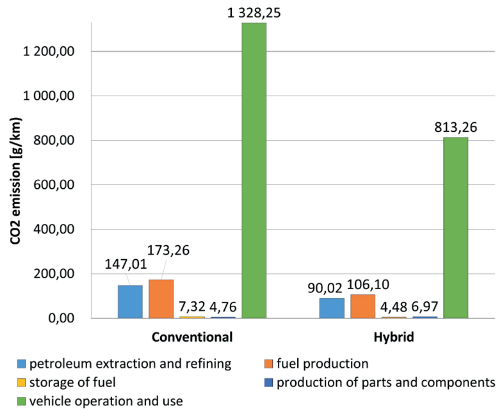

Fig. 2. CO_2 emissions level for individual stages of the life cycle of the conventional and hybrid bus

The hybrid bus can be characterized by a 37% lower level of carbon dioxide emissions than a bus with the conventional drive. The highest share in the CO_2 emission value falls on the phase of the vehicle operation and use. This share amounts to 79% for a conventional bus, and 77% for a hybrid one.

The nitrogen oxides (NO_x) and sulphur oxides (SO_x) emission levels for the life cycles of the analysed vehicles were presented on the Fig. 3.

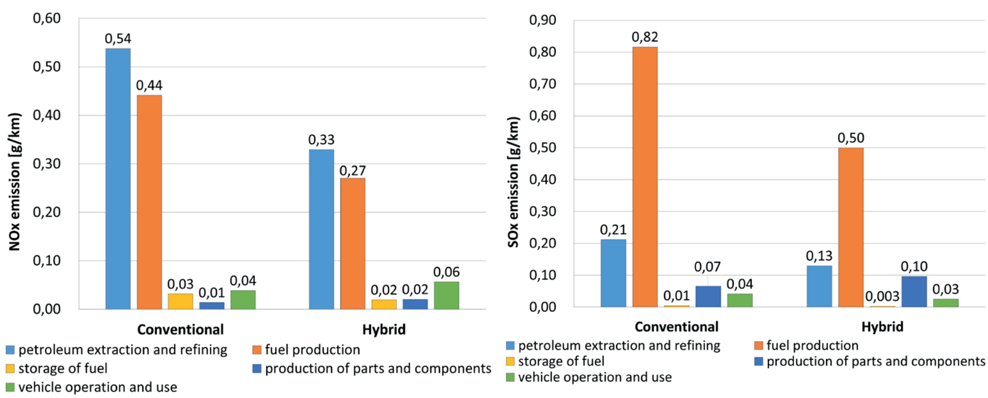

Fig. 3. Emission levels: NO_x (on the left) and SO_x (on the right) for the individual phases of the life cycle of the city buses

The hybrid bus exhibits 33% lower NO_x emission compared to a conventional drive vehicle. The largest share in the emission of nitrogen oxides falls to the phases of production, distribution and storage of fuel. The share of this phase in the NO_x emission for a conventional-powered bus is 62.5%, and for hybrids - 57.2%. The hybrid-powered bus produces a 34% lower emission of sulphur oxides compared to the conventional-powered bus (Fig. 3). The highest share in the value of emissions of sulphur oxides in the life cycle of the analysed vehicles falls on the phase of fuel production.

For a conventional-powered bus it is 71.3%, and for hybrids – 65.8%. The analysed vehicles exhibit a similar level of SO_x emissions in the operation phase. The share of this stage is 3.3% for hybrid buses and 3.6% for conventional buses. The level of particulate matter (PM_x) emission and volatile organic compounds (VOC) for the life cycles of the analysed vehicles was shown on Fig. 4.

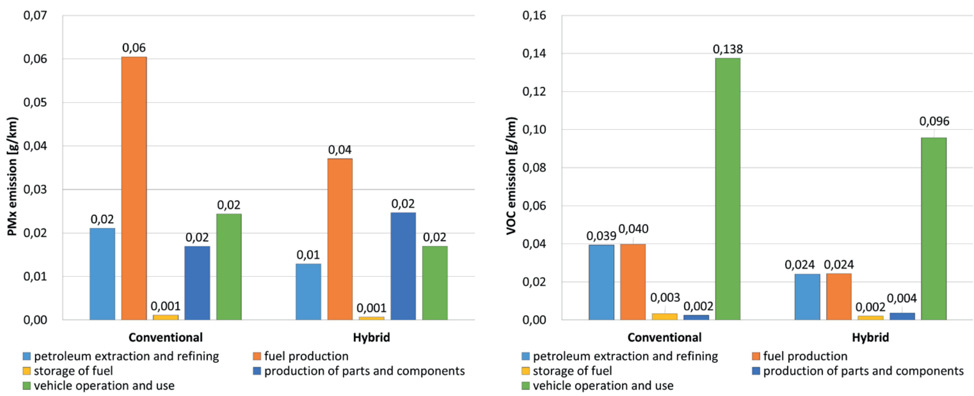

Fig. 4. Emission levels: PMx (on the left) and VOC (on the right) for the individual phases of the life cycle of the city buses

