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Electricity consumption of electric bus with supercapacitor on the EKO 1 line in Belgrade in different periods of the year

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JKP GSP " Belgrade " is the carrier of the public transport system in Belgrade.
One of the largest public transport companies in South East Europe.
A long history of the company that dates back to 1892.

official logo

- ✓ **14. October 1892. - the first horse-drawn tram**
- ✓ **1894. year - the first electric tram line was put into operation..**
- ✓ **1925. year-the first bus line was put into operation**
- ✓ **1947. year-the first trolleybus line was put into operation.**
- ✓ **2016. year-the first E-bus line was put into operation**

JKP GSP ''Beograd'', consists of three transport subsystems:

- **Bus subsystem (609 buses in operation 1/9/2018)**

Solaris Urbino 18 (Euro 5)

- **Tram subsystem (150 trams in operation 1/9/2018)**

CAF (high capacity tram)

- **Trolleybus subsystem (94 trolly in operation 1/9/2018)**

BKM-321

***PhD Candidate - University of Kragujevac,**
Faculty of Engineering (Department for motor vehicles and engines)

City of Kragujevac is the seat of the automobile industry in Serbia,

- formerly Zastava, in period 1956-2010.year
- Today FIAT, since 2010.year
- Only car factory in South-Eastern Europe

E-bus
a new concept of environmentally clean and energy efficient public transport in Belgrade

New E-bus Line (opened to regular operation 1st September 2016.)

5 E.buses in exploitation



Promotion of clean and sustainable public transport in Belgrade

The line: EKO 1 (Vuk's monument-Belvile)

The choice of a new line on which electric buses operate, comes after a detailed analysis of the following criteria

- **A central city line, so that the environmental impact of the "0" emission is the biggest.**
- **The high attractiveness of line from the aspect of passenger requirements.**
- **Suitability of the line or terminal from the aspect of providing energy requirements for chargers**
- **Line length, such that at the end of the journey there is a minimum of 20% of the available power in the supercapacitors.**
- **One of the first lines in Europe where the E-bus is working exclusively**

The mean length of the EKO 1 line is 8 km. (Direction ''A'' 7,47 km, Direction ''B'' 8.5 km)
The line with a flat configuration with a slight climb

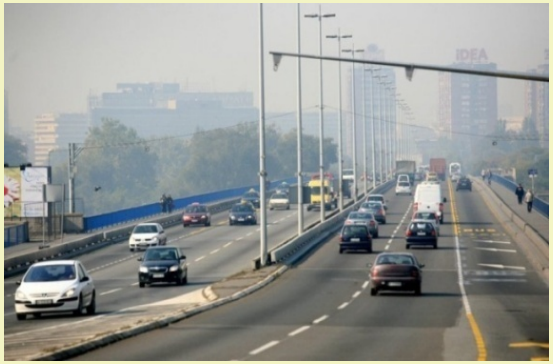
- Line EKO 1 (High atractions)

Belville (residential area)

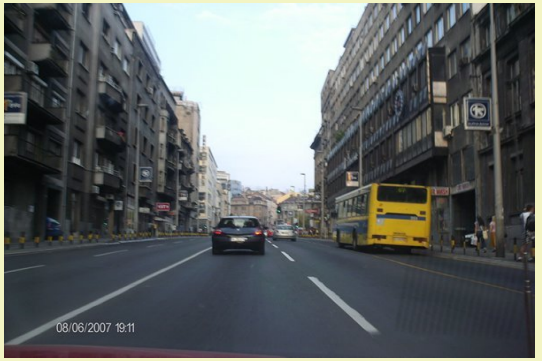
Air port-city (business zone)

Belgarde-Stark- sports arena

Usce (shopping mall)



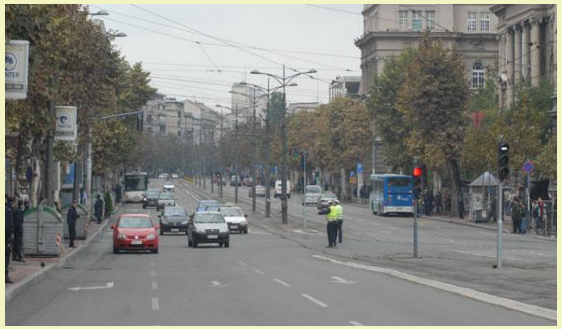
Branko's bridge



Brankova street

Nikola Pasic Square

National Assembly



Faculty of Electrical Engineering

Choice the type of E-bus / charging system

By analizing the experiences in exploitation of electric drive buses from different manufacturers with different charging systems(overnight-slow, opportunely-fast) and electrical energy storing (batery, ultracapacitors) for the exploitation conditions in Belgrade, the most appropriate charging system would be the pantograph system of fast-charging at terminials.

The advantages of the pantograph charging system

- **The acceptable charging time 5-10 min**
- **The possibility of attaching the charger to tram/trolly network (DC) or public distribution network (AC)**
- **Power of charger ≥ 150 kW**
- **E-bus can be in operation full working time (patricularly important in summer/winter conditions with the use of air-conditioning or heating system)**

E-Bus " Higer" - charging phase

E-bus (technical data)

Manufacturer ..... Higher
Type ..... Electric KLQ6
Length / width / height ..... 12000/2550/3680 mm
Curb weight.....12540 kg
Passengers.....82+1
Max-speed.....70 km / h
Charging the terminus: 660 V DC or 380 V AC, 580 V DC output, 250 A
Charging time at the terminus ... . 5-10 minutes
storage system
Electricity ..... super capacitors
Capacity ..... 20 kWh
Manufacturer ..... Aowei
Type ..... U-CAP (37DT6-03210)
Traction motors 2
Manufacturer ..... Siemens
Type 1PV5135
Power ..... 2x150 kW (peak opt.)..... ... 2x61 kW (nom. Opt.)
Torque .....2x430 Nm
Inverter ..... DC / AC
Manufacturer .....Siemens
Type ..... IEVD 130-60ZO6GA
Working range ..... 580 V DC / AC 500-650V
Convereter..... DC / DC
Manufacturer ..... Siemens
Type DY074C
Working range .....12-24-48 V DC
Charging system:
Pantograph ..... Aowei 37DT6-03212
Auxiliary systems:
Air conditioning ..... Thermoking 81DT6
Pump control ..... KVD HDZXB 1416
Compressor ..... IEM ER 230
UC-Cooler ..... Aowei 37DT6
Traction control ..... Siemens 10DT6
External display ..... Novatronic

