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Energetic and Ecological Aspects of the Application of Electric Drive Vehicles in Serbia

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Abstract: This paper considers the analysis of energetic and environmental aspects of electric drive vehicles application in Serbia. The analysis implies real conditions of road transport and electricity production in our country and evaluates the estimation of energy consumption and CO_2 emission (Well-to-Wheel), under the assumption of hypothetical transition from classic internal combustion (IC) engine to pure electric drive of vehicles. For this purpose the real estimations of IC engines efficiency under the road conditions of operation and the global efficiency of electric drive system (electricity production, transmission network, battery and electric motor) were necessary. The results show that in the case of present reality of electricity production from coal (lignite), CO_2 emission would be even higher. However, under the assumption of significantly more efficient electricity production (for example using combine cycle of gas turbine – CCGT), CO_2 emission would be decreased. In this paper some experimental data of city bus fuel consumption and efficiency measurements are also presented.

Keywords: Efficiency, Internal combustion engine, Electric vehicle, CO_2 emission

1. Introduction

From the very beginning of motor vehicles development in the late 19th century, internal combustion (IC) engine has been practically the exclusive source of driving power of the road vehicle. The characteristics that made IC engine superior to alternative propulsion systems are: high specific power output, availability of fuel and good fuel economy, reliability in operation, reasonable price etc. During the development that lasted longer than a century, these characteristics have been constantly improved so that the exclusivity of IC engine application has remained up to the present days.

For many years, some negative characteristics of IC engines were ignored. However, when humanity became aware of the increasing environmental pollution, with significant share of motor vehicles, the development of IC engines, in addition to the performance, focused on their environmental characteristics: exhaust emissions and noise.

In the field of protection against pollution from motor vehicles, the regulations limiting the emissions were adopted firstly in developed western countries and then practically all over the world. These regulations have gradually become more and more severe and provoked very intensive development of technologies for engine emission control. As the result, the emission of harmful gases has been drastically reduced, so that modern vehicles emission of harmful gases is on the level of only couple percent of the emission before the beginning of emission control. However, the additional problem is carbon dioxide (CO_2) emission, which is one of the main gases responsible for the greenhouse effect and global warming of the earth.

Another problem that has been increased in recent decades is the energy efficiency of motor vehicles because the road transport substantially participates in energy consumption. Energy efficiency is also in close connection with CO_2 emission control.

All these problems have led to intensive research of alternative fuels application and alternative propulsion systems. These alternative systems include: fuel cells, hybrid drive and a purely electric drive. Although the research of fuel cells started the earliest, this technology has not yet reached any commercialization, primarily due to the extremely high prices.

The development of hybrid propulsion systems is much more advanced and renowned manufacturers of vehicles have included models with hybrid drive in their commercial offer. Hybrid drive system includes in addition to internal combustion engine an electric motor and a battery for storing electric energy. Internal combustion engine powers a generator that charges the battery and the wheels of vehicles are powered with electric motor (serial hybrid). In another variant, besides electric motor the wheels are powered with internal combustion engine, if necessary (parallel hybrid). Although good fuel economy and low emissions of hybrid drive has been proven in practice, hybrid vehicles for now occupy practically insignificant share of the fleet of vehicles, primarily due to their still high prices. There are also hybrid vehicles with the possibility of battery charging by connecting to electric network (so called “plug-in hybrid”).

The research and development of pure electric drive vehicles was strongly motivated by their environmental characteristics („zero emission” and low noise) and some attempts date from 1970ies [1]. However, the problems such as: great weight, small battery capacity and consequently small driving autonomy, long period of charge and necessity of battery replacement, did not allow practical application. Last decade, the interest for electric vehicles has significantly grown, primary due to the development of a new battery systems, and a lot of manufacturers of passenger cars, and even city buses, have included in their offer the vehicles with purely electric drive.

2. Energy efficiency and emission characteristics of electric vehicles

With regards the protection of the environment, only CO_2 emissions will be evaluated and compared in this paper. The reason is that the emission of harmful pollutants (CO, HC, NOx, PM etc.) can by very efficiently reduced and controlled by modern technologies, especially in the field of motor vehicles. On the other hand, the emission of CO_2 cannot be reduced by any technology since it is the product of complete combustion of carbon in fuel and the only possibility is to reduce fuel consumption or to use fuel with less content of carbon.

