PATHWAY OF REDUCING CO_2 EMISSION AND HARMFUL EXHAUST GASES IN TRANSPORT BY USING ELECTRIC BUSES-THE EXAMPLE OF BELGRADE

by

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The buses have an irreplaceable role in the public transport system, regardless of city size. Buses powered by internal combustion engines (diesel, CNG) are still the most common concept of city buses, but in the last few years, the use of fully electric buses (E-buses) has been growing. One of the reasons for the increasing use of electric buses is their environmental advantages over conventional buses: zero emissions at the local level (Tank-To-Wheel) emission, more favourable carbon dioxide (CO_2) emissions at the regional or national level (Well-To-Wheel), and higher energy efficiency. The EKO1 line (Vukov Spomenik-Belvil) has operated in Belgrade since 2016, with five full electric buses. The paper will present the environmental aspects of using electric buses on line EKO1 compared to diesel and CNG buses. The environmental aspects of E-buses were researched through the effects of reducing the emission of harmful exhaust gases caused by eliminating the use of diesel-powered or CNG-powered buses and introducing E-buses. Within the ecological suitability of the using E-buses, the emission of carbon dioxide (CO_2) that occurs indirectly during electricity production was researched and a comparison was made with the emissions of CO_2 caused by the combustion of diesel fuel and CNG in buses with conventional propulsion. The paper also examined the energy efficiency of buses with different drive systems on the line EKO1, based on the analyzed energy consumption. As a result of the analysis, the introduction of electric buses on the EKO1 line was justified from the point of view of improving the environment through the reduction of harmful gas emissions and decarbonization as well as better energy efficiency.

Key words: electric bus, CO_2 emission, harmful gas emissions, environment, transport, energy consumption

1. Introduction

The transport sector has a significant role to play in meeting the needs of society in the transport of passengers and goods. At the same time, the transport sector is a significant generator of emissions of harmful gases and carbon dioxide (CO_2). Emissions of harmful gases from road vehicles (passenger vehicles, buses, trucks) are the main polluters of the environment in cities [1]. For vehicles powered by internal combustion engines, the impact on the environment is manifested by the emission of harmful gases: carbon monoxide (CO), unburned hydrocarbons (C_xH_y), nitrogen oxides (NO_x) and suspended

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particles with a diameter of $PM_{2.5}$, PM_5, PM_{10}, sulfur compounds, aldehydes, benzene, etc. A problem that remains with vehicles with conventional propulsion (diesel, CNG) is the emission of carbon dioxide, which is directly proportional to the amount of burned fossil fuels [2]. The buses used in urban public transport are mostly powered by diesel engines. Diesel engines emit enormous amounts of suspended particles and nitrogen oxides, especially during cold engine operation, at full load. Trends in increasing motorization rate and the negative impact vehicles of diesel and petrol propulsion on the environment, impose the growing importance of using alternative propulsion in vehicles. The most important alternative propulsion is electricity, and hydrogen from renewable energy sources. In the public transport sector, the replacement of diesel buses with electric buses is increasingly present in the cities of China, Europe, North and South America. The paper aims to examine the environmental impact of using electric buses on city routes, i.e. the effects of reducing harmful exhaust gas emissions and carbon dioxide emissions, as a result of replacing buses with diesel or CNG buses. The research in the paper is based on the following starting hypotheses:

H1. Electric buses are more environmentally friendly than diesel or CNG buses in terms of the amount of carbon dioxide (CO_2) emissions, viewed through WTW (Well-To-Wheel) analysis.

H2. If electric buses are used instead of diesel or CNG buses, it contributes to reducing the emission of harmful exhaust gases in cities (local pollution) observed through the analysis, TTV (Tank-To-Wheel) and it is possible to estimate the amount of pollutants that will not be emitted as a result of using electric buses.

H3. Electric-powered buses have a higher energy efficiency compared to buses powered by diesel fuel and CNG, expressed in energy consumed per unit of traveled distance (kWh/km).