Electrical energy storage by ultra capacitors

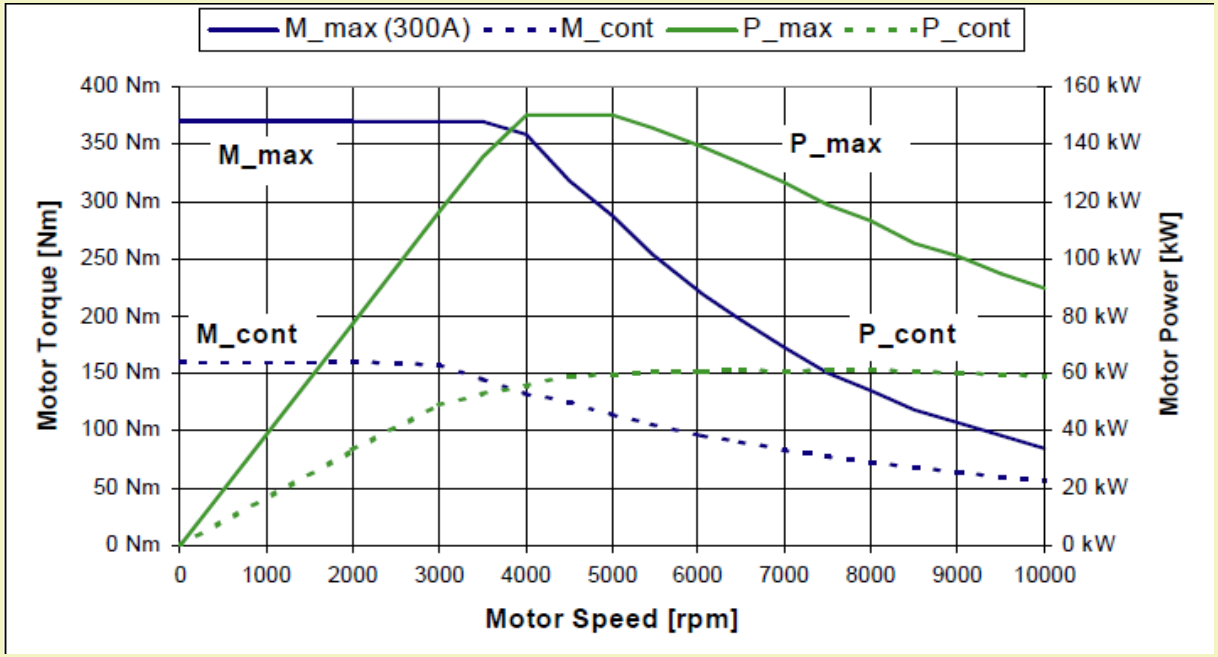
- **Principle: Electric-static**
- **Flexibility for rapid charging and discharging**
- **High efficiency: 92-98%**
- **Acceptable mass: 900 kg**
- **Temperature range: -40 to +65 C**
- **Charging time defined by factor C >10**
- **The possibility of accepting the entire electrical energy in the recuperation phase**
- **Can withstand deep discharge**
- **Suitable for recycling**
- **Life time, at least 10 years, the real 15 years**

The position of the ultra capacitor

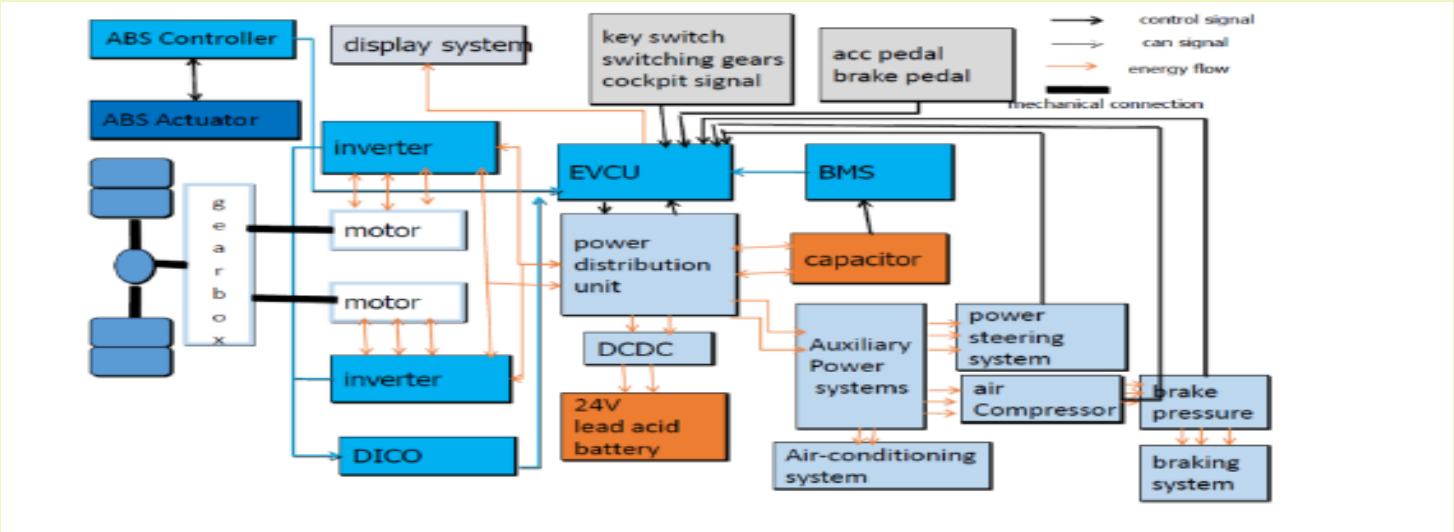
passenger space

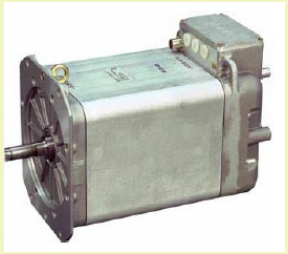
Drive Motor 1PV5135-4WS24

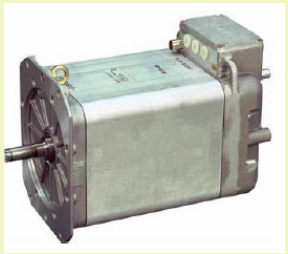
Type	AC Induction Motor
Cooling Media	Water-Glycol
Rated Voltage DC	520 V
Rated Power	61 KW
Rated Torque	160 Nm
Max. Torque	370 Nm @ 300A
Rated Current	145 A
Max. Speed	10,000 rpm
Weight	90 kg
Dim. (LxWxH)	425 x 245 x 245 mm
Ambient Temperature	- 30 °C to 70 °C
Degree of Protection	IP 65 / 9k



