Pol. J. Environ. Stud. Vol. 29, No. 5 (2020), 3339-3351
DOI: *10.15244/pjoes/112899* ONLINE PUBLICATION DATE: 2020-03-05

Original Research

Replacing Diesel Buses with Electric Buses for Sustainable Public Transportation and Reduction of CO_2 Emissions

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Received: 19 June 2019
Accepted: 8 October 2019

Abstract

Public buses ensure mobility for more than 450 billion passengers annually as a necessary means of transportation in cities around the world. However, buses have an image problem in the eyes of the urban population, because half of the buses in the EU urban transport fleet are in the best case classed as Euro 3 (European emission standards). Consequently, the renewal of bus fleets should be a priority in order to provide sustainable urban mobility. Our paper presents the benefits of replacing diesel buses in the fleet of Compania de Transport Public (CTP) Cluj-Napoca with electric buses and the impact of this change on the environment. Following the introduction of 11 electric buses into urban transportation, to replace the same number of diesel buses this study evaluates and highlights the reduction of CO_2 as the greatest bulk component of greenhouse gas (GHG) emissions. In the context of renewing the public transport fleet of CTP Cluj-Napoca, the present work investigates the quantity of CO_2 emissions removed from city traffic. Currently, in major cities of the world, there are policies to reduce GHG emissions by introducing the electric buses in the public transport fleet, moving toward the gradual replacement of diesel buses.

Keywords: sustainable transportation, CO_2 emissions, electric buses, diesel buses, energy consumption

Introduction

According to public information, Compania de Transport Public (CTP) Cluj-Napoca operates with 41 bus lines, providing transportation for 67.5% of the total number of passengers, by means of a fleet made up of 256 classical buses equipped with diesel engines meeting emission standards between Euro 0 and Euro 6, as well as a number of electric buses, with zero local pollution, on a road infrastructure of 567 km [1-3].

Regarding the Euro 6 emission standards, the new regulations make significant changes to the 50% reduction in the level of emissions measured for the following indicators: carbon dioxide (CO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and non-methane hydrocarbons (NMHCs). For electric propulsion systems, all of the above emission indicators are zero (local). The amount of CO_2 emitted per year from transport activity and calculated according to the amount of fuel consumed represents the carbon footprint of road transport. Approximately 25% of CO_2 emissions from road transport comes from trucks, buses, and coaches, and this is expected to increase by about 10% by 2030 [4, 5]. The transport sector, with

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vehicles equipped with conventional fossil fuel engines, is responsible for more than 70% of air pollution in big cities [2]. Annually, the quantity of CO_2 emitted into the atmosphere has a mass four times the mass of the emitting vehicle [2]. The high degree of air pollution in the transportation sector results from the sector's direct dependence on fossil fuels. The negative impact on the environment in large urban agglomerations due to increased numbers of vehicles with classical propulsion systems is highlighted by European energy and environmental policies. Urban traffic is estimated to generate up to 40% of CO_2 emissions and up to 70% of other pollutant emissions [2, 6]. Around the world, approximately 3.7 million people in a billion die prematurely annually due to atmospheric pollution [7]. Cardiovascular, pulmonary, and cognitive diseases can be aggravated by the air-polluting emissions from the atmosphere.

The Green Vehicle Directive (2009/33/EC) [8] requires public transport operators, when purchasing new buses, to consider in their assessment of energy, environmental, and operational impact of at least the following: energy consumption, CO_2 and NO_x emissions, NMHCs, and particulates. European Commission (EC) Regulation 443/2009 [9], which refers to the M1 vehicle category, aims to reduce emissions from new vehicles and imposes limits on CO_2 emissions to a value of 95 g CO_2/km by 2020, compared to the current standard of 130 g CO_2/km. European Union (EU) Regulation 2400/2017 [10], which implements EC Regulation 595/2009 [11] and amends Directive 2007/46/EC [12] and EU Regulation 582/2011 [13], indicates that emissions from trucks, coaches, and buses are currently about 25% of the total CO_2 emissions from road transport, and are expected to increase further in the future [14]. Reducing CO_2 emissions from heavy-duty vehicles and buses requires the implementation of effective measures to achieve the 60% reduction target by 2050.

Topal et al. [15] highlight that the increased pollutant emissions from classical road transport systems requires the development of sustainable transport systems with zero local pollutant emissions.

In the reduction of CO_2 emissions in Cluj-Napoca city, the chosen solution is to replace 11 diesel buses with electric buses. Thus, considering the desiderata [2, 16] for achieving this objective, Fig. 1 shows the advantages [2, 5] and disadvantages [2] of replacing diesel buses with electric buses for public transport.

Kivekas et al. [17] showed that in crowded urban areas, where driving cycles are demanding, traffic is heavy, and travel speeds are reduced, it is necessary to replace diesel buses with as many electric buses with low energy consumption as possible.

Topal et al. [15] proposed a new approach called the zero-emission bus purchase and operation model (ZEBusPOM) to move from the classical polluting public transport system to a sustainable system with zero local pollutant emissions according to the following algorithm:

1. Monitor the real-time operation of diesel/electric buses in urban traffic after a predetermined schedule, with passengers, under hot/cold weather conditions.
2. Develop a database with monitored results during the operation of diesel/electric buses.
3. Compare the two bus models in terms of energy efficiency.

The purpose of this paper is to highlight the need to replace diesel buses with Euro 0 emission standards with electric buses with zero local pollution. This paper

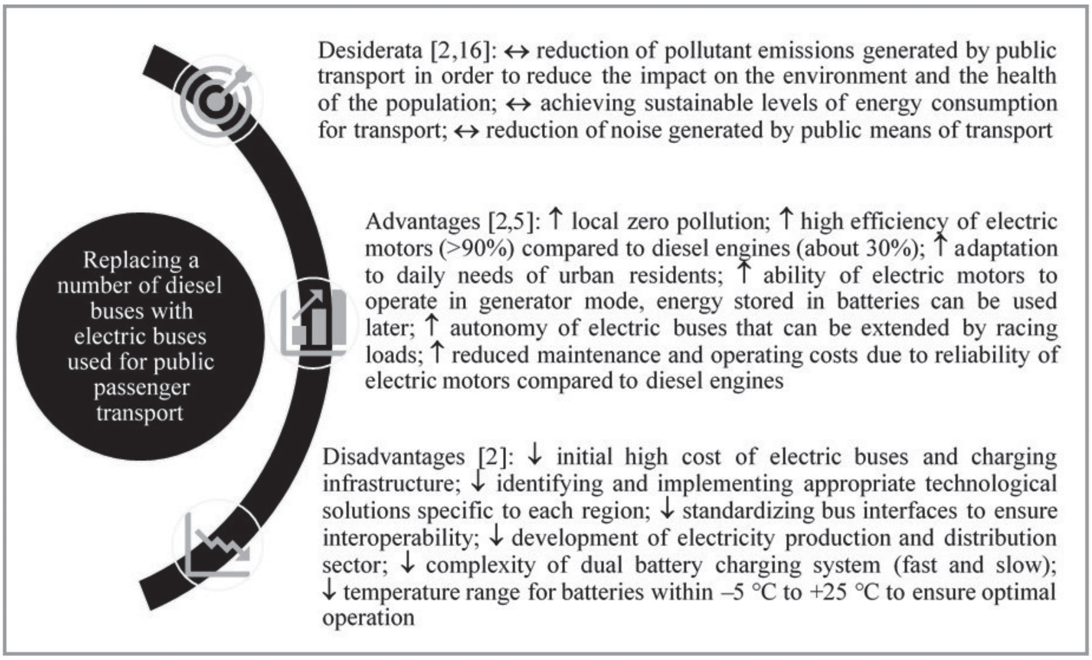

Fig. 1. Desiderata, advantages, and disadvantages of the solution for replacing electric buses for public transport.