Electric vehicle drive is without a doubt energy efficient and with “zero emission“, if so called „Tank-to-Wheel” (TTW) efficiency and emission are considered. In other words, the vehicle itself is very efficient and does not produce any emission. However, the whole process of electricity production and transmission to the battery charging place should be taken into account and so called “Well-to-Wheel” (WTW) efficiency and emission are important in order to estimate global impact to the environment.

While the efficiency and exhaust emission of the vehicles driven by EC engines are more and less similar in all countries, especially in developed countries, the efficiency and emission of electricity production vary largely, even in these countries. The production of electric energy can be in thermal electric plants with various fuels: coal, oil fuel or gaseous fuel, with different efficiency and emission. On the other hand, hydro and nuclear electric plants do not produce any emission, which is even more the case when using the energy of sun or wind. In most countries, electricity production is a combination of several different systems. Therefore, the comparison of efficiency and emission of conventional drive and electric drive can largely vary from country to country. As the illustration, figure 1. shows the standard CO_2 emission factors of electricity consumption of EU countries [2]. The authors added standard CO_2 emission factor of our country calculated on the bases of data given in next section of this paper. Standard emission factor includes only the emission that occurs directly or indirectly due to electricity production within local authority while LCA emission factor takes under consideration all emissions of the supply chain (fuel exploitation, transport, processing etc.).

As it can be seen, the variations of emission factors between countries are extremely high, from very low in countries with predominantly nuclear or hydro electricity production (France, Sweden) to very high in the countries with thermal electric plants (Greece, Poland).

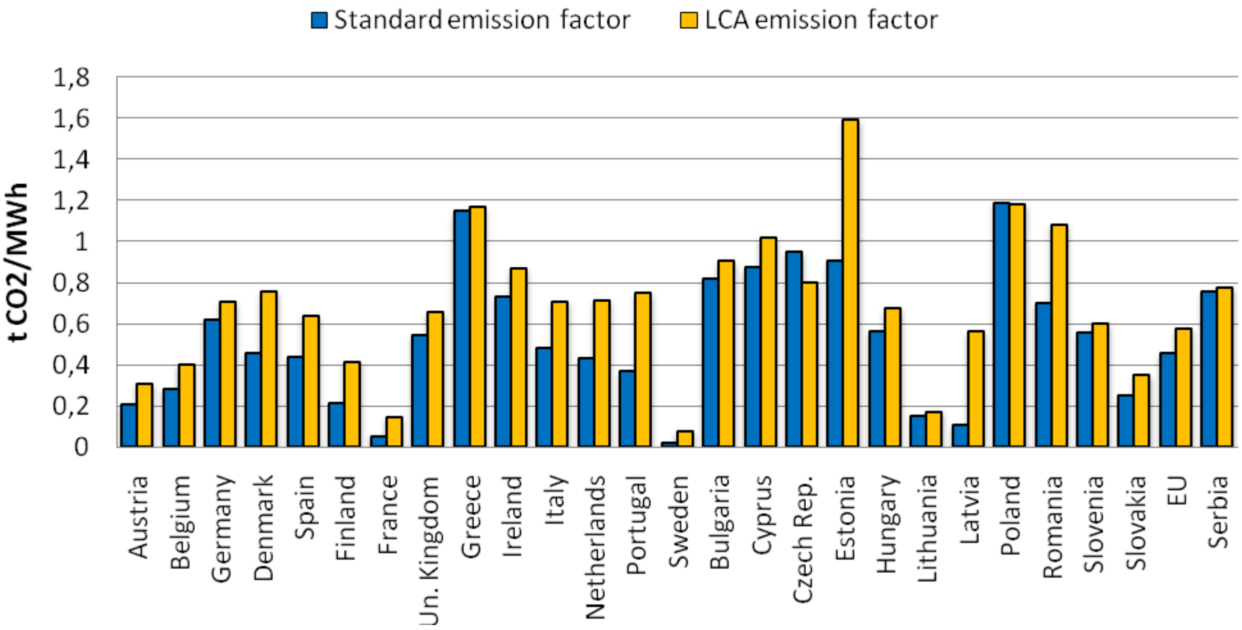

Figure 1. Standard CO_2 emission factors and LCA emission factors of the EU countries [2]

Figure 2. shows the benefit in CO_2 emission of electric and hybrid city buses versus diesel bus as a baseline [3]. The source is the report of Ricardo Institute, one of the world leading institutions in the field of IC engines and motor vehicles research. The estimation is based on United Kingdom current CO_2 specific emission of electricity production of 164 g CO_2eq/MJ (0.59 t CO_2/MWh). The estimated WTW benefit of app. 30% in the case of battery electric buses is significant. However, it implies the ability of electricity production with relatively low CO_2 emission.