Block diagram of '' Higer'' E-bus components







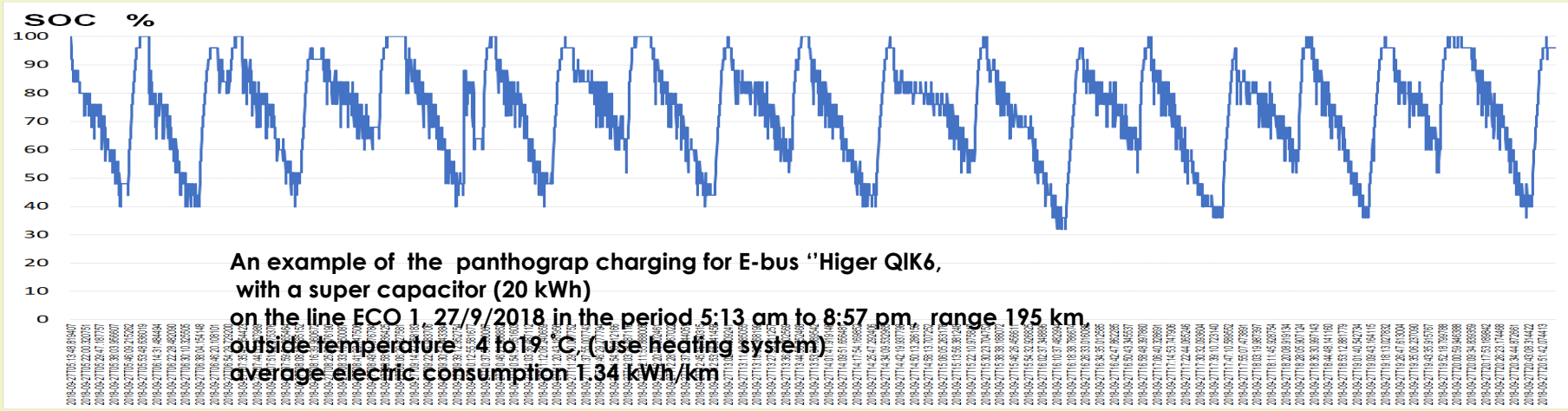
EXPLOITATION INDICATORS ON THE LINE EKO 1

Analyzing the period of operation of buses on electric power from 01/09/2016 to 1/9/2018, E-buses have had the following results :

- **Working hours per vehicle per day 16÷18 h**
- **Average daily mileage per vehicle 190÷215 km**
- **Exploitation speed: 14.8 km·h^{-1}**
- **Daily number of passengers transported per vehicle 900÷1200 passengers**
- **Reliability of work on the line: 97.5%**
- **Depending on operating mode, number of passengers, traffic conditions,driving style,iImpact of the system for heating and air conditioning of the vehicle), Electric consumption may vary:**

In the spring/autumn period, direction "A" 0.82÷1.15 kWh·km^{-1} , direction "B" 1.2÷1.45 kWh·km^{-1}

- **In the summer period average consumption is higher by 23.3%, than the transition period**
- **In the winter period average consumption is higher by 45.4%, compared with transition period**
- **Loss of electricity in the charging phase (network, charger, pantograph, super capacitor) about 5%**
- **E-bus realized recovery of electricity in the braking phase of about 25-30% compared to the energy consumed to drive**



An example of the panthograp charging for E-bus ''Higer QIK6, with a super capacitor (20 kWh) on the line ECO 1, 27/9/2018 in the period 5:13 am to 8:57 pm, range 195 km, outside temperature 4 to19 °C, (use heating system) average electric consumption 1.34 kWh/km

Influence factors on electricity consumption at E-bus

E-bus

Total

consumption of electricity

(kWh / km)

Traction

Driwing cycles (accleration, speed, recovery, stops, stations…)
Load
Tophography
Driwing style
Losses (elec.motor,transmission,battery,charging)

[kWh/km]

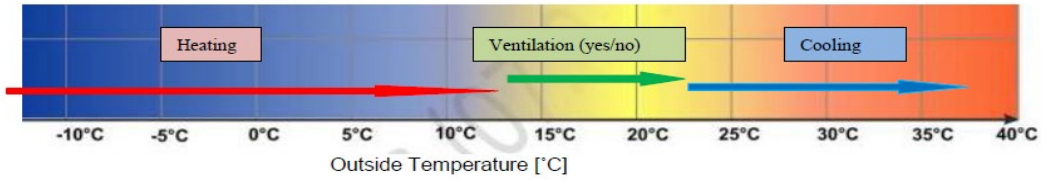
Auxiliary devices

Compresor
Stering pump
Lights, displey
Low voltage

Outside Temperature

[kWh/km]

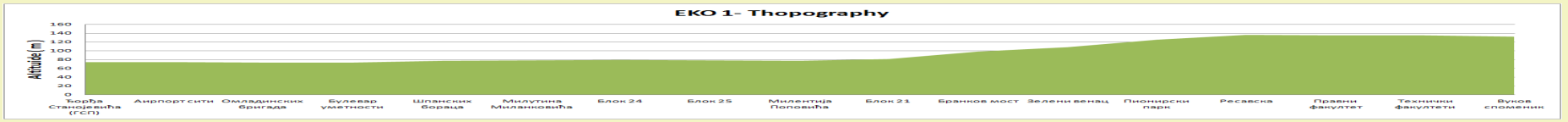
Air conditioning system
Heating system
Ventilation