The particulate matter emission level for a hybrid bus is 17% lower compared to a conventional drive vehicle. The highest share in the emission of particulates for the life cycles of the analysed vehicles falls on the phases related to the production, distribution and storage of fuel. It is 59% for a Diesel-powered bus and 43% for the hybrid one. The life cycle emission level during the operation phase for a vehicle with a hybrid drive is 14.5%, while for a vehicle with a classical drive is 17.3%.

Volatile organic compounds are aliphatic hydrocarbons (decane, octane, hexane), aromatic hydrocarbons (toluene, xylene, benzene), benzene alkyl derivatives, aldehydes, ketones, amines, alcohols, esters, terpenes and others. The highest share in the value of VOC emissions for the life cycles of the analysed vehicles is in the period of operation. For a bus with conventional drive this share is 55%, and for hybrids – 50%.

Emission values of harmful compounds were presented in the form of costs calculated in accordance to the rates estimated in the Directive of the European Parliament and European Council on the promotion of clean and energy-efficient road transport vehicles [26]. The lifecycle cost includes the cost of purchase, costs of fuel consumption, repairs and maintenance, in the case of hybrid buses it is also a cost of battery replacement and costs of emissions. The GREET program does not determine the emission level in distinction to the configurations of the hybrid propulsion system, therefore, the same emission levels of the considered substances harmful to the parallel and serial hybrid were assumed. Fig. 5 presents the life cycle cost for buses with conventional and hybrid parallel (PHEV) and series (SHEV) drives.

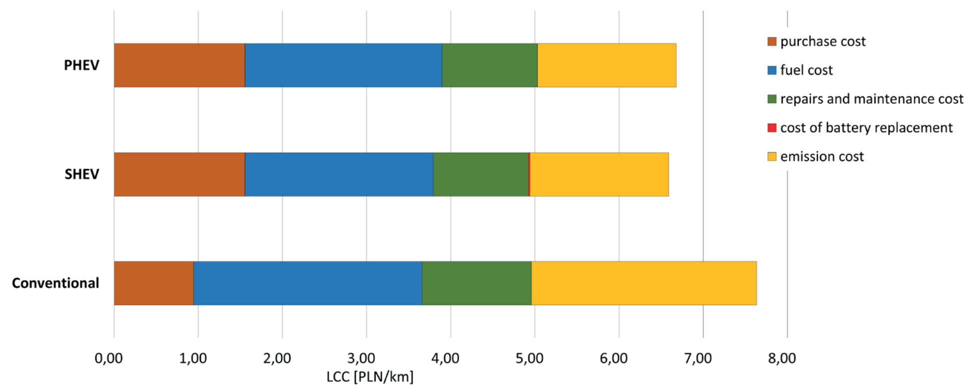

Fig. 5. LCC of city buses per 1 km of total mileage [PLN/km]

Hybrid buses can be characterized by a lower life cycle cost than conventional drive vehicles. The lowest life cycle cost is for a hybrid series bus. The LCC of the series hybrid is 14% lower than the LCC of the bus with the conventional drive. The hybrid parallel-powered vehicle has a 12% lower life cycle cost compared to a "classic" diesel-powered engine bus. Fig. 6 presents the shares of individual categories of costs in LCC.