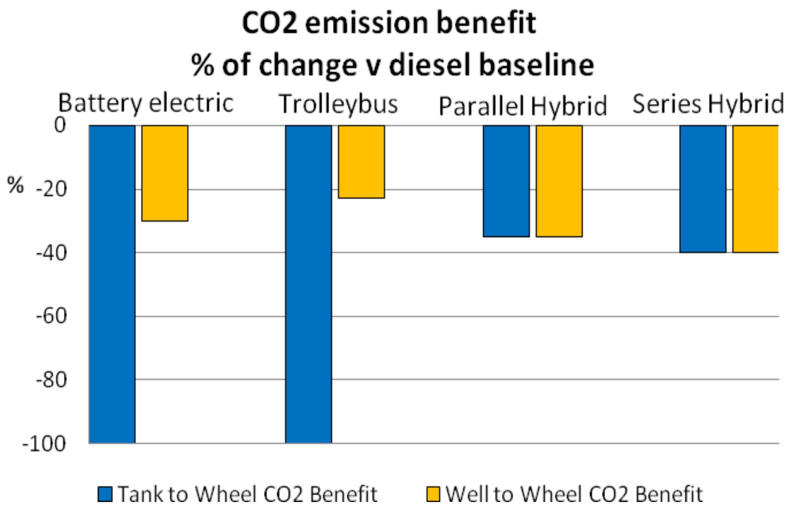

Figure 2. Comparison of WTW and TTW CO_2 emission benefits of alternative drive systems versus diesel baseline [3]

Another Danish study considers WTW CO_2 emission of passenger cars with various drive systems, states for 2010, 2015 and the estimation for year 2020 [4]. The designation “electric car max.” means electric car with increased battery capacity for large vehicle autonomy. As it can be seen from figure 3., the benefit of electric drive application is relatively small and in the case of “electric car max.” it is just a little bit better than gasoline and worse than diesel.

Given examples clearly show that the estimations of electric vehicles WTW CO_2 emission significantly vary from country to country and depend of the vehicle type and condition of electricity production and transmission.

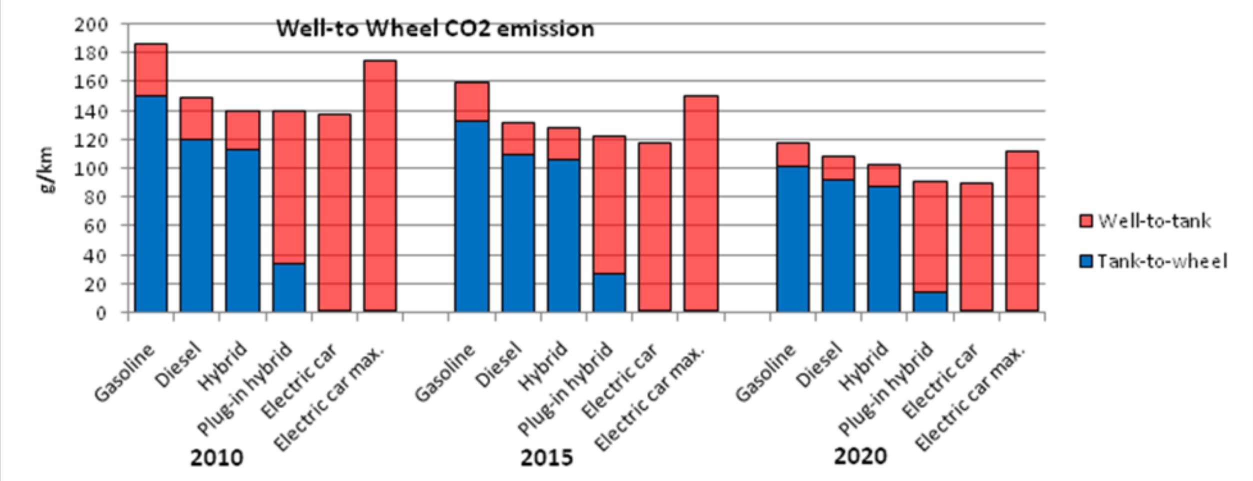

Figure 3. Tank-to-Wheel, Well-to-Tank and Well-to-Wheel CO_2 emission of passenger cars with different drive systems [4]