Table 1. Technical characteristics of considered buses.

Parameters	Unit	Renault R312	Solaris Urbino 12e
Length/width/height	m	11.99/2.50/2.95	12.00/2.55/3.25
Nominal/loaded weight	kg	11550/19000	13000/19000
Number of seats/total passenger capacity	–	28/107	23/70
Engine/motor (tip)	–	Diesel Euro 0	Electric asynchronous
Maximum engine power	kW	180	160
Maximum engine torque	Nm	925	1450
Batteries (type)	–	–	Lithium
Battery capacity	kWh	–	210
Tank capacity	l	250	–
Energy consumption summer/winter	kWh/km	–	1.00/2.00
Fuel consumption summer/winter	l/100 km	34/37.4	–
Autonomy (by producer)	km	600	105
CO emissions (Euro standard)	g/kWh	12.30	0 local
HC emissions (Euro standard)	g/kWh	2.60	0 local
NO_x emissions (Euro standard)	g/kWh	15.80	0 local

reports research carried out on the quantity of CO_2 emissions reduced from urban traffic in Cluj-Napoca, Romania, following the replacement of 11 diesel buses with 11 electric buses. With this purpose, weather conditions (temperature and humidity) were considered for the investigated period (July-December 2018*).* The environmental data, along with statistics on fuel consumption (for diesel buses), energy consumption (for electric buses), and the distances traveled were the basis for assessing the amount of CO_2 reduced by the introduction of electric buses. At the same time, these data allowed evaluation of the optimal energy consumption of the electric buses according to temperature and humidity during the considered period.

Material and Methods

Bus Technology Comparisons

At present, the CTP Cluj-Napoca fleet [3] has 40 Solaris Urbino 12e electric buses, of which 11 were purchased in May 2018 and 12 were purchased earlier this year (2019), and another 17 arrived in Cluj-Napoca

Table 2. Bus line characteristics.

Parameters	Unit	27	28	30	32
Line length (tour-retour)	km	9.700	8.500	17.700	6.600
Average time (tour-retour)	min	41	36	78	35
Number of stops (tour-retour)	–	17	15	31	13
Average distance between stops	km	0.571	0.567	0.571	0.510
Number of buses per line	–	2	1	6	2
Total number of lines (working days)	–	30	11	60	44
Total number of lines (Saturday)	–	22	10	30	24
Total number of lines (Sunday)	–	20	9	24	24
Total distance per line (working days)	km	38121	12249	139122	38042
Total distance per line (Saturday)	km	5548	2210	13806	4118
Total distance per line (Sunday)	km	5238	2066	11470	4277
Total distance per line (July-December 2018)	km	27	28	30	32

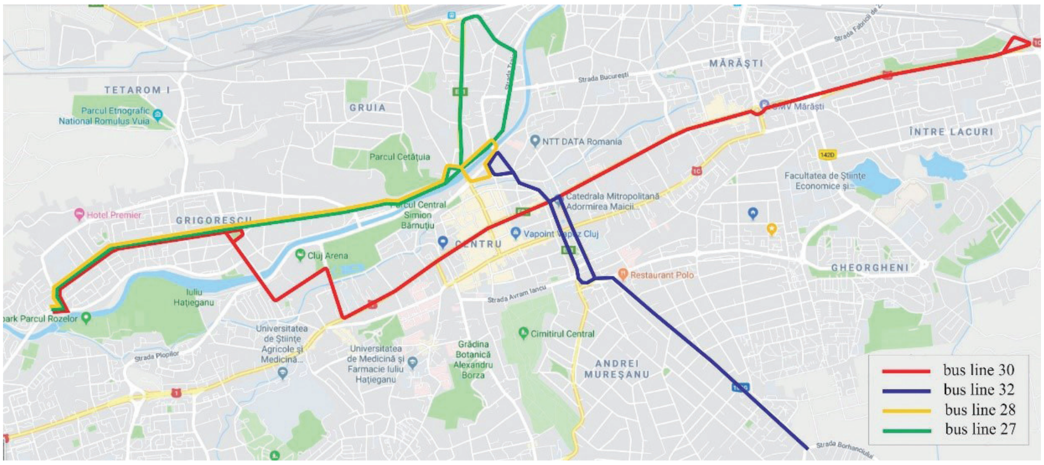

Fig. 2. Bus line characteristics.

in mid-2019. The 11 electric buses that have been in the fleet since 2018 operate on lines 27, 28, 30, and 32 [2, 3]. The Solaris Urbino 12e buses already in operation have replaced the same number of diesel buses, Renault R312 type manufactured between 1990 and 1993, with Euro 0 emission standards. Not all diesel buses were replaced on the considered lines; some still run alongside the electric buses. The technical characteristics of the two types of buses are shown in Table 1 [18-23].

Operating Lines of Tested Buses

The bus lines on which the electric buses are used are 27, 28, 30, and 32. According to data provided by CTP Cluj-Napoca [1, 24], the characteristics of these public transport lines are detailed in Table 2 and Fig. 2. To define the altitude of points for the bus line, we used the GpsPrune application [25], which is designed for viewing, editing, and converging coordinate data obtained by the global positioning system (GPS) (Fig. 3).

The altitude profile of a line is a very important parameter for an electric vehicle in terms of its autonomy. In [2], among other factors, the altitude characteristics of the public transport lines in Cluj-Napoca city were taken into consideration to study the designation of lines on which the electric buses would operate.

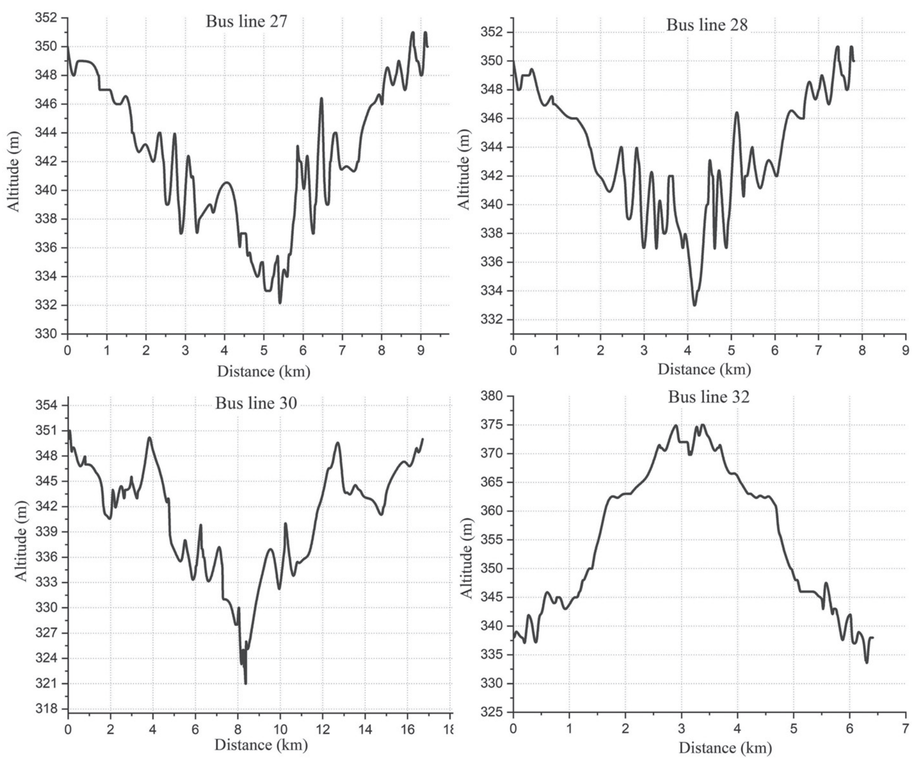

Fig. 3. Altitude profiles for evaluated bus lines (27, 28, 30, 32).