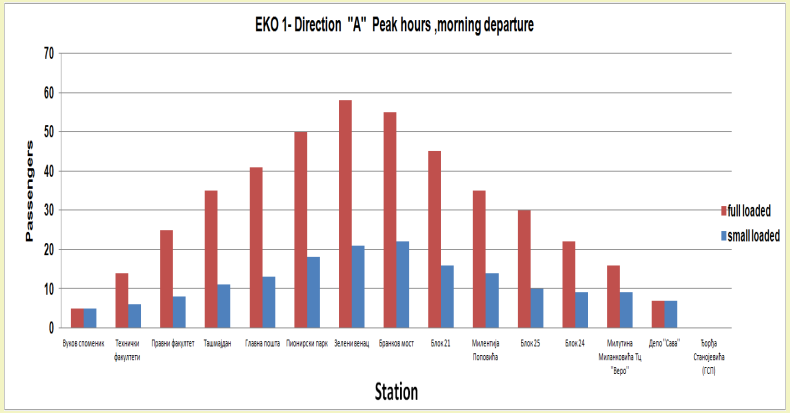


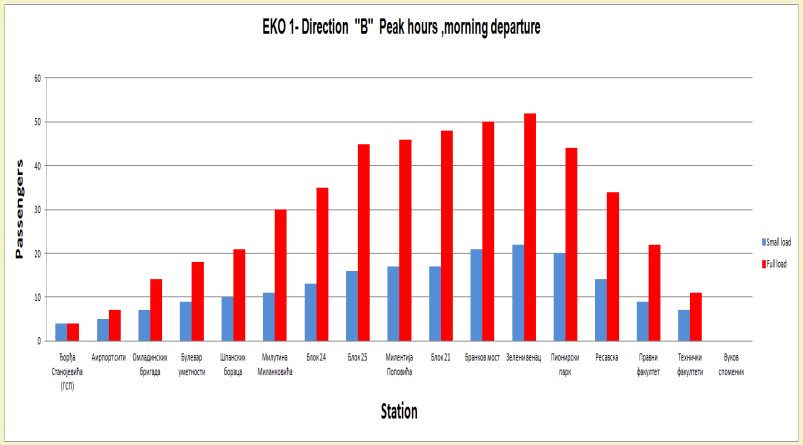
Electricity consumption-Belgrade , line EKO 1, Case 1

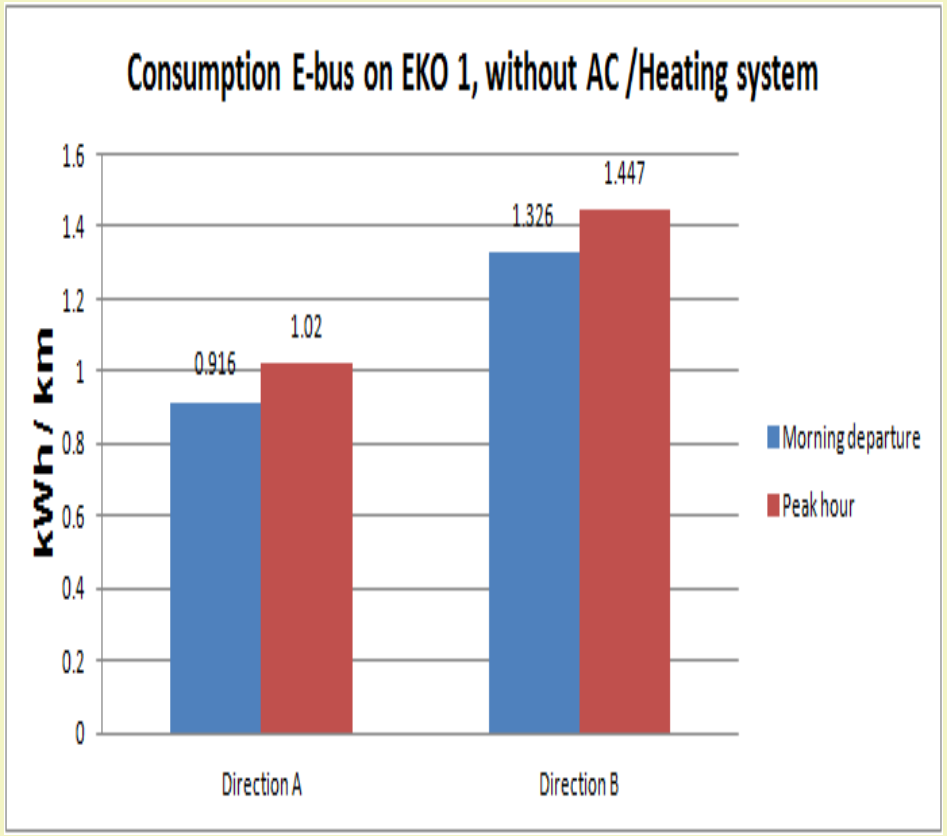
Regime of exploitation without the use of heating and air conditioning (spring, autumn)

The biggest impact on consumption is the load on the vehicle with passengers









Electricity consumption-Belgrade , line EKO 1, Case 2

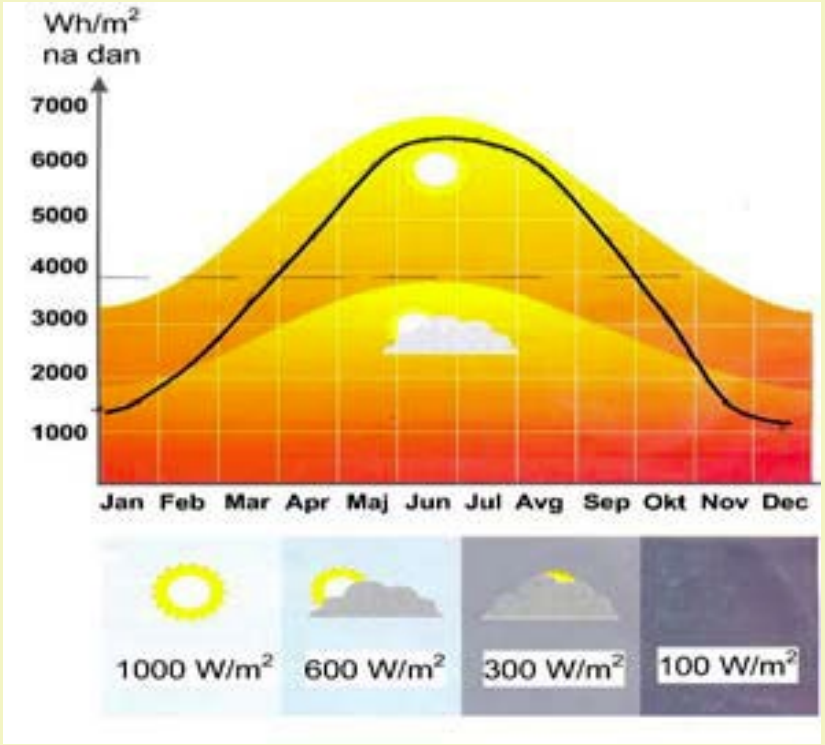
Regime of exploitation when the use of heating and air conditioning (winter, summer)