2. Comparison of energetic and emission characteristics of electric and fossil fuel vehicles regarding the conditions in Serbia

For energy consumption and CO_2 emission evaluation in a particular country the estimation of whole energy supply chain efficiency is required. Figures 4. and 5. show the estimation of Well-to-Tank, Tank-to-Wheel and total Well-to-Wheel efficiencies in the cases of classic vehicle drive using IC engine and battery electric vehicle drive with respect to the condition in our country. These estimations are crucial for proper energy consumption and CO_2 emission evaluation and comparison of different vehicle drive systems.

In the case of fossil fuels (gasoline, diesel, LPG), the energy consumption WTT (exploitation, transport and fuel processing) is usually estimated as app. 20% of produced fuel energy content (or 17% of total energy) and the efficiency WTT can be estimated as 83% [2],[4]. The estimation of average TTW efficiency of spark ignition and diesel engines in vehicle driving conditions is a very complex task. The efficiency of modern spark ignition engines is about 30-36 % in optimal operating regime, while modern vehicle diesel engines achieve 35-44%, whereby lower values are for passenger cars and higher for busses and trucks. Under vehicle driving conditions the efficiency is much lower, especially in the case of spark ignition engines. Having in mind the age of vehicle fleet in our country, the estimation of average efficiency in exploitation of 20% for spark ignition engine and 26% for diesel engines seems to be reasonable. These estimations are slightly higher than American assessments, and approximately agree with some European assessments [4],[5].

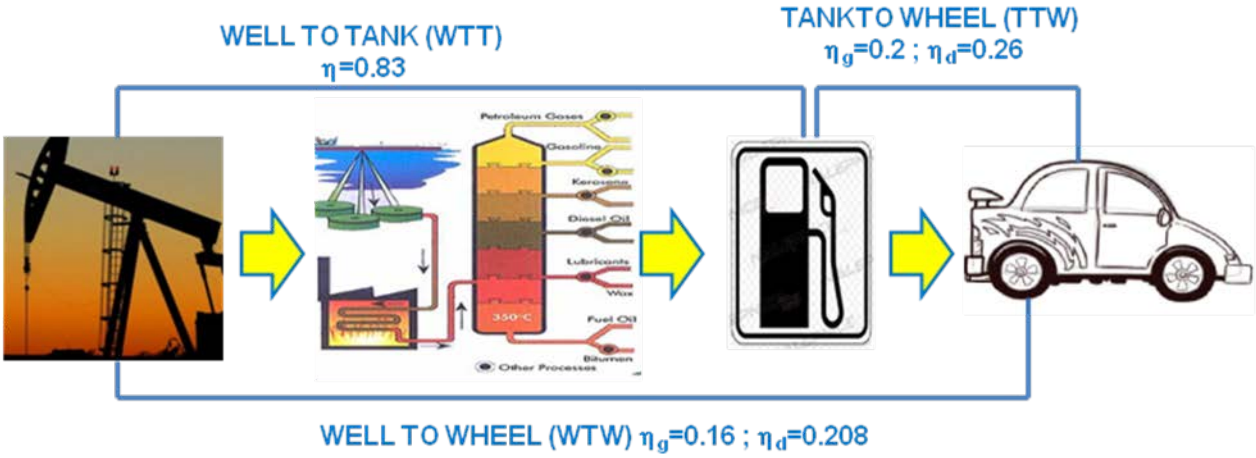

Figure 4. The estimation of whole supply chain average efficiency in the case of fossil fuel application in vehicle with IC engine (fuel exploitation, transport, processing and combustion).