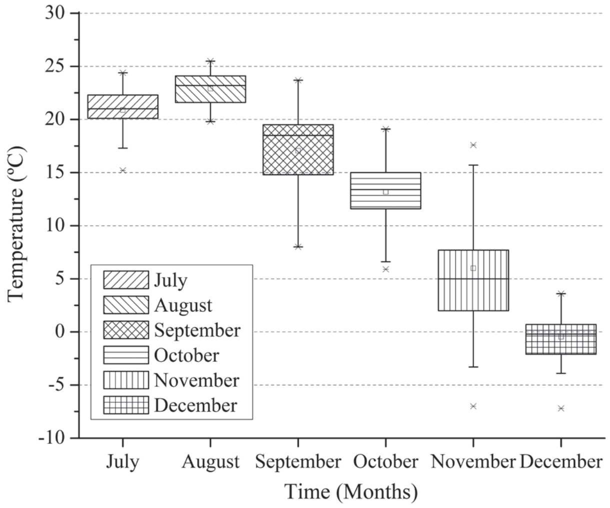

Fig. 4. Temperature values recorded for the considered period.

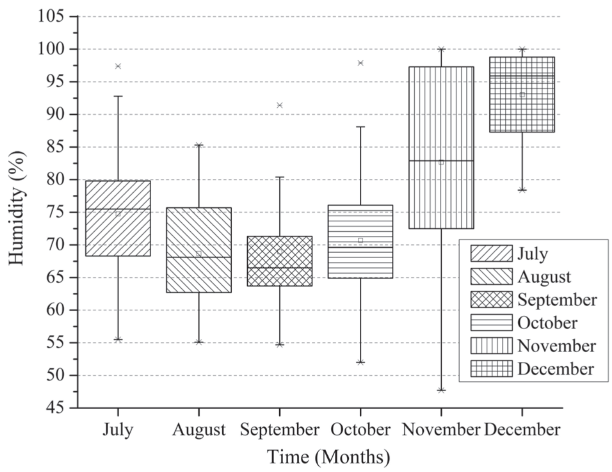

Fig. 5. Humidity values for the considered period.

Environmental Data

Regarding the ambient data, the temperature in Cluj-Napoca in the time interval between 05:00, when the buses start working ($T_{5.00}$ (ºC)) and 23:00, when the buses finish working ($T_{23.00}$ (ºC)), was monitored for the whole considered period (July-December 2018). The temperatures were downloaded from rp5.ru [26] considering the temperature during each hour of the considered range. Since fuel/energy consumption is monitored as a statistical value per bus per day, the average daily temperature ($T_{average}$ (ºC)) was calculated from the relationship:

$$T_{average}\ (^{\circ}C) = AVERAGE(T_{5.00}:T_{23.00}) \quad (1)$$

The evaluation of recorded temperature for the considered period is represented in a boxplot (Fig. 4), which, based on the daily quantitative data of temperature variation, generated a statistical model for each monitored month. The main elements generated by the boxplot (Table 3) were mean (μ), standard deviation (SD), minimum value (min), lower quartile (Q1) (delimits the lowest 25% of recorded values), median (med; delimits the lower 50% of recorded values, with 50% of the highest recorded values dividing the set of values into two equal parts), upper quartile (Q3) (delimits the highest 25% of recorded values), and maximum value (max).

Similar to temperature values, the daily average values for atmospheric humidity were downloaded and calculated and, after statistical processing, are presented in a boxplot (Fig. 5 and Table 4).

Electric Power Generation

Electric buses, propelled by electric motors powered by batteries recharged from the public electricity grid, have zero local pollutant emissions. Charging is carried out in loading stations located at the ends of the lines on which the buses run. There are slow charging stations (overnight), where batteries charge up to 100% of capacity in 4-6 hours, and fast charging stations, where batteries can be charged with a lot of energy in a short period of time (10 minutes), to extend the autonomy of electric buses in the intervals between runs.

This energy comes from both renewable sources (nuclear, geothermal, biomass, wind, solar, hydro) and polluting sources (coal, gas, oil) in different proportions, depending on a multitude of factors. The ElectricityMap Live [27] application and the monthly electricity market monitoring reports (Table 5) of the Romanian National Regulatory Authority for Energy (ANRE) [28-30]

Table 3. Boxplot analysis of thermal variation (ºC).

Month	μ (mean)	SD (standard deviation)	min (minimum value)	Q1 (lower quartile)	med (median)	Q3 (upper quartile)	max (maximum value)
July	20.88	2.09	15.20	20.20	21.00	22.30	24.40
August	22.90	1.54	19.80	21.60	23.20	24.10	25.50
September	17.04	4.38	8.00	14.40	18.60	19.60	23.70
October	13.17	3.05	5.90	11.60	13.40	15.10	19.10
November	5.98	5.81	–7.00	2.00	5.00	7.80	17.60
December	–0.46	2.21	–7.20	–1.80	–0.20	0.90	3.60

Table 4. Boxplot analysis of variation in atmospheric humidity values (%).

Month	µ (mean)	SD (standard deviation)	min (minimum value)	Q1 (lower quartile)	med (median)	Q3 (upper quartile)	max (maximum value)
July	74.74	9.69	55.50	68.20	75.50	79.80	97.40
August	68.65	8.94	55.10	62.70	68.10	75.75	85.30
September	68.94	8.71	54.70	63.90	66.50	71.10	91.40
October	70.68	9.93	52.00	65.00	69.60	76.10	97.90
November	82.67	14.74	47.70	72.50	84.70	97.30	100
December	93.02	7.14	78.40	87.30	95.90	98.80	100

Table 5. Structure of electricity resources delivered in Romania, by type.

Energy Source	2018						CO_2 emissions (g CO_2/kWh)
	July	Aug	Sept	Oct	Nov	Dec	
Nuclear (%)	18.20	18.89	19.04	19.86	18.62	18.50	12
Biomass (%)	0.06	0.06	0.00	0.11	0.20	0.16	230
Coal (%)	22.56	23.35	24.53	24.26	26.27	25.64	820
Wind (%)	4.21	7.36	11.35	12.42	11.77	11.85	11
Solar (%)	1.77	1.99	1.78	1.46	0.58	0.41	45
Hydro (%)	41.28	32.43	26.79	22.09	20.02	18.84	24
Gas (%)	11.90	15.87	16.47	19.78	22.46	24.57	490
Oil (%)	0.02	0.05	0.04	0.02	0.08	0.02	650
Low carbon	34.54	39.33	41.04	44.17	49.01	50.39	–
Renewable	65.46	60.67	58.96	55.83	50.99	49.61	–
Total energy (TWh)	4.43	4.47	4.27	4.61	4.88	5.26	–
Total CO_2 emissions (gCO_2/kWh)	256.92	281.45	292.87	305.95	335.04	339.37	–

show the quantity of CO_2 emissions between July and December 2018 (Fig. 6). These data are based on the national energy system production structure by the type of resource, from which the amount of energy consumed by electric buses to operate during the monitored period was obtained.