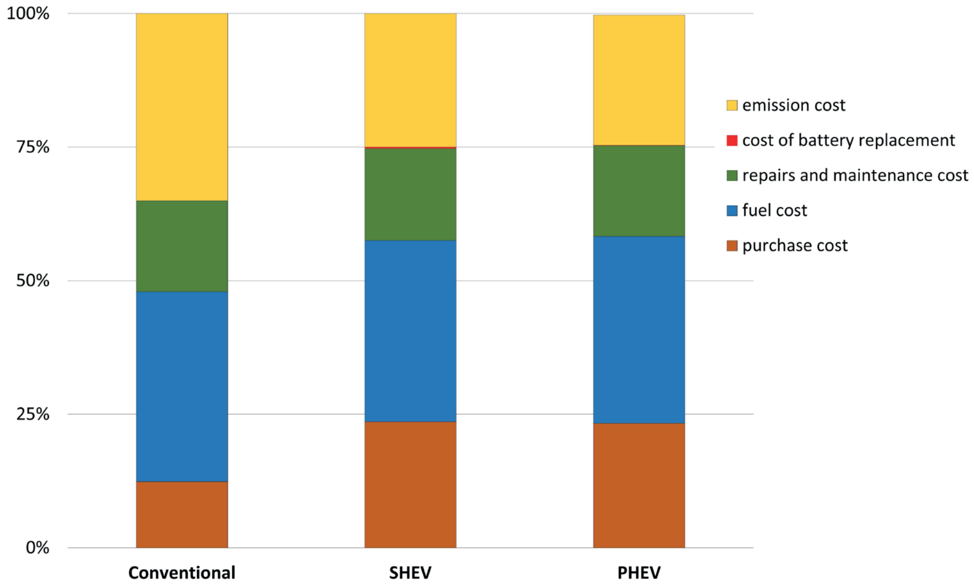

Fig. 6. Share of costs for LCC of a city bus with a conventional, hybrid series (SHEV), and hybrid parallel (PHEV) drives

The highest share of the life cycle costs is the cost of fuel consumption. For the conventional vehicle LCC, the share of this category of costs is 35.5%, for the series hybrid it is 33.8%, and in the case of the parallel hybrid – 35%. Purchase costs are the large part of the LCC, especially for hybrid buses. They constitute over 23% of the LCC. The costs of repairs and maintenance in the LCC of the analysed vehicles are 17%. Conventional buses have the highest share of the emission costs. They amount up to 35% of the life cycle cost. In the case of a series hybrid this share is 24.4%, and for a parallel hybrid – 25%.

4. Recapitulation and conclusions

The LCC value reflects the costs associated with the purchase of a vehicle, its operation and use and costs associated with the emission of harmful substances during its production and use. Evaluation of the life cycle cost of buses with different types of drives can be the basis for their assessment and can play an important role in the case of making decisions on replacement of the vehicle fleet and purchase of new buses.

The following conclusions can be drawn from the analysis:

- buses with hybrid drive have a lower life cycle cost than the buses with a conventional drive;

- the lowest LCC value was obtained for a hybrid series vehicle;
- the highest share in LCC of the analysed city buses is the cost of fuel;
- hybrid buses can be characterized by about 40% lower costs of emissions compared with conventional buses;
- the purchase cost of hybrids is around 24% LCC, while the cost of purchasing conventional buses is around 12.4% LCC.

The results presented in that study can be compared with studies presented in section 1. Several of them have echoed that hybrid buses can be an economically competitive to conventional buses. The life cycle cost estimated in paper [1] assumed lower LCC values for conventional urban bus. Similarly, the results provided in research [23] shown that replacing the conventional bus by a hybrid bus may bring a 12-year lifecycle cost savings of 8 550$. The presented analysis has not included the emission cost. In study [6] it has been shown that the hybrid bus significantly reduces the environmental impacts and has lower life cycle cost than conventional bus.

As observed in literature review the some analysis bring a quite opposite results. In paper [16] the life cycle cost was estimated based on simulation of fuel consumption and emission under different drive cycles. The analysis shows the LCC of hybrid bus is slightly higher than conventional bus. Paper [19] provides life cycle cost estimated for 4 bus types based on data gathered by the National Renewable Energy Laboratory concerning urban buses evaluation and demonstration studies conducted over the period 2003–2009. According to the authors the hybrid buses have lower emissions cost than conventional buses, but these emissions savings come at an increase in costs, especially purchase costs. The results presented in study [18] points the higher life cycle cost for hybrid bus. However, the operation costs of parallel hybrid bus and series hybrid bus assumed lower by an average of 8-15% than conventional bus. The analysis conducted in study [28] shows the conventional bus had lower the life cycle cost than hybrid bus. However, when the external funding pays for 80% of bus purchase costs the hybrid became more cost-effective than conventional bus.

The life cycle cost analysis presented in these paper and the results derived in many studies indicate the hybrid buses have a lower emission of harmful substances and greenhouse gases emission than a conventional bus. From economic point of view, the purchase price of hybrids and others alternative powered/ fuelled vehicles is significantly higher than the classic diesel buses. That is serious barrier which discourages from purchase. The solution can be the government subsidies and external funding for low emission vehicles.

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