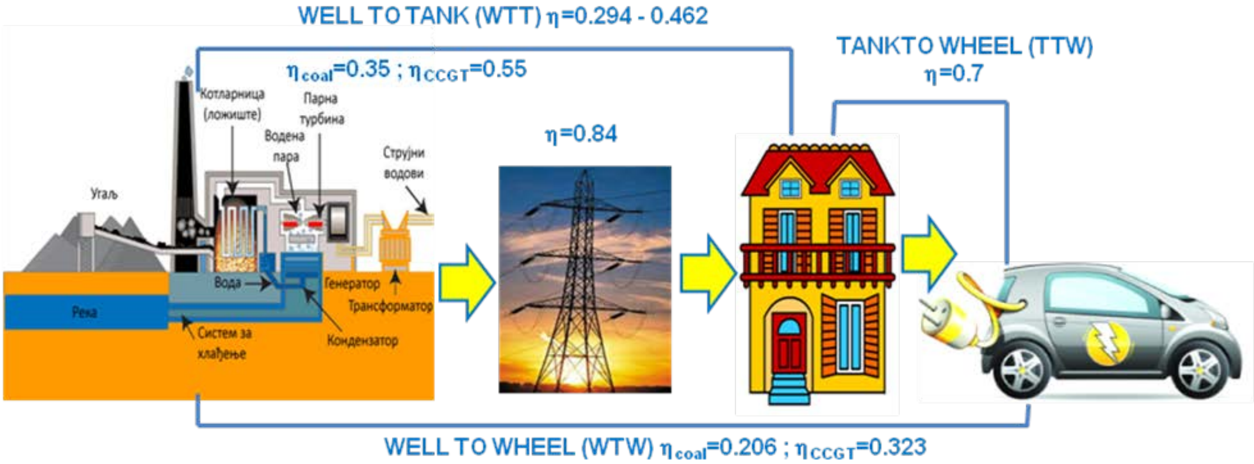

Figure 5. The estimation of whole energy supply chain average efficiency in the case of battery electric vehicle drive (electricity production, transmission and distribution network, battery charging and electric motor).

In the case of battery electric vehicle drive (figure 5.), the WTT efficiency consists of the efficiency of electricity production in electric plant and the efficiency of electricity transmission network. The assessments are based on the actual situation in our country. For many years the average electricity production in our country has been app. 70% in thermal electric plants, with coal (lignite) as a fuel, and app. 30% in hydro electric plants. The chances for significant increase of hydro potential use are very small and only real possibility of electricity production increase in foreseeable future is through thermal electric plants. Their average efficiency is app. 35% in current situation of using lignite as a fuel. Beside this current situation, for the purpose of electric and fossil fuel vehicle drive comparison, the hypothetic situation of much more efficient electricity production using the system "combined cycle with gas turbine" (CCGT) in thermal electric plants, was also considered. Such a system can achieve the efficiency of app. 60 %, and an average efficiency of 55% may be adopted for further work [5]. The data for electricity transmission losses in different countries can be found in the report of World Bank [6]. According to this data the electricity transmission looses in our country are app. 16%.

The average efficiency of battery electric drive TTW can be estimated at the level of 70% [5]. This includes: approximately 88-90% for the charger and 85-95% for the charging and discharging cycle with lithium batteries; 96-98% for the electronic engine management; and 90-95% for the electric motor.

For the evaluation of required energy and CO_2 emission of fossil fuel and battery electric vehicles, the data of fossil fuels consumption and electricity production in our country are required. The data taken from the official annual reports of the Association of Serbian Oil Companies and Electric Distribution Company of Serbia (EPS) for year 2013 were used as representative.

Table 1. shows the consumption of motor fossil fuels in Serbia in the year 2013, and table 2. the characteristics of these fuels. Emissions of CO_2 are calculated under the assumption that the entire carbon from the fuel is burned into CO_2. In other words the emissions of carbon monoxide (CO) and unburned hydrocarbons (HC) are neglected as much smaller. In this case CO_2 emission can be calculated using very simple relation:

$$m_{CO2}=m_f*g_c*44/14 \qquad (1)$$

where: m_{CO2} - mass of CO_2; m_f - mass of fuel burnt; g_c[kgC/kgFuel] - mass content of carbon (C) in fuel; 44 and 14 molar masses of CO_2 and C respectively.

In table 2., the energy "on the wheels", i.e. the energy used for vehicles propulsion, is calculated using foregoing adopted average efficiencies for spark ignition (gasoline and LPG) and diesel engines. Specific CO_2 emission refers to energy "on the wheels".

Table 1. Motor fuels consumption in Serbia 2013; source [7].