2. Literature Review

In 2022, about 66000 electric buses have been sold worldwide, representing about 4.5% of total bus sales worldwide. China continues to dominate the production and sales of electric buses. In 2022, 54000 new electric buses were sold in China, representing 18% of total sales in China and about 80% of global sales [3]. In addition, many electric buses sold in Latin America, North America, and Europe are Chinese brands. The number of newly registered electric buses in 2022 was 5000 E-buses in Europe, 2000 E-buses in the USA, and 4000 E-buses in other parts of the world, South America, India and Australia [3]. According to the Chatrou CME Solutions report from February 2024, in the countries that include the European Union, the United Kingdom, Iceland, Norway, and Switzerland, in 2023, the total number of new registered electric buses was 6354 vehicles which is 53% increase compared to 2022, when the number was 4152 [4]. EU Directive 2019/1161, which entered into force in August 2021, obliges all member states to have at least a 22.5% share in the procurement of zero-emission buses (E-buses, Fuel-cell), for 2021-2025 [5]. About four billion (55%) of the world's population lives in cities, and it is expected that in 2045 the number of people living in cities will reach six billion [6]. According to a European Commission report, in 2020, in Europe, 94% of the transport sector uses oil as a fuel. With its negative impacts, transport generally accounts for about 24% of greenhouse gas (GHG) emissions in 2020, of which carbon dioxide is the most abundant and road transport is responsible for one-fifth of total emissions [7]. After the global COVID-19 pandemic, CO_2 emissions from the transport sector are increasing. In 2021, its share in EU countries was 25% [8]. To achieve the limit on global warming, the EU established the "European Green Deal" on 14 July 2021 to reduce global emissions (greenhouse gas emissions) compared to 1990 levels by 55% by 2030. year. Every economic sector including the transport sector, must achieve these challenging goals on this path. To achieve climate neutrality in the EU by 2050, EU emissions regulations have set ambitious targets in the transport sector. This means a 90% reduction in greenhouse gas emissions from transport by 2050 [8]. In 2012 a report from the World Health Organization (WHO) announced that 3.7 million people worldwide die each year as a result of air pollution [9]. Numerous studies conducted worldwide have shown that the impact of suspended particles as a result of air pollution is directly related to the higher likelihood of lung cancer in humans as well as the increased rate of morbidity and mortality due to cardiovascular and respiratory diseases [10]. Reducing emissions from transport requires significant efforts from various disciplines. Reducing vehicle weight, improving drive efficiency, using clean fuels, and using improved public transport are potential options for reducing emissions [11]. The UITP claims that there are about 55000 different types of city buses in the European Union in the 100 largest cities today, about 80% of transport work expressed in places-kilometers (places-km) [12]. In EU cities, only 3 to 6% of transport emissions stem from public transport [13].

In Europe according to a study by Glotz-Richter & Koch, 2016 one articulated bus running on city lines consumes about 40000 liters of diesel fuel per year [14]. The results of a Study Alternative powertrains for Europe, 2012, which included more than 40 partners from the European Union (vehicle manufacturers, operators, institutions, etc.) showed that fully electric buses had carbon dioxide emissions between 1050÷1150 g/km, diesel buses had a carbon dioxide emission of 1350 g/km, by Well-To-Wheel analysis [15]. In the case study of electric buses in the Chinese cities Zhengzhou and Shenzhen, the carbon dioxide emissions were 720÷790 g/km, for electric buses, compared to 1311 g/km for diesel buses using Well-To-Wheel analysis [16]. In 2015, the emission of carbon dioxide CO_2 in New York amounted to 577.29 Mt, and in the case of substitution of all 5761 diesel, hybrid, and CNG buses with electric buses, CO_2 emissions would amount to 91.22 Mt [17].

Analysis of carbon dioxide emissions for the transport sector in the Czech Republic and Slovakia for electric vehicles, method of electricity production, production efficiency, and losses in electricity transmission are presented in a paper by Skrúcanỳ et al. [18]. The potential of using solar energy and obtaining electricity using photovoltaic collectors for charging electric buses is presented in the work of Mattes et al. [19]. Research by Vepsäläinen et.al. studied the energy consumption of E-buses. The operating conditions such as weather and payload caused variations in the bus energy consumption and emissions of CO_2 [20]. Gharaei, Ahmadi & Ashjaee, conducted the Comparative Life Cycle Assessment of diesel, hydrogen, and electric buses on four urban public transport lines in Teheran. The results proved that a diesel bus has the highest CO_2 emissions of 201 kg/100km, a fuel cell bus of 130 kg/100km, and an electric bus 121 kg/100km [21]. London already has one of the largest electric bus fleets in Europe. The plan is to accelerate the delivery of a zero-emission bus fleet by 2030. This would reduce 500000 tons of carbon emissions annually in the transport system [22].

3. Research scope

The bus subsystem is the backbone of the public transport services in Belgrade. There are 1140 diesel buses in operation on weekdays. The largest operator JKP GSP "Beograd" participates with 645 buses on weekdays which consume about 31.2 million liters of Euro diesel fuel annually [23]. The first public transport line in Belgrade with fully electric buses, EKO1 (Vukov spomenik - Belvil), kicked off on September 1, 2016. The introduction of five electric buses Higer KLQ6125GEV3, is a significant development project and represents the beginning of using a new concept of environmentally and energy-efficient vehicles in public transport. EKO1 is a line designed for fully electric bus operation, aimed to maximize the energy and environmental benefits of E-buses in the central city area of Belgrade. The spatial position of the route of the EKO1 line are shown in Figure 1. The average length of the EKO1 line is 7995 m. The length of the route in the direction "A" is 7477 m, with 15 stops. In the direction "B", the route length is 8513 m, with 17 stops. The average transport speed is 14.1 km/h, with typical urban driving cycle characterictics [24]. The geometric characteristics of the route of the EKO 1 line are characterized by a flat configuration with small terrain gradients, primarily in New Belgrade, which makes the route relatively easy in terms of topographical characteristics to overcome road resistance during vehicle movement.