Reducing GHG emissions and dependence on fossil fuel markets and diversification of the energy supply can be achieved by using energy from renewable sources. Most public transportation systems use buses equipped with internal combustion engines that run on fossil fuels (as the main power source). The use of renewable sources has been universally accepted as a solution to replace fossil fuels in order to reduce global GHG emissions. However, this solution has many limitations in terms of environmental protection.

Bus Monitoring Data

Real-time monitoring of buses operating in Cluj-Napoca is done by the Thoreb tracking and traffic monitoring system [31], a GPS tracking system that allows for real-time surveillance of buses on a digital map based on the signals generated by GPS modules installed on the buses and transmitted to dispatchers using general packet radio service (GPRS) technology. At the same time, a range of data is collected on the technical condition of the buses, the distance traveled, fuel/energy consumption, number of passengers transported, etc., and transmitted to the dispatchers from the controller area network (CAN) bus.

Diesel Bus Monitoring Data

The data regarding the fuel consumption (l/100 km) of diesel buses for the considered period were taken from the opportunity study conducted by CTP Cluj-Napoca [3] and were evaluated using a boxplot (Fig. 7) based on estimated fuel consumption values, generating a statistical model for each monitored month. The main elements generated by the boxplot are presented in Table 6.

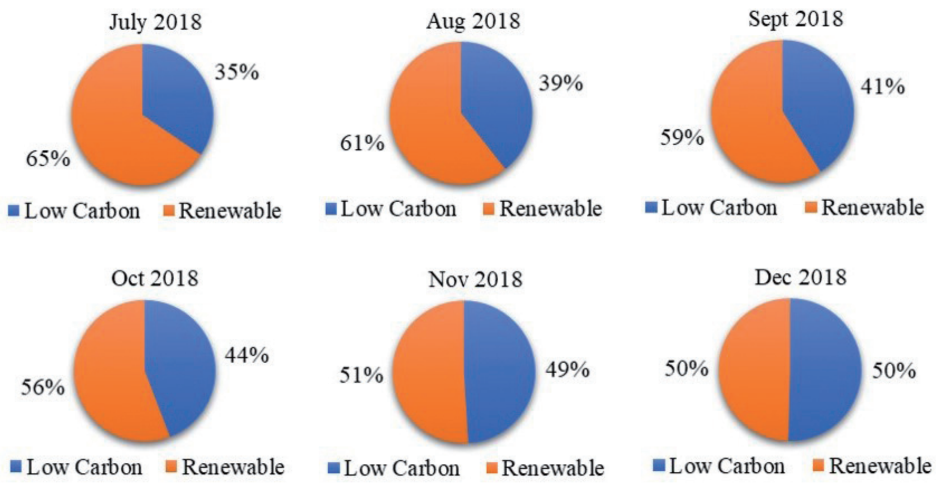

Fig. 6. Types of resources used to obtain electricity during the considered period (July–December 2018).

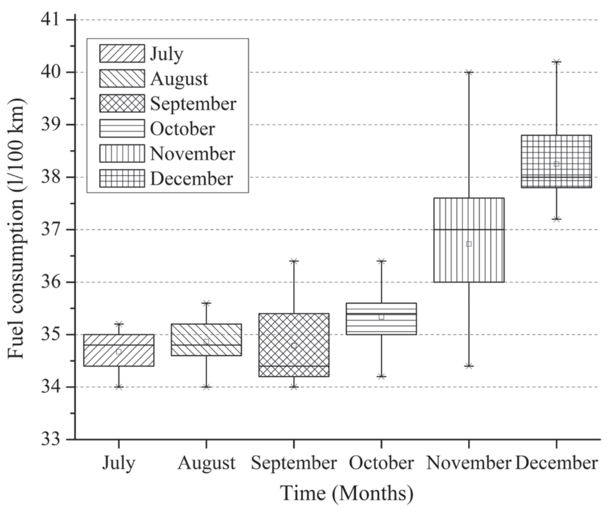

Fig. 7. Fuel consumption (l/100 km) of diesel buses in the considered period.

Electric Bus Monitoring Data

The evaluation of recording of energy consumption in the considered period was done with a boxplot (Fig. 8) based on the initial data, generating a statistical model for each monitored month. The main elements generated by the boxplot are presented in Table 7.

Analysis of Monitoring Data

Diesel Bus Monitoring Data Analysis

The methodology for calculating CO_2 emissions for the assessed buses is based on the provisions of Directive 2009/33/EC [8], which promotes clean and energy-efficient vehicles and targets the increased use of green vehicles (in this case electric buses) by highlighting the energy and environmental impact.

In his study, Jovanovic [32] show that due to its extremely high share of regular diesel buses in urban public transport of Belgrade, CO_2 emissions are not as efficient as they should be and if urban transport supports rail use (electric propulsion system), the CO_2 emissions are much lower than emissions of regular buses (diesel propulsion system).

Kadiyala et al. [33] monitored the concentrations of pollutant emissions over a period of one year, recording other factors that are important in their production (weather conditions, annual monitoring period, source

Table 6. Boxplot analysis of fuel consumption of diesel buses (l/100 km).

Month	µ (mean)	SD (standard deviation)	min (minimum value)	Q1 (lower quartile)	med (median)	Q3 (upper quartile)	max (maximum value)
July	34.67	0.32	34.00	34.40	34.80	35.00	35.20
August	34.86	0.45	34.00	34.60	34.80	35.20	35.60
September	34.78	0.77	34.00	34.20	34.40	35.40	36.40
October	35.33	0.57	34.20	35.00	35.40	35.60	36.40
November	36.72	1.31	34.40	36.00	37.00	37.60	40.00
December	38.25	0.69	37.20	37.80	38.00	38.80	40.20

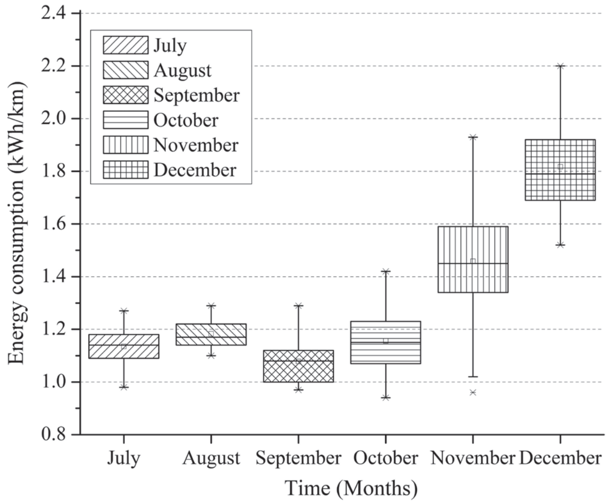

Fig. 8. Energy consumption (kWh/km) of electric buses during the considered period.

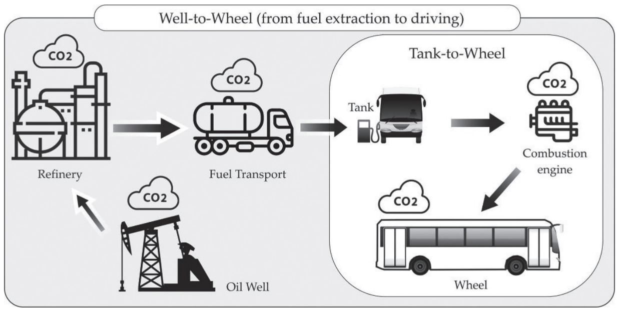

Fig. 9. Well-to-wheels (WTW) concept for diesel buses.

of samples, etc.). Following the monitoring, the authors found that pollutant emissions increased proportionally with humidity in the ambient environment and decreased with ambient temperature decrease.