	Units	Diesel	Gasoline	LPG	Total
Quantity of fuel	[t]	1400684	386967	315469	2103120

Table 2. Motor fuels characteristics: chemical energy content, carbon content and calculated CO_2 emission

	Units	Diesel	Gasoline	LPG	Total
Lower heating value	[MJ/kg]	43	43	45.4	
Energy content	[GJ]	60.2*10^6	16.64*10^6	14.28*10^6	91.12*10^6
	[GWh]	16.73*10^3	4.62*10^3	3.97*10^3	25.32*10^3
Carbon content	[kgC/kgFuel]	0.86	0.86	0.825	6.07*10^3
CO_2 emission TTW	[t]	4.416*10^6	1.22*10^6	0.954*10^6	6.59*10^6
CO_2 emission WTW	[t]	5.32*10^6	1.47*10^6	1.15*10^6	7.94*10^6
Energy "on the wheels" (Average efficiency in driving conditions: diesel engines 0.26 ; spark ignition engines 0.2)	[GWh]	4.35*10^3	0.924*10^3	0.794*10^3	6.07*10^3
Specific CO_2 emission WTW	[g/kWh]	1223	1591	1448	1308

Table 3. shows produced electric energy and the quantity of used coal (lignite) in Serbia for the year 2013 and table 4. shows CO_2 emission calculated in the same way as for fossil fuels. The data for carbon content in used lignite coals are taken from [9].

Table 3. Electric energy production and coal consumption in Serbia 2013; source [8].

		Thermal electric plants (TE)			Hydro electric plants (HE)	Total
		TENT	Kostolac	Total TE		
Produced electric energy	[GWh]	20.232*10^3	6.472*10^3	26.704*10^3	10.729*10^3	37.433*10^3
Quantity of coal (lignite)	[t]	29152350	8606211	37758561		

Table 4. Calculated CO_2 emission from thermal electric plants in Serbia 2013; source for coal mass analysis [9].

		Termal electric plants (TE)		Total (TE)	Total (TE*HE)
		Kolubara (TENT)	Kostolac		
Carbon content	[kgC/kgFuel]	0.198	0.221		
CO_2 emission	[t]	21.16*10^6	6.97*10^6	28.13*10^6	28.13*10^6
CO_2 specific emission (standard emission factor of electricity production)	[g/kWh]	1046	1077	1053	751.5

Table 5. Required equivalent electric energy for battery electric vehicles and WTW CO_2 emission

	Units	Diesel	Gasoline	LPG	Total
Required energy "on the wheels"	[GWh]	4.35*10^3	0.924*10^3	0.794*10^3	6.07*10^3
Required electric energy on charging plug (Average efficiency of el. motor, inverters and battery, in total - 0.7)	[GWh]	6.21*10^3	1.32*10^3	1.134*10^3	8.664*10^3
Required electric energy on electric plant (Average losses of transmission network 16%)	[GWh]	7.39*10^3	1.57*10^3	1.35*10^3	10.31*10^3
Required quantity of coal	[t]	10.45*10^6	2.22*10^6	1.909*10^6	14.58*10^6
CO_2 emission (proportional to required coal consumption)	[t]	7.78*10^6	1.65*10^6	1.42*10^3	10.85*10^6
Specific CO_2 emission WTW	[g/kWh]	1789	1786	1788	1787
Increase of specific CO_2 emission WTW compared to fossil fuel drive	[%]	+46	+12.2	+23.4	+36.6

Table 5. shows the required electric energy production in the hypothetical situation that all vehicles use battery electric drive instead of IC engines and fossil fuels. Shown data are calculated using the foregoing adopted WTW efficiencies for battery electric and fossil fuel drive and under the assumption that electric energy is produced in thermal electric plants using lignite as a fuel.

Total required energy of $10.3*10^3$ GWh is 27.5% of total electric energy produced in the year 2013, i.e. in considered situation electricity production should be increased by 27.5% or 38.6% if only increase in thermal plants is assumed. As it can be seen, CO_2 emission would be greater than in the case of vehicles drive using classic IC engine for all kinds of fossil fuels.

The decrease of CO_2 emission with battery electric vehicle drive could be achieved in the case of electricity production in thermal electric plants using combined cycle with gas turbine (CCGT), which presupposes the use of liquid or gas fuel. These results are shown in table 6. Achieved benefit in CO_2 emission depends on fossil fuel and it is greater in the case of electric drive use instead of spark ignition engines (gasoline and LPG) and less in the case of diesel engines.

The results given in tables 5. and 6. are graphically shown in the figures 6. and 7.