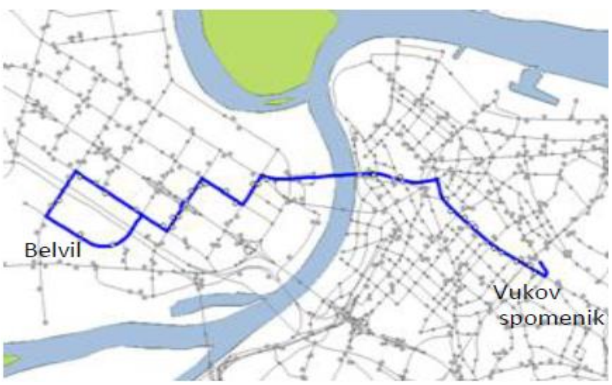

Figure 1. Spatial position of the line EKO1 in Belgrade

The route of the line with a negative slope is 61.8% of the length of the line in the "A" direction, with an average slope value of -0.305% and a maximum slope value of the section with a drop at the inter-distance: Zeleni venac-Block 21 of -3.14% [24]. Examples of the driving cycle on the EKO1 line and the achieved speeds of the E-bus that were taken over via the S-CAN network of the E-bus in the period from 7:38:01 to 8:09:30 in the direction of "A" are shown in Figure 2 [24].

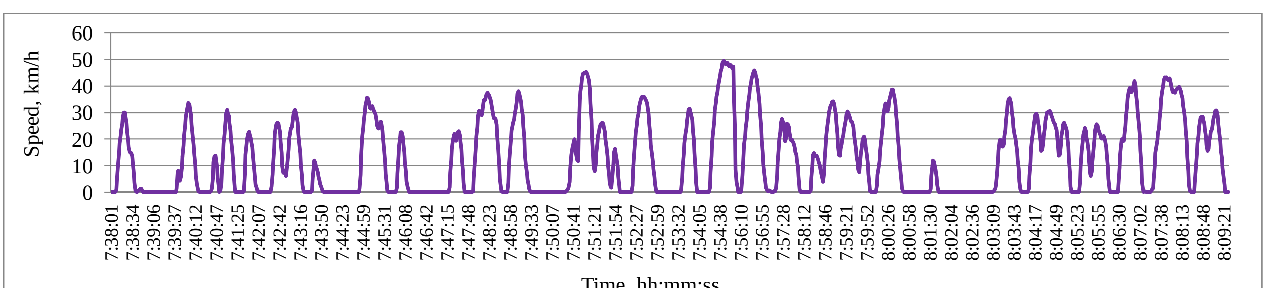

Figure 2. Driving cycle on the line EKO1, direction "A", period 7:38:01 to 8:09:30

4. Electric bus type and ultracapacitor technology

The electric bus Higer KLQ6125GEV3 is a low-floor standard city bus that meets all technical requirements per European Commission Directive 2007/46 and Regulation 136/2014 which refers to the fulfillment of technical conditions for buses for urban public transport, including electric buses. The E-bus is equipped with a 20 kWh ultracapacitor to store electricity. Fast charging is done at the first and last stops (terminals) and 150 kW chargers are installed at each terminal. Figure 3 shows the Higer KLQ6125GEV3 electric bus in the charging phase on terminal "Belvil". E-bus technical characteristics are shown in Table 1 [25].

Figure 3. Higer KLQ6125GEV3, electric bus

Table 1. Technical characteristics

Type	Higer KLQ6125GEV3
Length/width/ height	12000/2550/3680 mm
Max. speed	70 km/h
Passengers	82+1
Traction motors	Siemens (x2) 1PV5135
Power	2x90 kW (peak), 2x67 kW (nominal)
Torque	2x430 Nm
Traction control	Siemens 10DT6
Supercapacitor	AOWEI, 20 kWh
Charging time at the terminus	5÷10 minutes
Curb weight of E-bus	12540 kg

The ultracapacitor (supercapacitor) consists of many interconnected capacitors, thus achieving the required characteristics. The principle of operation of the capacitor is electrostatic, where an electric field is created between the plates of the capacitor, separated by an insulator. The electricity stored in the capacitor is determined by the following equations:

$$E_C = \frac{1}{2} C_C \cdot U_C^{\ 2}, \text{ J}, \quad (1)$$

$$E_C = \frac{1}{7.2 \cdot 10^6} C_C \cdot U_C^{\ 2}, \text{ kWh}, \quad (2)$$

E_c – stored electricity
C_c – capacitor capacity, F,
U_c – capacitor voltage, V.

Capacitors are connected in series, in parallel, or in combination, thus forming a capacitor battery. In the case of many capacitors the system is called an ultracapacitor. Table 2 gives a comparative overview of the characteristics of the applied technologies (ultracapacitors and batteries) for electricity storage in electric buses [26, 27].

Table 2. Characteristics of ultracapacitors and lithium batteries [26, 27]

Characteristic	Ultracapacitors	Li-Batteries
Working principle	Electrostatic	Electrochemical
Cell voltage, V	2.3÷2.7	2.2÷3.8
Power to capacity ratio	High power, kW lower capacity, kWh	Higher available capacity, kWh, lower power, kW
Specific energy, Wh/kg	2.5-15	100-265
Specific power, W/kg	500-5000	250-340
Efficiency	90÷98 %	85÷98 %
Operating temperature range	-40 ℃ to +60 ℃	-40 ℃ to +50 ℃
Charging process	very fast, "C">1000	slow/fast, "C"<100
Number of charging cycles	1000000	100000
Fast discharges and charges	Flexibility to fast discharges and charges	Sensitivity to fast discharges and charges
Lifespan	10÷15 years	8÷10 years
Recycling	Suitable for recycling	Higher recycling requirements

Ultracapacitors used in electric buses are characterized by high specific power, high efficiency, fast charging time, long service life, and easier recycling. The disadvantages are the lower specific energy and capacity they have compared to batteries. Ultracapacitors make better use of available energy storage capacity. Ultracapacitors can withstand deep discharge without the risk of permanent damage, while batteries are usually discharged up to 20% of the maximum charge level.