In their study, Hernandez-Paniagua et al. [34] used boxplot analysis to highlight the statistical values of pollutant emissions, comparing emissions from urban areas with diesel bus transportation with emissions from areas with trolleybus transportation (electric propulsion system).

Grijalva et al. [14] expressed the values of CO_2 emissions for diesel buses based on the well-to-wheels (WTW) and life cycle analysis (LCA) concepts, which examine the impact of CO_2 emitted into the atmosphere on the environment for all phases in the flow of power from extraction (oil well), refining, fuel transport, distribution, feed pump, tank, combustion process, power distribution to the propulsion system, and consumption on the wheels (Fig. 9).

The WTW concept is a method of analysis for evaluating the environmental impact of the extraction, distribution, supply and transformation the propulsion energy into kinetic energy for vehicles. CO_2 emissions are not only the result of the fuel burned in internal combustion engines (ICE). These emissions are produced in all the stages mentioned above. For real, correct and complete evaluation of the emissions that result from the operation of the diesel buses we must consider the equivalent CO_2 emission values and results in all the stages between the process of extraction of the raw material and until the power supply of the vehicle.

In conclusion, we can say that the net value of CO_2 emissions result from the operation of diesel buses is equal to the CO_2 emissions generate by ICE, plus the contribution of CO_2 emissions resulting directly or indirectly from the extraction of raw materials up to the energy conversion.

Thus, for a diesel bus, CO_2 emissions are calculated by considering the average fuel consumption and the distance traveled over a period of time, but also the coefficient corresponding to the WTW stages.

The estimation of the amount of CO_2 emitted by diesel buses for a distance traveled over a period of time is from Equation (2):

$$Q_{CO_2}^{diesel}(kg) = n_{buses}^{diesel} \cdot f_{WTWCO_2}^{diesel}(kgCO_2eq/l) \cdot \sum_{m=1}^{i} \frac{cd_m(l/100\ km) \cdot d_m(km)}{100\ (km)} \quad (2)$$

…where $Q_{CO_2}^{diesel}$(kg) is the total amount of CO_2 emitted in the atmosphere by the diesel buses evaluated during the considered period, n_{buses}^{diesel} is the number of buses, m is a month in the assessment period, i is total months of the considered period, cd_m(l/100 km) is average fuel

Table 7. Boxplot analysis of power consumption of electric buses (kWh/km).

Month	μ (mean)	SD (standard deviation)	min (minimum value)	Q1 (lower quartile)	med (median)	Q3 (upper quartile)	max (maximum value)
July	1.13	0.07	0.98	1.09	1.14	1.18	1.27
August	1.18	0.05	1.10	1.14	1.17	1.22	1.29
September	1.07	0.07	0.97	1.00	1.08	1.12	1.29
October	1.15	0.11	0.94	1.07	1.15	1.23	1.42
November	1.45	0.24	0.96	1.31	1.45	1.59	1.93
December	1.81	0.17	1.52	1.69	1.79	1.92	2.20

consumption for diesel buses in the considered month, d_m(km) is the distance traveled by a diesel bus for the considered month, and $f^{diesel}_{WTWCO_2}$ ($kgCO_2eq/l$) is the amount of CO_2 emitted to produce a liter of fuel based on the WTW concept.

For a proper delimitation of the CO_2 emissions value, which can be used for both buses (diesel and electric), it was considered that the CO_2 emissions for WTW concept is formed by CO_2 emissions from the well-to-tank (WTT) section – the stages corresponding to the processes of extraction, transport and distribution of the fuel ($f^{diesel}_{WTTCO_2}$ ($kgCO_2eq/l$) [14, 35]) and the tank-to-wheels (TTW) section – the stages corresponding to the processes of the fuel supply and the fuel conversion ($f^{diesel}_{TTWCO_2}$ ($kgCO_2eq/l$)) [36], according to Equation (3):

$$f^{diesel}_{WTWCO_2}(kgCO_2eq/l) = f^{diesel}_{WTTCO_2}(kgCO_2eq/l) + f^{diesel}_{TTWCO_2}(kgCO_2eq/l) \quad (3)$$

In order to assess the amount of CO_2 emitted in the atmosphere by the diesel buses during the considered period, their fuel consumption is converted to the distance traveled (l/100 km) in equivalent energy consumption (kWh/km). In this respect, considering the lower heating value (LHV) of 43100 kJ/kg [37] for diesel fuel and converting this into kWh (1kWh = 3600 kJ), 12 kWh/kg is obtained, equivalent to 10 kWh/l (1 kg = 1.2 liters of diesel). The equivalent energy consumption based on the LHV of the fuel is an abstract value that allows for a comparison between energy efficiency and the emissions of the diesel and electric buses. The total amount of CO_2 emission for each diesel bus in a month is calculated as the product of the amount of fuel and the sum of conversion factor corresponding to the entire cycle of LCA. The equivalent consumption per km for each month of the monitored period results from the ratio between the total amount of CO_2 emissions for each diesel bus and the distance traveled in that month.

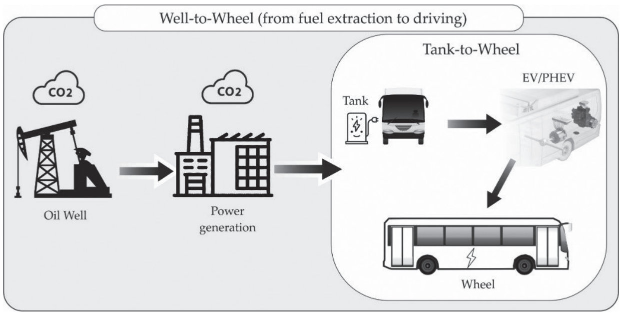

Fig. 10. WTW concept for electric buses.

The results using Equation (2) and the conversion factors specified above are presented in Table 8.

Electric Bus Monitoring Data Analysis

For electric buses powered by the national electricity grid, the WTW concept comprises the following steps: oil well, transport, distribution, production of electrical energy (power generation), transport and distribution of electricity (power transmission and distribution), charging the battery, powering the engine, power delivery system, and energy consumption at wheels (Fig. 10) [6, 30, 37-39].

The WTW concept consists of WTW and TTW sections. To assess the amount of CO_2 emitted into the atmosphere to produce the energy consumed during

Table 8. Consumption of equivalent energy for diesel buses.

Parameters	Unit	2018					
		July	Aug	Sept	Oct	Nov	Dec
Fuel consumption (cd_m)	l/100 km	34.80	34.80	34.40	35.40	37.00	38.00
Equivalent energy consumption (LHV_{diesel} = 43100 kJ/kg)	kJ/km	12499	12499	12355	12715	13289	13648
Equivalent energy consumption (1 kWh = 3600 kJ)	kWh/km	3.472	3.472	3.432	3.532	3.691	3.791
Distance traveled/month (d_m)	km	46432	47315	43946	47315	45578	45682
Fuel consumption/month	l	15973	16655	15117	16750	16864	17359
Equivalent energy consumption/month	kWh	161209	164275	150824	167107	168248	173190
WTT factor ($f^{diesel}_{WTTCO_2}$) (see [14])	$kgCO_2$ eq/km	0.162	0.162	0.162	0.162	0.162	0.162
WTT factor ($f^{diesel}_{WTTCO_2}$) (fuel consumption)	$kgCO_2eq/l$	0.460	0.460	0.465	0.452	0.432	0.421
TTW factor ($f^{diesel}_{TTWCO_2}$) (see [36])	$kgCO_2eq/l$	2.4416	2.4416	2.4416	2.4416	2.4416	2.4416
CO_2 emissions (buses/month)	kg	46344	48322	43941	48467	48468	49693
Total CO_2 emissions ($Q^{diesel}_{CO_2}$)	kg	285235					
Total CO_2/km	kg CO_2 eq/km	0.998	1.021	1.000	1.024	1.063	1.088

Table 9. Energy consumption for electric buses.