Table 6 . Required quantity of fuels for battery electric vehicles and CO_2 emission, under the assumption that the same fuels are used for electricity production in thermal electric plants using combined cycle with gas turbine (CCGT).

	Units	Diesel	Gasoline	LPG	Total
Required quantity of fuel WTW (Average efficiency of CCGT 55%)	[t]	$1.356*10^6$	$0.288*10^6$	$0.232*10^6$	
CO_2 emission WTW	[t]	$4.28*10^6$	$0.908*10^6$	$0.703*10^6$	$5.9*10^6$
Specific CO_2 emission WTW	[g/kWh]	984	983	985	980
Decrease of CO_2 emission WTW	[%]	-19.5	-38.2	-38.2	-24.9

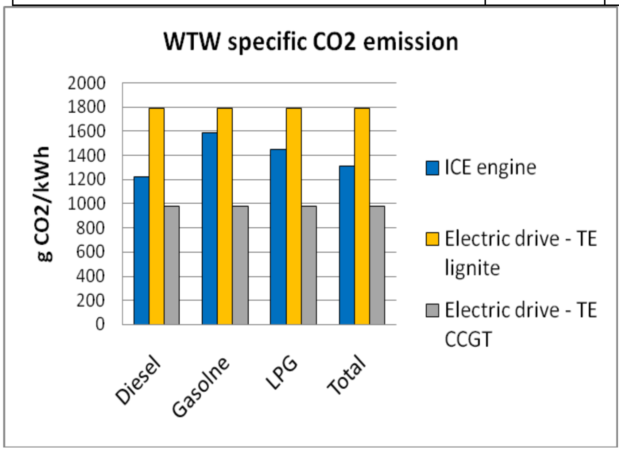

Figure 6. The comparison of WTW CO_2 emission for fossil fuels and electric drive vehicles for different systems of electricity production

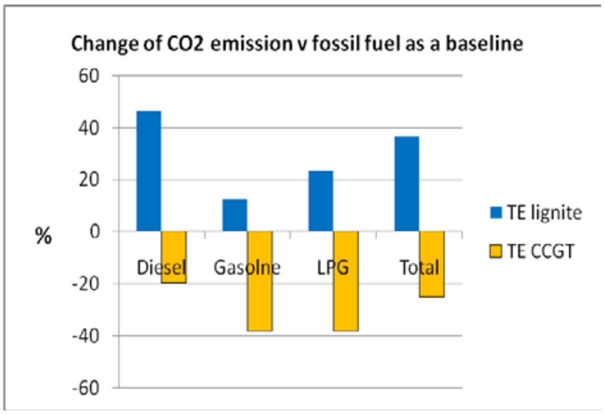

Figure 7. Change of WTW CO_2 emission of battery electric drive vehicles for different systems of electricity production

4. Results of city bus fuel consumption and efficiency measurement

Experimental investigation of city bus fuel consumption and efficiency under real driving condition was carried out in the framework of the project "Research and Development of Alternative Fuel and Drive Systems for Urban Buses and Refuse Vehicles with Regard to the Improvements of Energy Efficiency and Environmental Characteristics" which is currently realized under financial support of the Ministry of Science and Technology of Serbia [10]. The obtained results are used for supplementing the above analysis and the comparison of CO_2 emission of diesel drive and battery electric drive in the case of city basses.

The main data about test bus is given in table 7. and the recorded experimental results in table 8. The evaluation of energy efficiency and specific WTW CO_2 emission for diesel drive bus are based on recorded data for fuel consumption and the energy delivered on the engine flywheel. In the case of hypothetical conversion to battery electric drive, the foregoing adopted estimations for TTW and WTW efficiencies for electric drive and electricity production were used. These results are given in table 9. and graphically shown in the figures 8. and 9.