5. Methodology for calculation emissions

According to Directive (EU) 2019/1161, buses are classified as zero-emission vehicles since they use only electricity for propulsion. The impact of buses in public transport on the environment can be analyzed in two ways. Firstly, at the micro-level where vehicles are in operation (local level), which in the literature is called TTW (Tank-To-Wheel), and secondly, as an impact on the wider environment which is a region or state known as analysis WTW (Well-To-Wheel). In the case of TTW analysis, the electric bus propulsion system has zero emissions: carbon monoxide, nitrogen oxides, hydrocarbons, and microparticles.

The environmental impact at the local level is minimal, as the only negative impact on the environment comes from the formation of microparticles and dust due to contact of tires and roads, from the friction of brake linings and evaporation of working fluids (transmission lubricating oil, antifreeze, etc.) which can be ignored. The TTW analysis of electric buses can be viewed in the context of the environmental effect achieved by replacing buses using diesel fuel or CNG, by quantifying the amount of pollutants that will not be emitted into the atmosphere as a result of vehicle substitution.

The impact of the production of electricity, diesel, petrol, or natural gas on carbon dioxide emissions can be defined through the standard emission factor, SEF (Standard Emission Factor), which refers to the emission of carbon dioxide directly from energy consumption or through the emission factor life cycle, LCA (Life Cycle Assessment), which includes the complete fuel production chain (flotation of coal from a mine or open-pit mine, extraction of oil from oil fields, transport to a thermal power plant or refinery, refining and transport to the end-user). The methodology UITP Environmental, was used to calculate CO, C_xH_y, CH_4, NO_x, PM_{10} emissions from diesel and CNG buses, expressed in g/km [28]. The emission calculation was obtained based on input data on diesel fuel consumption expressed in L/100km, CNG consumption in kg/100km, maximum emission values of CO, C_xH_y, CH_4, NOx, and PM_{10} expressed in g/kWh depending of the level emission norms of engines, according to the ETC TEST (Directive 2005/55/EC, European regulation no.595/2009) and the specific fuel consumption expressed in g/kWh. Carbon dioxide (CO_2) emissions for diesel-powered buses and CNG buses according to TTW analysis were obtained using Equation 3 [29].

$$m_{CO_2} = m_f \cdot g_C \cdot \frac{44}{12} \tag{3}$$

m_{CO_2} - mass of formed carbon dioxide, g,

m_f - mass of fossil fuel that burns, g,

g_C - carbon content in the fuel, %,

44 - molar mass of carbon dioxide, g/mol,

12 - molar mass of carbon, g/mol.

The largest quantities of crude oil come from the Middle East region (Iraq, Iran, Saudi Arabia, and Syria). The analysis of WTT (Well-to-Tank) carbon dioxide emissions for diesel fuel is shown in Table 3 [30]. One kilogram of diesel fuel contains about 0.861 kilograms of carbon or about 86.1%. Since one liter of diesel fuel has an energy power of 36 MJ, if it is assumed that the specific weight of diesel fuel is 832 g/L, it follows that 1 kg of diesel fuel has an energy power of 43.1 MJ [28]. Based on Equation 3, it follows that the combustion of 1 kg of diesel fuel produces 3.16 kg of carbon dioxide, or the combustion of 1 L produces 2.63 kg of carbon dioxide, which is the emission of carbon dioxide that occurs during combustion in the vehicle engine, TTW (Tank-to-Wheel). If the analysis WTT were observed for the Republic of Serbia, it would include crude oil transport through Serbia to the refinery, processing into diesel fuel, and distribution to the end-user. In that case, the estimated carbon dioxide emissions WTT would be about 10.4 g/MJ. The total carbon dioxide emissions WTW caused by the combustion of diesel fuel in vehicles are shown in Table 4 [24].

Table 3. CO_2 emissions from diesel fuel, WTT (Well-to-Tank)

Diesel fuel	Emission CO_2 $g \cdot MJ^{-1}$
Crude oil extraction	5.3
Crude oil transport	0.9
Refinery-processing	8.6
Distribution	1.0
Total	15.8

Table 4. CO_2 emissions from diesel fuel, WTT, TTW, WTW

Diesel fuel	Emission CO_2 $g \cdot MJ^{-1}$
WTT	10.4
TTW	73.25
WTW	83.65

For CNG-powered buses, a similar analysis can be done as in the case of the use of diesel fuel. The specificity of the CO_2 emissions analysis if observed from the aspect WTT is the resulting emissions in the transport phase through the pipeline. Natural gas made up largely of methane, about 95% in the presence of other hydrocarbons and CO_2. Using Equation 3, the combustion of one kilogram of natural gas produces approximately 2.54 kg of carbon dioxide, which represents the TTW emission of carbon dioxide. If the lower value of thermal power is 33 MJ, and the density is 0.732 kg/m^3, the energy power of natural gas per kilogram is 45.1 MJ [28]. The total carbon dioxide emissions for CNG vehicles, aspects WTT, TTW and WTW are shown in Table 5 [30].