Parameters	Unit	2018					
		July	Aug	Sept	Oct	Nov	Dec
Energy consumption (ce_m)	kWh/km	1.14	1.17	1.08	1.15	1.45	1.78
Distance traveled/month (d_m)	km	46432	47315	43946	47315	45578	45682
Energy consumption/month	kWh	52932	55359	47462	54412	66088	81314
CO_2 emissions (WTT section see Table 5)	gCO_2/kWh	256.92	281.45	292.87	305.95	335.04	339.37
WTT factor ($f_{WTTCO_2}^{diesel}$) (WTT section see Table 5)	$kgCO_2/kWh$	0.257	0.282	0.293	0.306	0.335	0.339
CO_2 emissions (buses/month)	kg	13599	15581	13900	16647	22142	27596
Total CO_2 emissions ($Q_{CO_2}^{electric}$)	kg	109465					
Total CO_2/km	kg CO_2/km	0.293	0.329	0.316	0.352	0.486	0.604

the considered period, only CO_2 emissions are considered in the WTT section, whose values are given in Table 9 [14, 40-42]. The electric buses with zero local pollution are much more efficient also from the point of view of energy efficiency, having much lower energy consumption.

The total amount of CO_2 emissions for each electric bus over a month is calculated as the product of energy consumption and the conversion factor corresponding to the WTT section. The equivalent consumption per km for each month of the monitored period results from the ratio between the total amount of CO_2 emissions for each electric bus and the distance traveled in that month.

The estimation of CO_2 emitted for production, transport, and charging electric buses to cover the traveled distance over the considered period is derived from Equation (4):

$$Q_{CO_2}^{electric}(kg) = n_{buses}^{electric} \cdot f_{WTTCO_2}^{electric}(kgCO_2/kWh) \cdot \sum_{m=1}^{i}[ce_m(kWh/km) \cdot d_m(km)] \quad (4)$$

...where $Q_{CO_2}^{electric}(kg)$ is the total amount of CO_2 emitted into the atmosphere by the production of energy consumed by electric buses during the considered period, $n_{buses}^{electric}$ is the number of evaluated electrical buses, m is a month during the assessment period, i is the total number of months for the considered period, ce_m(kWh/km) is the average energy consumption of an electric bus for the considered month, d_m(km) is the distance traveled by an electric bus for the considered month, and $f_{WTTCO_2}^{electric}(kgCO_2/kWh)$ is the amount of CO_2 emitted to produce 1 kWh of energy based on the WTT section (see Table 5).

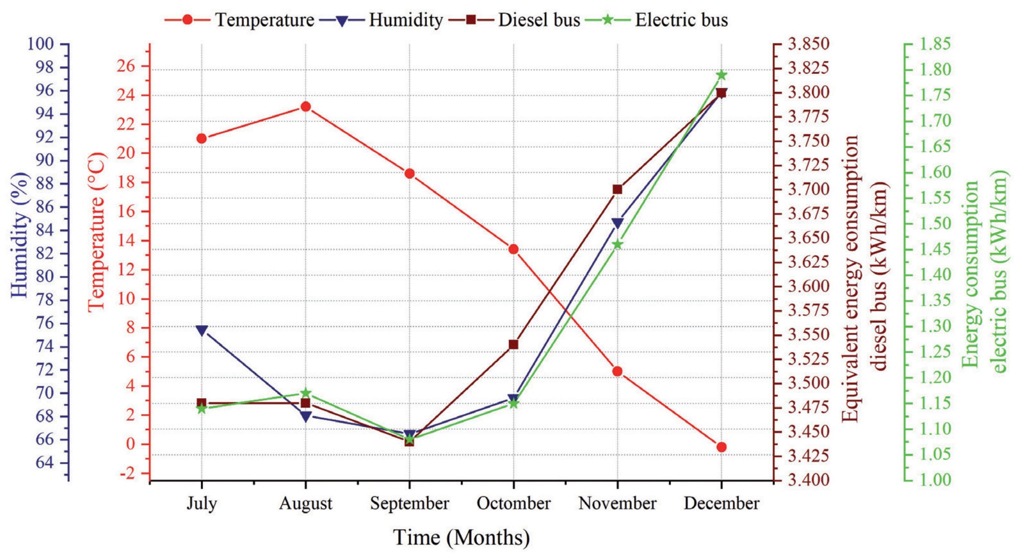

Fig. 11. Energy consumption (kWh/km) vs. temperature (ºC) and humidity (%).

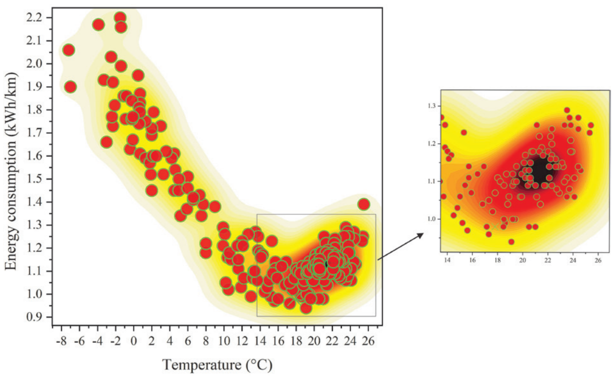

Fig. 12. Energy consumption (kWh/km) vs. temperature (ºC) for electric buses.

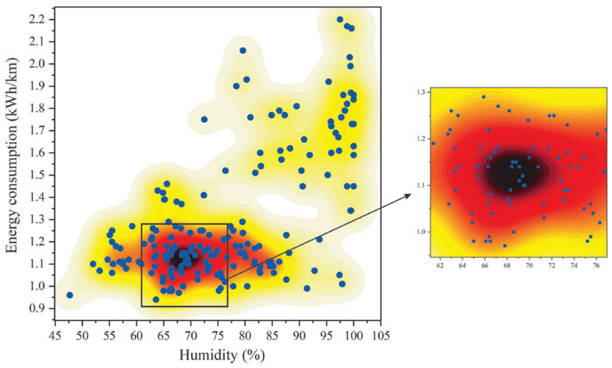

Fig. 13. Energy consumption (kWh/km) vs. humidity (%) for electric buses.

Results and Discussion

As a result of data processing, Fig. 11 shows the variation in energy consumption of diesel and electric buses considered over the set period, depending on ambient temperature and atmospheric humidity.

The obtained results (see Fig. 11) highlight the significant influence of ambient temperature and atmospheric humidity on energy consumption. Thus, it can be seen that the humidity curve approaches the energy consumption curve. The increased energy consumption in the summer months (July and August) is due to air-conditioning (AC) in electric buses. The replaced diesel buses did not have AC, so they did not consume extra fuel during this period. Compared to climatic conditions in the summer and early autumn, in winter, when the ambient temperature falls below freezing and the humidity is high, energy consumption can double. Due to this, there may be situations where electric buses cannot be used during the working day because of the drastic decrease in autonomy. In such situations, it is necessary to introduce fast charging stations at some stops on the line or reduce the working hours of electric buses by half.