The biggest impact on consumption is the use of heating system and AC-system

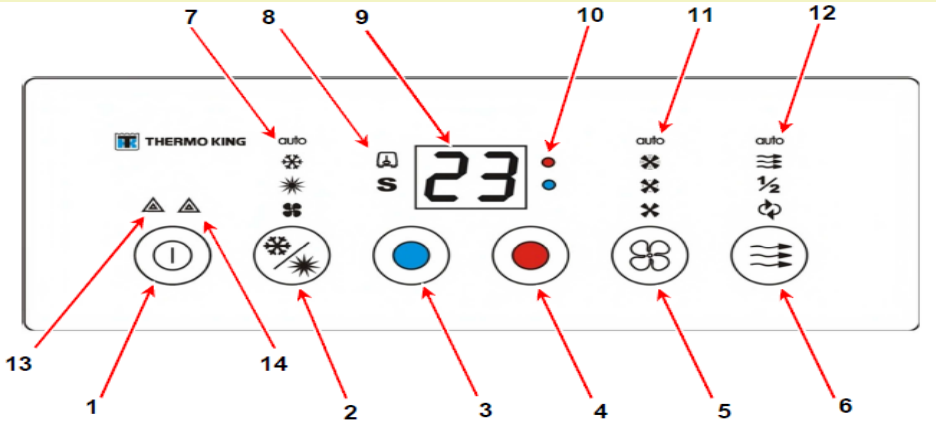
Typical periods of exploitation in Belgrade

Month / Period of exploitation	Winter	Summer	Transition
Janauary	x		
February	x		
March	x		
April			x
1 st ½ May			x
2 nd ½ May		x	
June		x	
July		x	
August		x	
1 st ½ September		x	
2 nd ½ September			x
1 st ½ October			x
2 nd ½ October	x		
November	x		
December	x		

Daily energy potential of the sun for the city of Belgrade, measured over a year



AIR-CONDITIONING AND HEATING SYSTEM IN E-BUS "HIGER", WHICH IS IN EXPLOITATION IN BELGRADE



Control panel air conditioning


Position radiators for heating

The power of the air conditioners in the cooling mode is max. 24 kW.

The heating system in the vehicle is designed as an electric, type manufacturer "Spheros". Heating system power is max. 30 kW. There are special temperature regulators for the air in passengers salon and driver's cab. The system consists of 9 heaters. For the driver's windshield warming is used "Defroster", particular or together with the "Spheros" system .

The heating system complies with UN ECE 122 or 2001/56/EC regulations.

WINTER PERIOD OF EXPLOITATION

In the following example will be presented the results of measuring the electric energy consumption of the heating system and the temperature of the interior space for the E-bus (garage number 2103), which was conducted in the Belgrade, 2nd March 2018 [1] . The outside air temperature was -1 ˚C. A measurement was performed according to the following plan:

-Installation of measuring equipment in the E-bus garage number 2103, which was performed in the enclosure of the depot "Dorćol". The measured temperature in the depot was 11.5 ˚C.

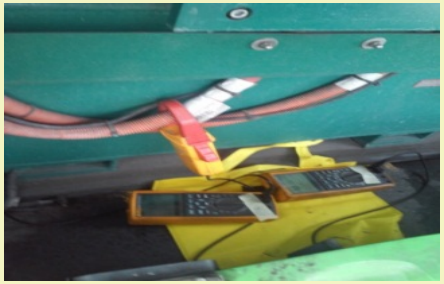
-Measurement of electricity consumption of heating and temperature systems in the passenger compartment on depot "Dorćol" - Terminal of the Vuk monument, without passengers, without opening the door.

-Measurement of the electrical energy consumption of the heating system, passenger compartment temperatures, energy consumption and recovery at the super condenser in real exploitation, direction "A" (Vuk's monument-Belvil).

Measuring equipment was used "Fluke 189", "Fluke 289" and current clamps, and measured the following sizes: Voltage on the supercapacitor, discharge/charging current of the supercapacitor, "Spheros" system heating energy consumption and heaters windscreen "Defroster", the interior temperature of the passenger compartment. The measuring device for recording the ambient temperature of the interior of the vehicle was placed in the middle part of the vehicle at a height of 1.5 m.

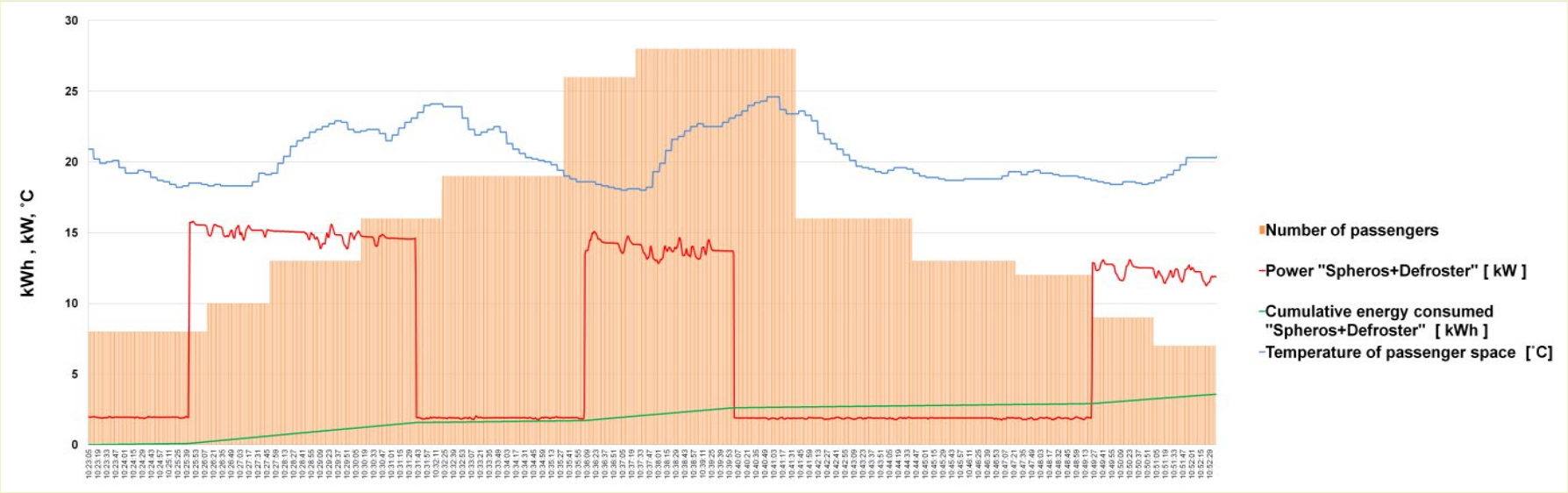
E-bus "Higer"

Measuring the temperature of the passenger compartment



Measurement of voltage and current on a supercondenser

Measurement of the current consumption of the system for heating the passenger compartment



Graphical display of the results of measurements in the period 10:23:05 - 10:52:40 am, direction "A"

Results of measuring the consumption of electricity in the period 10:23:05 - 10:52:40 am, direction "A"