Table 5. CO_2 emissions from CNG, WTT, TTW and WTW

CNG	Lenght of pipeline 7000 km Emission CO_2, $g \cdot MJ^{-1}$	Lenght of pipeline 4000 km Emission CO_2, $g \cdot MJ^{-1}$	Lenght of pipeline 1000 km Emission CO_2, $g \cdot MJ^{-1}$
WTT	22.3	14.5	8.7
TTW	56.2	56.2	56.2
WTW	78.5	70.7	64.9

In the Republic of Serbia, the typical value of methane content in natural gas is 96%. The specific gravity of natural gas for a standard cubic meter of gas is 0.710 kg/m^3, and the calorific value is 33.5 MJ/m^3 [31]. The average length of the gas pipeline for natural gas transport across the Republic of Serbia is 2459 km [32]. The analysis of carbon dioxide (CO_2) emissions (WTW), which includes WTT and TTW analysis in the territory of the Republic of Serbia, would give the following results: WTT 9.30 g/MJ, TTW 53.84 g/MJ and WTW 63.14 g/MJ [24]. The value of carbon dioxide (CO_2) emissions, if calculated according to WTW analysis, is obtained by increasing the value of carbon dioxide emissions obtained by TTW analysis for a factor of 14.2% for diesel fuel, which takes into consideration emissions from processing and transport and 17.3% for CNG, which are the most realistic for the Republic of Serbia [24].

The method of electricity production and transmission are essential when analyzing the impacts of the environmental performance of electric buses on a regional or national level, or WTW analysis. Analysis of WTW carbon dioxide emissions is important to consider and compare the emission levels emitted by buses with different propulsion systems, including purely electric buses. The carbon dioxide emissions that occur in the phase of electricity production are highly important, considering that electricity is obtained from various sources. The values of LCA factors of carbon dioxide emissions from gross electricity production in different European countries in 2019 in gCO_{2eq}/kWh are shown in Figure 4[33].

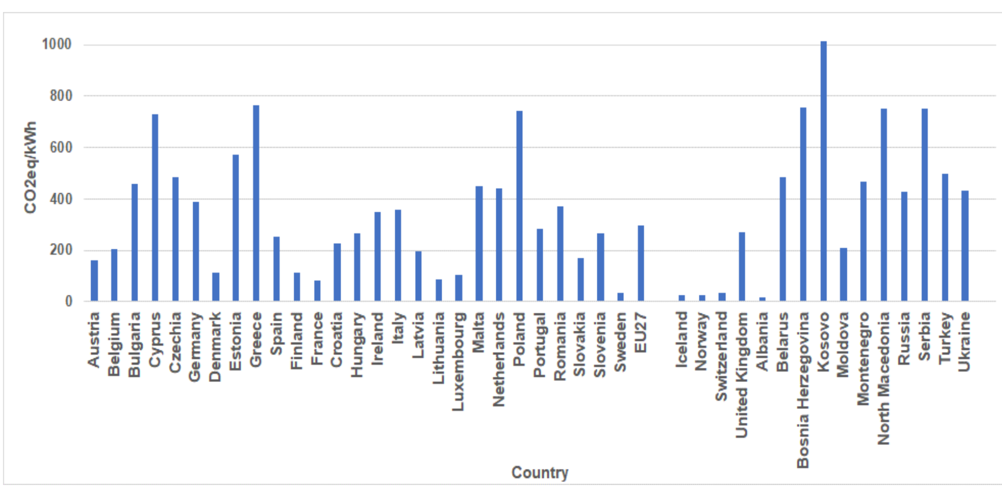

Figure 4. CO2 emissions from gross electricity production in European countries in 2019

Countries with a larger share of electricity obtained from renewable sources (wind, solar, hydroelectric power plants) or nuclear plants have a more favourable balance. In the case of electric buses, the calculation of CO_2 emissions according to the WTW analysis was obtained using Equation 4 [29].

$$CO_{2_{WTW}} = \frac{E_{ebus}}{\eta_{ch}} \cdot LCA_{CO_2} \cdot f_{gpee} \tag{4}$$

$CO_{2_{WTW}}$ - carbon dioxide emissions according to WTW-analysis, g/km,

E_{ebus} - electricity consumption of E-bus, kWh/km,

η_{ch} - charger efficiency coefficient (~0.95),

LCA_{CO_2} - emission factor of the total cycle of electricity production in Serbia, adopted 774 g/kWh,

f_{gpee} - coefficient of loss in electricity transmission, adopted 7.5% .

In the Republic of Serbia, electricity is dominantly obtained from thermal power plants with a share of about 70% [32].

5. Results of TTW and WTW analysis of different bus drive systems on the line EKO1

The Higer KLQ6125GEV3 electric buses operate exclusively on the urban line EKO1. The results of electricity consumption of E-buses were monitored in the period from 2016 to 2019 year, by downloading data from the BMS unit (Battery management system) of the vehicles, on a total sample of over 2000 measurements, where the spring-autumn, summer, and winter periods of operation were analyzed separately. The electricity consumption of electric buses on the EKO1 line, expressed in kWh/km, depending on the outside temperature expressed in ℃, or the period of operation is shown in Fig.5 and Fig.6 [24]. Consumption measurement results included consumption during characteristic periods of E-bus operation during the day (peak loads, intermediate loads, first/last departures). Losses that occur during the charging phase of the E-bus are also included in the consumption of electricity.