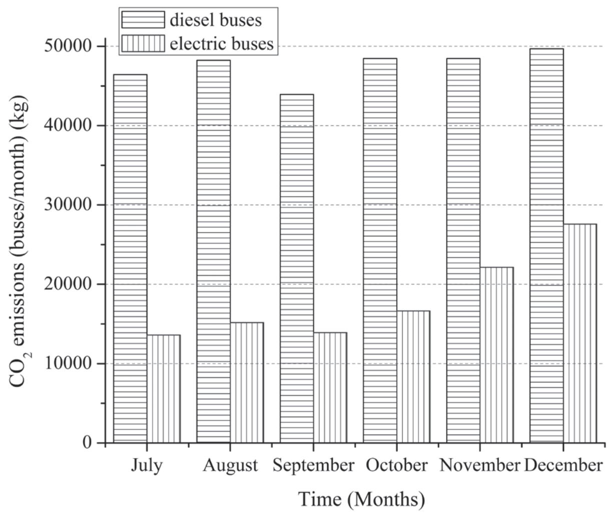

Fig. 14. Emission of CO_2 generated by the production of electric power (electric buses vs. diesel buses).

For the evaluated electric buses, the distribution of energy consumption during the considered period (July-December 2018) depending on ambient temperature and ambient humidity are shown in Figs 12 and 13, respectively. The maximum point concentration (zoom image) indicates an optimal energy consumption (1.125 kWh/km) relative to the optimal ambient temperature (21.2ºC) and ambient humidity (68.5%).

The energy efficiency of the electric buses is influenced by a number of external factors such as: the mass of the buses that depends on the number of passengers transported, the consumption generated by the auxiliary systems that depends on the climatic conditions (high temperatures – cooling system with AC, low temperatures – the heating system), the altitude profile of the urban route traveled by buses, etc.

In order to assess the results of CO_2 emissions from the production of electricity required for the operation of electric buses during July-December 2018, we analyzed the structure of types of electricity delivered in Romania in that period, for which these emissions were evaluated monthly. After analyzing the recorded data, we found that replacing diesel buses with electric buses had an immediate effect on eliminating local emissions in the circulation areas of Cluj-Napoca. At the same time, the emission of CO_2 generated by the production of electric power consumed by electric buses is 2.605 times lower than that generated by diesel buses (Fig. 14, see Tables 8 and 9).

The experimental data recorded for the monitored period include the climatic characteristics, from the point of view of the ambient temperatures and humidity, for the hot season (July-September) and for the cold season (October-December).

Conclusions

By replacing diesel buses with electric buses in the passenger fleet, Cluj-Napoca aims to develop sustainable urban public transport with clean vehicles. The purpose of this study is to demonstrate that by replacing a number of diesel buses with a maximum pollution factor (Euro 0 emission standards) with electric buses that do not emit local pollutants, the total amount of CO_2 emissions is significantly reduced (emissions are generated only when producing the necessary electricity to charge the buses).

In addition to reducing pollutant emissions from public transport, replacing diesel buses with electric buses has immediate advantages (reduced environmental noise, reduced shocks caused by thermal engines transmitted to the infrastructure, increased local/national/international confidence and visibility of areas that adopt such a modern solution, etc.) and medium- and long-term benefits (reduced operating costs and maintenance due to the reliability of electric buses based on the simple construction of the powertrain, and the possibility of reducing the cost of bus trips, so that as many citizens as possible will stop using personal vehicles in the city, resulting in less traffic and further reduction of pollution).

The energy efficiency of the electric buses depends on the specific conditions of each urban system in which these buses are integrated and operate, but regardless of these specific conditions there is a common positive impact, namely that the local emissions generated by the operation of these buses are zero. For the production of electricity, according to the analysis of the life cycle and the stages of the WTW concept, it can be said that the real impact on the environment depends on the renewable sources (nuclear, geothermal, biomass, wind, solar, hydro) and on the pollutants sources (coal, gas).

According to the research carried out in this paper, it was found that at the national level between 50 and 65% of the energy resources used to obtain electricity are renewable.

In addition, due to the specific conditions of the free market for electricity trading, in the national system, there is the possibility for the operator of the electric bus fleet to buy electricity labeled "green" electricity (obtained from renewable primary sources) in order to minimize the total amount of CO_2 emissions for each electric bus.

The fact that the purchase prices of electric buses are high is still a disadvantage, but national/international financing programs for the purchase of clean electric vehicles could facilitate the acquisition of clean vehicles.

Acknowledgements

The authors wish to thank CTP Cluj-Napoca for providing the data from the Opportunity Study.

Conflict of Interest

The authors declare no conflict of interest.

References

1. CTP Cluj-Napoca. Available online: http://ctpcj.ro/index.php/ro/ (accessed on 21 August **2019**) [In Romanian].
2. Primăria și Consiliul Local Cluj-Napoca. Studiu de Oportunitate 2018. Available online: https://storage.primariaclujnapoca.ro/userfiles/files/studiu-oportunitate-autobuze-final.pdf (accessed on 09 April **2019**) [In Romanian].
3. Primăria și Consiliul Local Cluj-Napoca. Studiu de Oportunitate 2018. Available online: https://files.primariaclujnapoca.ro/proiect_hotarare/2018/10/31/23k-1.pdf (accessed on 09 April **2019**) [In Romanian].
4. TOZZI M., BOUSSE Y., KARLSSON M.A., GUIDA U. A European initiative for more efficient and attractive bus systems: the EBSF_2 project. Transportation Research Procedia, **14**, 2640, **2016**.
5. VARGA B.O., ICLODEAN C., MARIAȘIU F. Electric and Hybrid Buses for Urban Transport Energy Efficiency Strategies, 1st ed.; Springer International Publishing: Switzerland, 85, **2016**.
6. WOO J.R., CHOI H., AHN J. Well-to-wheel analysis of greenhouse gas emissions for electric vehicles based on electricity generation mix: A global perspective. Transportation Research Part D, **51**, 340, **2017**.
7. SALEM M.Z., ALMUZAINI R.F., KISHAWI Y.S. The Impact of Road Transport on CO_2 Atmospheric Concentrations in Gaza City (Palestine), and Urban Vegetation as a Mitigation Measure. Polish Journal of Environmental Studies **26** (5), 2175, **2017**.
8. EUR-Lex. Directive 2009/33/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of clean and energy-efficient road transport vehicles. Available online: https://eur-lex.europa.eu/eli/dir/2009/33/oj (accessed on 09 April **2019**).
9. EUR-Lex. Regulation (EC) No 443/2009 of the European Parliament and of the Council of 23 April 2009 setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce CO_2 emissions from light-duty vehicles. Available online: https://eur-lex.europa.eu/eli/reg/2009/443/oj (accessed on 09 April **2019**).
10. EUR-Lex. Commission Regulation (EU) 2017/2400 of 12 December 2017 implementing Regulation (EC) No 595/2009 of the European Parliament and of the Council as regards the determination of the CO_2 emissions and fuel consumption of heavy-duty vehicles and amending Directive 2007/46/EC of the European Parliament and of the Council and Commission Regulation (EU) No 582/201. Available online: https://eur-lex.europa.eu/eli/reg/2017/2400/oj (accessed on 09 April **2019**).
11. EUR-Lex. Regulation (EC) No 595/2009 of the European Parliament and of the Council of 18 June 2009 on type-approval of motor vehicles and engines with respect to emissions from heavy duty vehicles (Euro VI) and on access to vehicle repair and maintenance information and amending Regulation (EC) No 715/2007 and Directive 2007/46/EC and repealing Directives 80/1269/EEC, 2005/55/EC and 2005/78/EC. Available online: https://eur-