Energy consumption from supercapacitor [kWh]	**13.165**
Energy consumption of heating system ''Spheros+Defroster'' [kWh]	**3.569**
Recovered energy in supercapacitor [kWh]	**-2.482**
Exchange energy in supercapacitor [kWh]	**10.63**
Recovery [%]	**18.9**
Lenght od line [km]	**7.47**
Average of consumption E-bus [kWh·km^{-1}]	**1.43**
Average of consumption E-bus [kWh·km^{-1}]*	**1.51**

* with estimated losses of 5% in the filling phase

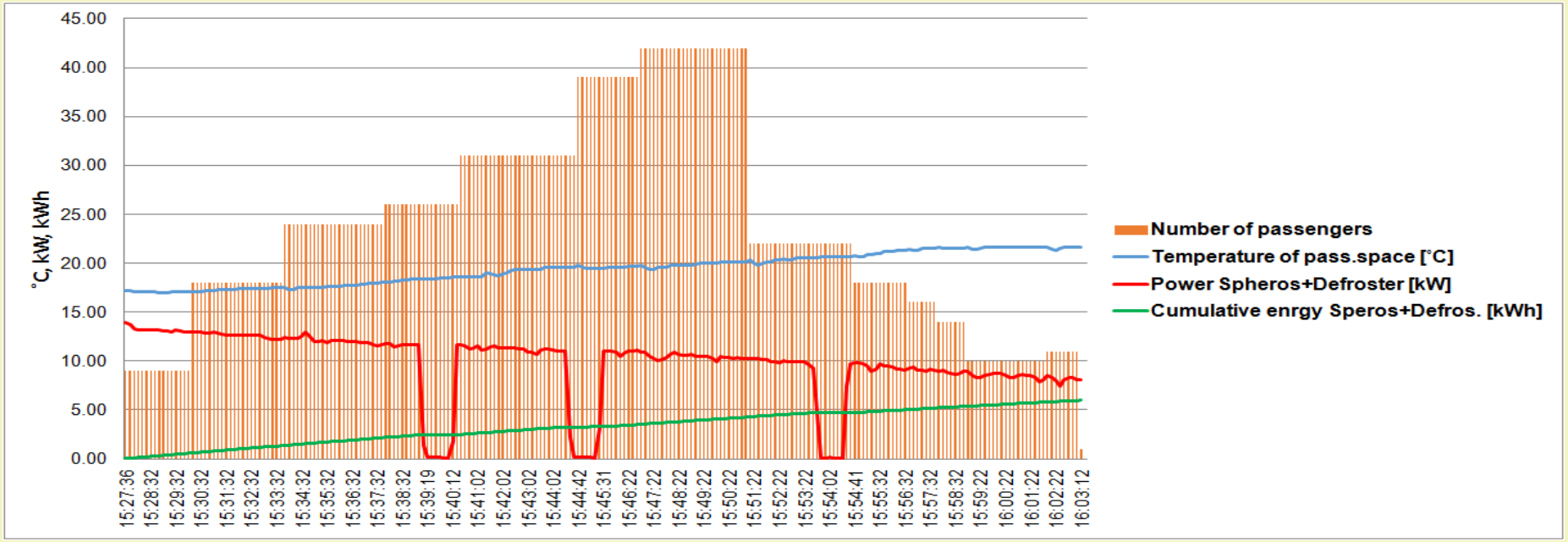
The results of the measurement of electricity consumption E-bus with switched "off" heating system 10:23:05-10:52:40 am, direction "A"

Energy consumption from supercapacitor [kWh]	**9.595**
Energy consumption of heating system ''Spheros+Defroster'' [kWh]	**0**
Recovered energy in supercapacitor [kWh]	**-2.482**
Exchange energy in supercapacitor [kWh]	**7.114**
Recovery [%]	**25.9**
Lenght od line [km]	**7,47**
Average of consymption E-bus [kWh·km^{-1}]	**0.95**
Average of consymption E-bus [kWh·km^{-1}]*	**1.01**

* with estimated losses of 5% in the filling phase

Analysis of the obtained results is shown that when an ambient temperature of -1 °C, the effect of the operation of the heating system to the energy efficiency of the E-bus decreased by 49.5%, compared with the heating system, when is not in operation.

In the following example are presented results of the measurements of the electricity consumption of the heating system "Spheros", which was done on 22nd December 2016, on the line EKO 1, direction "A" (Vuk monument - Belvil) in the period from 15:27:36 to 16:03:22 hours [1]. The outdoor air temperature was -6 ˚C. It was a strong southeast wind, which made the real outside temperature of -10 °C.



Results of measurement of electricity consumption from 22/12/2016, direction "A"

Energy consumption from supercapacitor [kWh]	**13.81**
Energy consumption of heating system Spheros [kWh]	**5.97**
Lenght od line [km]	**7.47**
Average of consumption E-bus [kWh·km^{-1}]	**1.848**
Average of consumption E-bus [kWh·km^{-1}]*	**1.940**

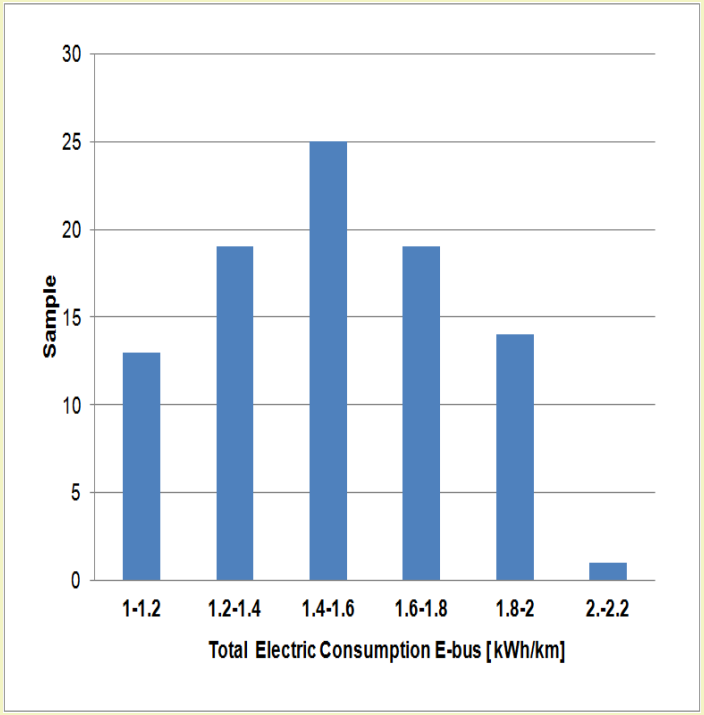
The results of the measurement of electricity consumption E-bus with switched ''off'' heating system from 22/12/2016, direction "A"