Table 7. Basic characteristics of test bus

Bus type		Ikarbus IK 206 Articulated bus
Curb weight (empty)	[kg]	15760
Diesel engine type		MAN D2066 LUH 11 Euro 4
Swept volume	[cm^3]	10518
Rated power/rpm	[kW/rpm]	199/1900
Rated torque/rpm	[Nm/rpm]	1250/1000-1400
Minimum specific effective fuel consumption	[g/kWh]	195
Transmission		Automatic VOITH 864.5

Table 8. Experimental results

Bus line	Belgrade Lasta line 83	
Length of the line	[km]	25.3
Number of cycles		8
Total distance traveled	[km]	202.42
Average speed	[km/h]	13.84
Average bus weight	[kg]	18500
Total fuel consumption	[kg]	97.8
Total energy delivered on engine flywheel	[kWh]	427

Table 9. Evaluation of WTW CO_2 specific emission

		Diesel engine drive	Battery electric drive
Energy of fuel burnt (H_{lower}=43 MJ/kg)	[kWh]	1168.17	
Energy delivered on engine flywheel	[kWh]	427	
Energy on the Wheels (average automatic transmission efficiency 0.9)	[kWh]	384	384
Average TTW efficiency	[-]	0.329	0.7
Specific CO_2 emission TTW	[g/kWh]	803	
Specific CO_2 emission WTW	[g/kWh]	967.4	
Required electric energy on charging plug place	[kWh]		548.6
Required energy on electric plant	[kWh]		653.1
CO_2 emission WTW (lignite)	[g/kWh]		1791
CO_2 emission WTW (CCGT)	[g/kWh]		816.3

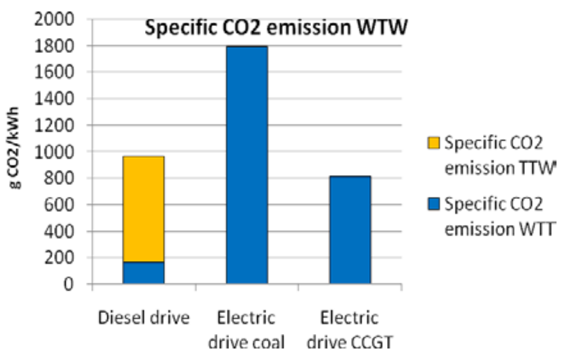

Figure 8. The comparison of WTW CO_2 emission for diesel drive bus and electric drive bus for different systems of electricity production

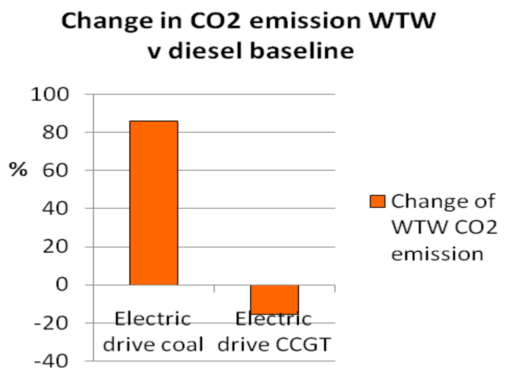

Figure 9. Change of WTW CO_2 emission of battery electric drive vehicles for different systems of electricity production

As it can be seen, the trends are similar as the foregoing analysis has shown. The results are more favorable for diesel drive bus because larger diesel engine has better thermal efficiency. Specific WTW CO_2 emission of battery electric drive is app. 85% worse in the case of electricity production in thermal plant with lignite as a fuel. Benefit of app. 15% compared to diesel powered bus could be achieved if electric energy would be produced in thermal plant with CCGT system.

4. Conclusions

1. In the hypothetical situation that all vehicles use battery electric drive instead of IC engine, the required increase of electricity production would be at the level of 27.5%. If only production increase in thermal power plants is assumed, which is a realistic assumption, the required increase would be at the level of 36.8%.

2. Battery electric vehicles have zero TTW CO_2 emission. However, under the current conditions that all thermal electric plants in our country use lignite as a fuel, the specific WTW CO_2 emission would be significantly increased. The increase level is in the range 12-46% and depends on the kind of fossil fuel used for vehicle propulsion.

3. Lower WTW CO_2 emission of battery electric vehicles in the range 19-38% compared to fossil fuels vehicles could be achieved in the case of more efficient electricity production in thermal plants, for example by using the system “combined cycle with gas turbine” (CCGT). Of course, electricity production using renewable energy with zero emission (solar or wind energy) would enable the greatest benefit. However, such a situation is not real in foreseeable future.

4. Experimental testing of diesel city bus in real operating conditions showed relatively high average thermal efficiency. On this basis calculated WTW CO_2 emission of diesel bus is significantly lower compared with the assumed bus with electric drive, even by 85%. Lower CO_2 emissions with electric drive by 15% compared to diesel drive could be achieved with more efficient production of electrical energy (CCGT).

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