lex.europa.eu/eli/reg/2009/595/oj (accessed on 09 April **2019**).
12. EUR-Lex. Directive 2007/46/EC of the European Parliament and of the Council of 5 September 2007 establishing a framework for the approval of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles. Available online: https://eur-lex.europa.eu/eli/dir/2007/46/oj (accessed on 09 April **2019**).
13. EUR-Lex. Commission Regulation (EU) No 582/2011 of 25 May 2011 implementing and amending Regulation (EC) No 595/2009 of the European Parliament and of the Council with respect to emissions from heavy duty vehicles (Euro VI) and amending Annexes I and III to Directive 2007/46/EC of the European Parliament and of the Council. Available online: https://eur-lex.europa.eu/eli/reg/2011/582/oj (accessed on 09 April **2019**).
14. GRIJALVA E.R., LÓPEZ MARTÍNEZ J.M. Analysis of the Reduction of CO_2 Emissions in Urban Environments by Replacing Conventional City Buses by Electric Bus Fleets: Spain Case Study. Energies, **12** (3), 525, **2019**.
15. TOPAL O., NAKIR I. Total Cost of Ownership Based Economic Analysis of Diesel, CNG and Electric Bus Concepts for the Public Transport in Istanbul City. Energies, **11** (9), 2369, **2018**.
16. BAK D.-B., BAK J.-S., KIM S.-Y. Strategies for Implementing Public Service Electric Bus Lines by Charging Type in Daegu Metropolitan City, South Korea. Sustainability, **10** (10), 3386, **2018**.
17. KIVEKÄS K., LAJUNEN A., VEPSÄLÄINEN J., TAMMI K. City Bus Powertrain Comparison: Driving Cycle Variation and Passenger Load Sensitivity Analysis. Energies, **11** (7), 1755, **2018**.
18. Renault R 312. Available online: https://www.transbus.org/construc/renault_r312.html (accessed on 09 April **2019**).
19. Urbino Electric. Available online: https://www.solarisbus.com/en/vehicles/alternative-drives/urbino-electric (accessed on 09 April **2019**).
20. NCTR. Article. Available online: https://www.nctr.usf.edu/2006/06/the-potential-for-bus-rapid-transit-to-reduce-transportation-related/ (accessed on 09 April **2019**).
21. Comparison of Modern CNG, Diesel and Diesel Hybrid-Electric Transit Buses. Available online: https://mjbradley.com/sites/default/files/CNG%20Diesel%20Hybrid%20Comparison%20FINAL%2005nov13.pdf (accessed on 09 April **2019**).
22. MERKISZ J., FUĆ F., LIJEWSKI P., PIELECHA J. Actual Emissions from Urban Buses Powered with Diesel and Gas Engines. Transportation Research Procedia, **14**, 3070, **2016**.
23. U.S. EPA. Article. Available online: https://www3.epa.gov/ttnchie1/conference/ei11/mobile/wilson.pdf (accessed on 09 April **2019**).
24. VEPSÄLÄINEN J., RITARI A., LAJUNEN A., KIVEKÄS K., TAMMI K. Energy Uncertainty Analysis of Electric Buses. Energies, **11** (12), 3267, **2018**.
25. Prune GPS. Available online: https://sourceforge.net/projects/prune-gps/ (accessed on 09 April **2019**).
26. Reliable Prognosis. Available online: https://rp5.ru/Vremea_%C3%AEn_Cluj-Napoca (accessed on 09 April **2019**).
27. Electricity Map application. Available online: https://www.electricitymap.org/?wind=false&solar=false&page=country&countryCode=RO&remote=true (accessed on 09 April **2019**).
28. ANRE. Available online: https://www.anre.ro/ro/energie-electrica/rapoarte/rezultate-monitorizare-piata-energie-electrica/20181526295071 (accessed on 09 April **2019**).
29. Production and consumption of electricity in Romania, by types of producers. Available online: http://pro.sistemulenergetic.com/ (accessed on 09 April **2019**).
30. EU Science Hub. Well-to-Wheels Analyses. Available online: https://ec.europa.eu/jrc/en/jec/activities/wtw (accessed on 09 April **2019**).
31. AB Thoreb Website. Available online: http://www.thoreb.com/index.php/ro/referinte/31-europe/70-ctp-cluj-napoca (accessed on 09 April **2019**).
32. JOVANOVIC M.M. Belgrade's Urban Transport CO_2 Emissions from an International Perspective. Polish Journal of Environmental Studies, **25** (2), 635, **2016**.
33. KADIYALA A., KUMAR A. An Examination of the Sensitivity of Sulfur Dioxide, Nitric Oxide, and Nitrogen Dioxide Concentrations to the Important Factors Affecting Air Quality Inside a Public Transportation Bus. Atmosphere, **3** (2), 266, **2012**.
34. HERNÁNDEZ-PANIAGUA I.Y., ANDRACA-AYALA G.L., DIEGO-AYALA U., RUIZ-SUAREZ L.G., ZAVALA-REYES J.C., CID-JUÁREZ S., TORRE-BOUSCOULET L., GOCHICOA-RANGEL L., ROSAS-PÉREZ I., JAZCILEVICH A. Personal Exposure to $PM_{2.5}$ in the Megacity of Mexico: A Multi-Mode Transport Study. Atmosphere, **9** (2), 57, **2018**.
35. ANDRÉ M., GARROT B., ROYNARD Y., VIDON R., TASSEL P., PERRET P. Operating conditions of buses in use in the Ile-de-France region of France for the evaluation of pollutant emissions. Atmospheric Environment, **39**, 2411, **2005**.
36. Romania General Transport Master Plan. National Guide for Transport Project Volume II. Available online: http://mt.gov.ro/web14/documente/master_plan/Volume%202_Appendix%20A_CBA%20Guidance_En.pdf (accessed on 09 April **2019**).
37. CURRAN S.J., WAGNER R.M., GRAVES R.L., KELLER M., GREEN JR. J.B. Well-to-wheel analysis of direct and indirect use of natural gas in passenger vehicles. Energy, **75**, 194, **2014**.
38. KHAN M.I., SHAHRESTANI M., HAYAT T., SHAKOOR A., VAHDATI M. Life cycle (well-to-wheel) energy and environmental assessment of natural gas as transportation fuel in Pakistan. Applied Energy, **242**, 1738, **2019**.
39. PENG T., ZHOU S., YUAN Z., OU X. Life Cycle Greenhouse Gas Analysis of Multiple Vehicle Fuel Pathways in China. Sustainability, **9** (12), 2183, **2017**.
40. DONATEO T., INGROSSO F., LICCI F., LAFORGIA D. A method to estimate the environmental impact of an electric city car during six months of testing in an Italian city. Journal of Power Sources, **270**, 487, **2014**.
41. LI F., ZHUANG J., CHENG X., LI M., WANG J., YAN Z. Investigation and Prediction of Heavy-Duty Diesel Passenger Bus Emissions in Hainan Using a COPERT Model. Atmosphere, **10** (3), 106, **2019**.
42. HUANG D., XIE H., MA H., SUN Q. Driving cycle prediction model based on bus route features. Transportation Research Part D: Transport and Environment, **54**, 99, **2017**.