Energy consumption from supercapacitor [kWh]	**7.84**
Energy consymption of heating system ''Spheros'' [kWh]	**0.0**
Lenght of line [km]	**7.47**
Average of consumption E-bus [kWh·km^{-1}]	**1.05**
Average of consumption E-bus [kWh·km^{-1}]*	**1.10**

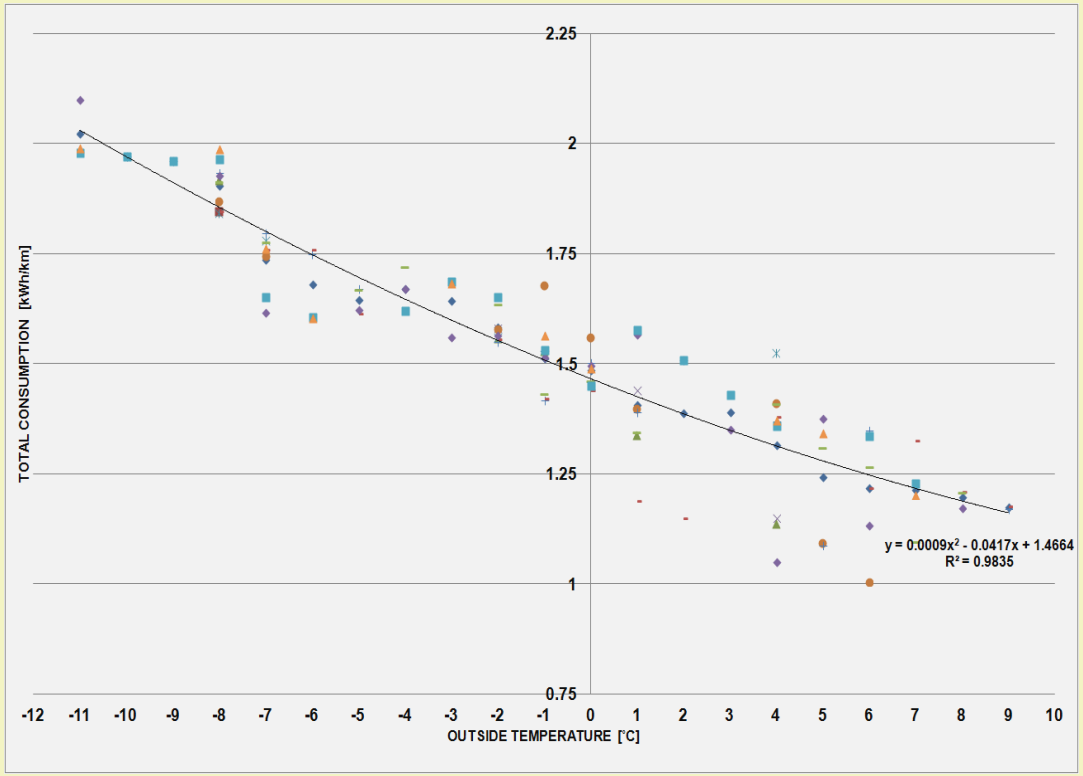
* with estimated losses of 5% in the filling phase

The analysis of the obtained results shows, at an ambient temperature of -10 °C, the effect of the operation of the heating system to the energy efficiency of the E-bus is extremely bad, and the total consumption of the E-bus is increased by 75.2% compared when the system for the heating not in operation

During of January and February 2018, recorded the changes in SOC for the different dates in which the outside temperature was in the range of -11 °C to + 10 °C . Analysis of a sample of 91 measurements overall consumption of E-bus (with calculated losses in the filling phase) expressed in kWh·km^{-1}, were in the range of 1.05 to 2.1 kWh·km^{-1} [1].



Distribution of total electricity consumption in the period January-February 2018 on the line EKO 1, direction "A"



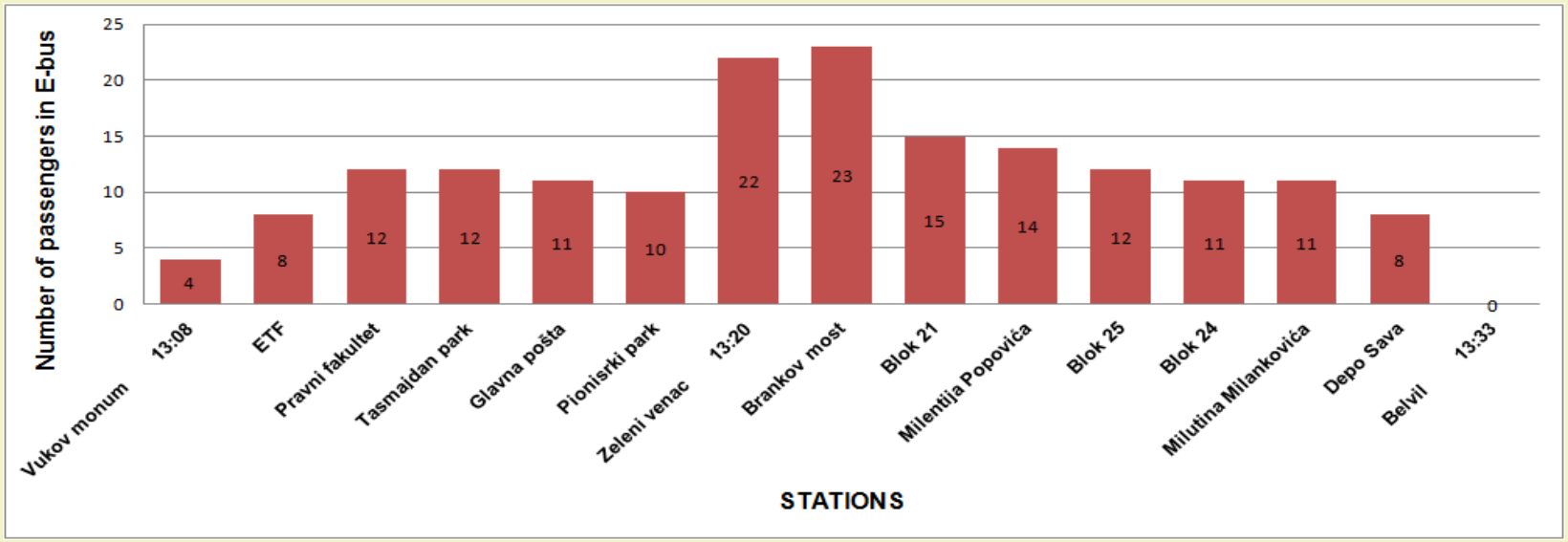
Total electricity consumption of E-bus expressed in kWh·km^{-1}, in the function of outside temperature (winter period), direction "A"

$$P\left(X_s - 1.96\frac{s_d}{\sqrt{n}} < \mu < X_s + 1.96\frac{s_d}{\sqrt{n}}\right) = 0.95 \qquad (8)$$

In the concrete case $P(1.465<\mu<1.574) = 0.95$, it can be considered that the average value of electric consumption of electric buses will be between 1.465 kWh·km^{-1} and 1.574 kWh·km^{-1} .