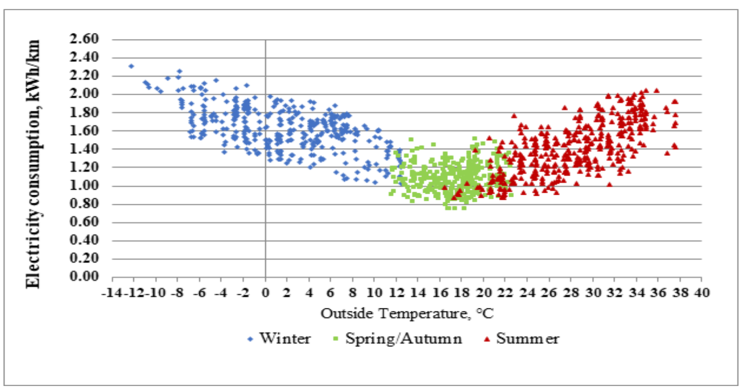

Figure 5. Electricity consumption and outside temperature, line EKO1, direction "A", winter, transition, summer period

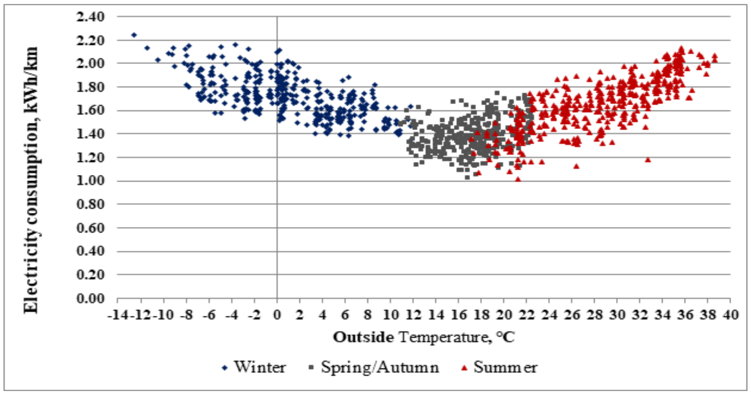

Figure 6. Electricity consumption and outside temperature, line EKO1, direction "B", winter, transition, summer period

The system for heating and cooling the passenger and driver compartment is electric, and variations in electricity consumption are highly pronounced. Estimated emissions of harmful gases and carbon dioxide of TTW and WTW analysis on line EKO1 of electric bus Higer KLQ6125GEV3 is shown in Table 6 [24].

Table 6. Energy consumption and emissions of E-bus KLQ6125GEV3 on line EKO1

Line EKO 1	Unit	Spring/ autumn	Summer	Winter
Average electricity consumption	$kWh\cdot km^{-1}$	1.237	1.539	1.670
Emission CO	$g\cdot km^{-1}$	-	-	-
Emission CxHy	$g\cdot km^{-1}$	-	-	-
Emission CH_4	$g\cdot km^{-1}$	-	-	-
Emission NO_x	$g\cdot km^{-1}$	-	-	-
Emission PM_{10}	$g\cdot km^{-1}$	-	-	-
Emission CO_2, TTW	$g\cdot km^{-1}$	-	-	-
Emission CO_2, WTW	$g\cdot km^{-1}$	1029.2	1280.5	1389.5

The fuel consumption measurement for standard-sized diesel and CNG buses was done on diesel buses IK-112N (EURO 4) and MAZ-203 CNG buses. The measurements were performed from the 12^{th} of August to the 5^{th} of October 2017, when due to infrastructural works in Roosevelt Street, the operation of electric buses was temporarily replaced with diesel and CNG buses. Moreover, additional recordings are done when electric buses were replaced by diesel and CNG buses due to the regular services of chargers, or in case of power outages in the charger zones. Estimated emissions of harmful gases and carbon dioxide of TTW and WTW analysis on line EKO 1 of the diesel bus IK-112N (EURO 4) are shown in Table 7 [24].

Table 7. Energy consumption and emissions of diesel bus IK-112N on line EKO1

Line EKO 1	Unit	Spring/ autumn	Summer	Winter
Average consumption of diesel	$L\cdot(100km)^{-1}$	43.87	52.77	46.16
Energy equivalent	$kWh\cdot km^{-1}$	4.387	5.277	4.616
Emission CO	$g\cdot km^{-1}$	6.489	7.805	6,828
Emission CxHy	$g\cdot km^{-1}$	0.892	1.073	0.939
Emission CH_4	$g\cdot km^{-1}$	-	-	-
Emission NO_x	$g\cdot km^{-1}$	5.678	6.830	5.974
Emission PM_{10}	$g\cdot km^{-1}$	0.049	0.059	0.051
Emission CO_2, TTW	$g\cdot km^{-1}$	1153.8	1387.9	1214.0
Emission CO_2, WTW	$g\cdot km^{-1}$	1317.6	1584.9	1386.4

Estimated emissions of harmful gases and carbon dioxide of TTW and WTW analysis on line EKO 1 of the bus with compressed natural gas MAZ-203 CNG, in which the Cummins ISL G powertrain, which meets the 2010 EPA/CARB and EURO 6 emission standards are presented in Table 8 [24].

Table 8. Energy consumption and emissions of bus MAZ-203 CNG on line EKO1

Line EKO 1	Unit	Spring/ autumn	Summer	Winter
Average consumption of CNG	$kg\cdot(100km)^{-1}$	46.70	53.85	49.95
Energy equivalent	$kWh\cdot km^{-1}$	6.120	7.057	6.546
Emission CO	$g\cdot km^{-1}$	7.009	8.083	7.497
Emission CxHy	$g\cdot km^{-1}$	0.280	0.323	0.300
Emission CH_4	$g\cdot km^{-1}$	0.876	1.010	0.937
Emission NO_x	$g\cdot km^{-1}$	0.473	0.546	0.506
Emission PM_{10}	$g\cdot km^{-1}$	0.018	0.020	0.019
Emission CO_2, TTW	$g\cdot km^{-1}$	1186.2	1367.8	1268.7

The annual energy consumption and emissions of E-buses, diesel buses and CNG buses on line EKO1, are shown in Table 9 [24].

Table 9. Energy consumption and emissions of E-buses, diesel buses and CNG buses on line EKO 1

Line EKO 1	Unit	E-bus Higer	Diesel bus IK-112N	CNG bus MAZ-203
Number of buses in operation		5	5	5
Annual mileage	km	62750	62750	62750
Average electricity consumption	$kWh\cdot km^{-1}$	1.493	-	-
Average consumption of diesel	$L\cdot(100km)^{-1}$	-	47.05	-
Average consumption of CNG	$kg\cdot(100km)^{-1}$	-	-	49.84
Emission CO	kg	-	2183.6	2347.1
Emission CxHy	kg	-	300.2	93.9
Emission CH_4	kg	-	-	293.4
Emission NO_x	kg	-	1910.6	158.5
Emission PM_{10}	kg	-	16.4	5.8
Emission CO_2, TTW	t	-	388.2	397.1
Emission CO_2, WTW	t	389.5	443.3	465.9

6. Discussion of results

Tables 6, 7, and 8 show the environmental effects of the Higer KLQ6125GEV3 E-bus on the EKO 1 line compared to the operation of diesel and CNG buses. For the TTW method, the E-bus has zero emission of CO, C_xH_y, NO_x, PM_{10}, and CO_2 (Table 6). Quantified emissions for diesel (table 7) or CNG (Table 8) buses in case of their operation on the EKO1 line, represent the effects of e-bus operation in the EKO1 line expressed in decrease emissions. In the summer period, the consumption of diesel fuel and CNG is the highest due to the impact of the cooling system on these vehicles. For E-buses, electricity consumption in the same period is significantly higher than in the spring-autumn (transition) period, but lower than in the winter period. Carbon dioxide (CO_2) emissions from the aspect of WTW analysis in the transition and summer period of operation prove that the E-bus has a lower level of CO_2 emissions compared to buses that use diesel fuel and buses that use CNG. CO_2 emissions from E-buses in the spring-autumn period of operation are 21.8% lower compared to buses powered by diesel fuel and 26.0% lower compared to buses powered by CNG. In the summer, CO_2 emissions from electric buses are lower by 19.2% compared to diesel buses and by 20.1% compared to CNG buses.

The results from Tables 6, 7, and 8 also show that CO_2 emissions from electric buses in the winter period, are slightly higher compared to CO_2 emissions from diesel buses, for E-bus is 1389.5 g/km and for the diesel bus 1386.4 g/km. This is mainly due to the intensive use of heating systems in E-buses during the winter which significantly increases the electricity consumption of vehicles as a whole there is no effect of reducing CO_2 emissions compared to diesel buses. The initial hypothesis H1, H2 and H3 is proven based on the results shown in the Table 9. The Higer KLQ6125GEV3 electric buses operating on the EKO 1 line annually have an indirect impact on the environment observed at the macro-level (Republic of Serbia) through the emission of 389.5 tons of carbon dioxide generated in the production of electricity. Compared to the carbon dioxide emissions from diesel-powered buses observed at the state level (WTW analysis), which amounts to 443.3 tons, it turns out that it is 12.1% lower for electric buses. An even more favorable case is the analysis of CO_2 emissions compared to CNG buses, which is 16.4% lower for electric buses. The obtained values of CO_2 emissions (WTW analysis) prove that electric buses have more favorable CO_2 emissions compared to diesel and CNG buses, which confirms the initial hypothesis H1. Finally, the energy efficiency of buses with different drive systems on the EKO1 line was analyzed based on the energy consumed in a representative period of operation.

The environmental benefit of using electric buses is proven by the example of the assessment of the amount of emissions of harmful exhaust gases that would be generated at the local level (TTW), are shown in Table 9. The operation of 5 diesel buses equipped with EURO 4 engines or the operation of 5 CNG-powered buses with EURO 6 engines, on line EKO1 in Belgrade. Five IK-112N diesel engine buses, which meet EURO 4 environmental standards, would emit harmful exhaust gases in the following amounts: carbon monoxide (CO) 2183.6 kg, hydrocarbons (C_xH_y) 300.2 kg, nitrogen oxides (NO_x) 1910.6 kg, suspended microparticles (PM_{10}) 16.4 kg. The total emission of 5 buses on CNG would be carbon monoxide (CO) 2347.1 kg, hydrocarbons (C_xH_y) 93.9 kg, methane residues (CH_4) 293.4 kg, nitrogen oxides (NO_x) 158.5 kg and suspended microparticles (PM_{10}) 5.8 kg. The aforementioned emissions of harmful exhaust gases are not present during the operation of electric buses on the EKO 1 line in Belgrade, which confirms the initial hypothesis H2.

The average consumption of diesel fuel in the spring-autumn period for the IK-112N bus was 43.87 L/100km, which is energy equivalent to 4.387 kWh/km, while the MAZ-203 CNG bus had an average consumption of 46.70 kg/100km, which is 6.120 kWh/km. Given that the E-bus Higer KLQ6125GEV3 achieved an average consumption of 1.237 kWh/km in the spring-autumn period of operation, it follows that the energy efficiency of the E-bus is 3.54 times higher than that of the IK-112N bus and 4.94 times higher compared to the MAZ-203 CNG bus, which confirms the initial hypothesis H3. The higher energy efficiency of electric-powered buses is a consequence of the greater degree of useful effect of the drive system (electric motor) compared to internal combustion engines and the possibility of recovery of electric energy during the braking and deceleration phase of the e-bus. On the EKO1 line, an electric bus can recover up to 28.5% of the total electrical energy consumed [24].

7. Next steps in implementing E-buses in Belgrade

Currently, 15 E-buses are operating on two urban public lines in Belgrade. The second E-bus line EKO2 (Dorcol – Belgrade Waterfront), on which 10 E-buses operate, was put into regular operation on January 24, 2022. Based on the first measurement results, the average consumption of electrically powered buses on the EKO2 line in Belgrade is 1.15 kWh/km, and the WTW CO_2 emission is 1007 g/km [34]. Under the same operating conditions on the EKO2 line, a diesel-powered bus would have an expected consumption of 42.5 L/100km, (4.25 kWh/km) and a CO_2 WTW emission of 1276 g/km. It can be concluded that the level of CO_2 emission WTW is about 21.1% lower for an electric bus than a diesel bus. Based on the data on power consumption on the EKO2 line, the electric-powered bus Higer KLQ6125GEV3 has 3.7 times higher energy efficiency than the diesel-powered bus. In the following period, the City of Belgrade, with an action plan for improving the air quality in the Belgrade agglomeration, plans to purchase another 40 electric buses by 2025 [35].

8. Conclusion

The introduction of electric buses into public transport systems in many cities of the world has a constant trend of growth as one of the effective ways to reduce air pollution originating from traffic. Reduction of emissions of harmful gases and carbon dioxide on public city transport lines can be significantly improved by energy and environmental management in the bus subsystem of public city transport, and one of the most effective ways is to replace existing conventionally driven buses with electric powered buses. In the paper, all three starting hypotheses (H1, H2, H3) are proven by using E-buses on the EKO1 line in Belgrade. Based on the WTW analysis, it can be concluded that electric buses operating on the EKO 1 route have an indirect impact on the environment viewed at a wider level (Republic of Serbia) through the emission of 389.5 tons of carbon dioxide (CO_2) in electricity production. Compared to the carbon dioxide emissions from diesel-powered buses, the annual level (WTW analysis) of 443.3 tons shows that electric-powered bus emissions are 12.1% lower. Compared to buses powered by natural compressed gas (CNG), CO_2 emissions on an annual basis are lower by

16.4% for buses powered by electricity. With greater use of renewable sources for electricity, the decarbonization effect would be even more significant. The environmental benefits of using electric buses at the local level (TTW), are proven by the estimation of the amount of emissions of harmful exhaust gases that would be generated by the operation of five EURO 4 diesel buses engines and five CNG EURO 6 on the EKO1 line in Belgrade. The mentioned emissions of harmful exhaust gases are not present during the operation of the electric buses on the EKO1 line in Belgrade. The energy efficiency of the E-bus is 3.54 times higher than that of the IK-112N bus and 4.94 times higher compared to the MAZ-203 CNG bus. The applied methodology and the results presented in the paper can serve as a basis for similar future research that will be conducted during the environmental analysis of the justification for the introduction of electric buses instead of conventionally powered buses.

Nomenclature

E-bus – electric bus
TTW– Tank-To-Wheel
WTW– Well-To-Wheel
CO_2 – carbon dioxide
CO – carbon monoxide
C_xH_y – unburned hydrocarbons
NO_x – nitrogen oxides
PM – particles maters
CNG – compresed natural gas
UITP – International association of public transport
WHO – World Health Organization
EU – European Union
ETC – European transient cycle test
SEF – Standard Emission Factor carbon dioxide
LCA – Life Cycle Assessment carbon dioxide
EKO1 – electric bus line in Belgrade

m_{CO_2} – mass of formed carbon dioxide, g
m_f – mass of fossil fuel that burns, g
g_c – carbon content in the fuel, %
44 – molar mass of carbon dioxide, g/mol
12 – molar mass of carbon, g/mol
E_c – stored electricity in ultracapacitor, kWh
C_c – capacitor capacity, F
U_c – capacitor voltage, V
$CO_{2_{WTW}}$ – carbon dioxide emissions according to WTW-analysis, g/km
E_{ebus} – electricity consumption of E-bus, kWh/km
η_{ch} – charger efficiency coefficient
LCA_{CO_2} – emission factor of the total cycle of electricity production, gCO_2/kWh
f_{gpee} – coefficient of loss in electricity transmission

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