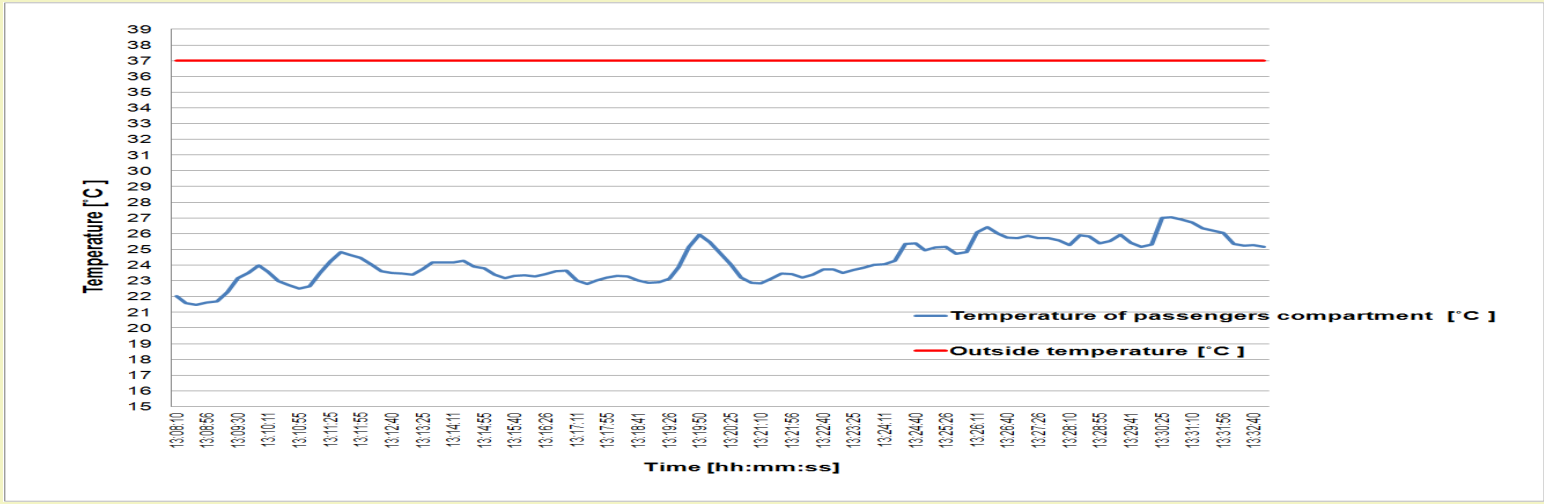
SUMMER PERIOD OF EXPLOITATION

During the summer period, there is the intense use of air conditioners in the vehicle to ensure a satisfactory temperature of the passenger compartment. The effect of the operation of the air conditioner and the impact on the electricity consumption of the E-bus, have been seen from the results of measurements performed on 11th August 2017 [1] , at an outside temperature of 37 ˚C. Measurement of the temperature of the passenger compartment was made by the measuring device "Fluke 189", which was placed on the central part of the vehicle. The measuring probe was set at a height of 1.5 m .



Number of passengers in the E-bus, period 13:08:10-13:32:56, direction "A"

For an average passenger weight of 68 kg and a height of 1.75 m, while sitting, during a journey, corresponding to a value of about 1 M_{et}, the passenger will give a heat of approximately 105 W.



Changing the current temperature in the passenger compartment during measurement, direction "A"

Total energy consumption of E-bus, direction "A" , period 13:08:10-13:33:09 for 11/8/2017

Direction "A"	Time [hh:mm:ss]	Outside temperature [°C]	SOC [%]	[kWh]	[kWh·km^{-1}]
Vuk monument	13:08:10	37	96		
Belvil	13:33:09	37	48		
Total consumpted energy				9.84	
Average consumption of E-bus					1.31
Average consumption of E-bus *					1.37

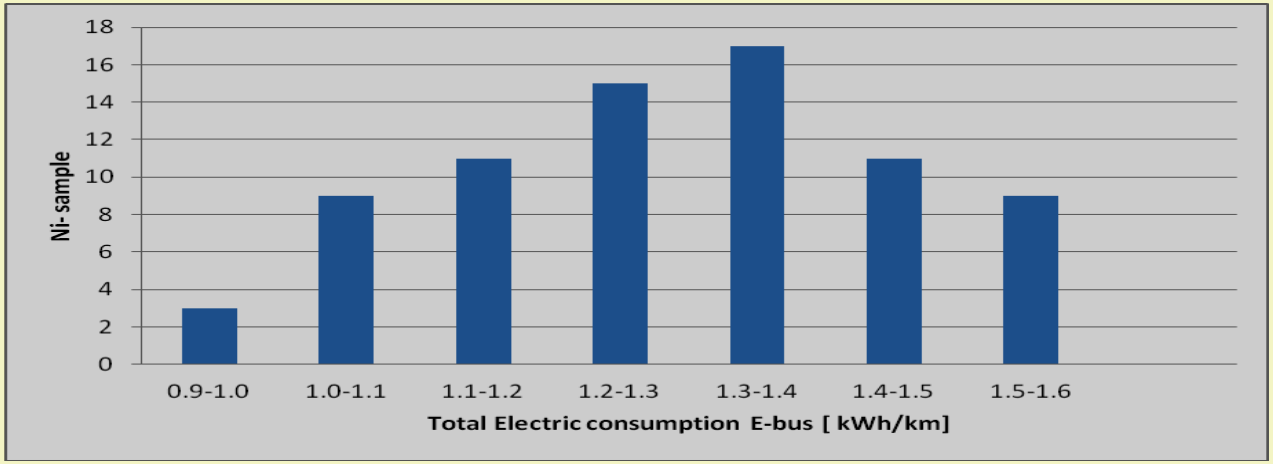
* with estimated losses of 5% in the filling phase

Results of the total consumption of E-bus, which was recorded 7.8.2017. year, in the same period of the day, but at an outside temperature of 20 ° C, when the air conditioner was not used, presented in Table

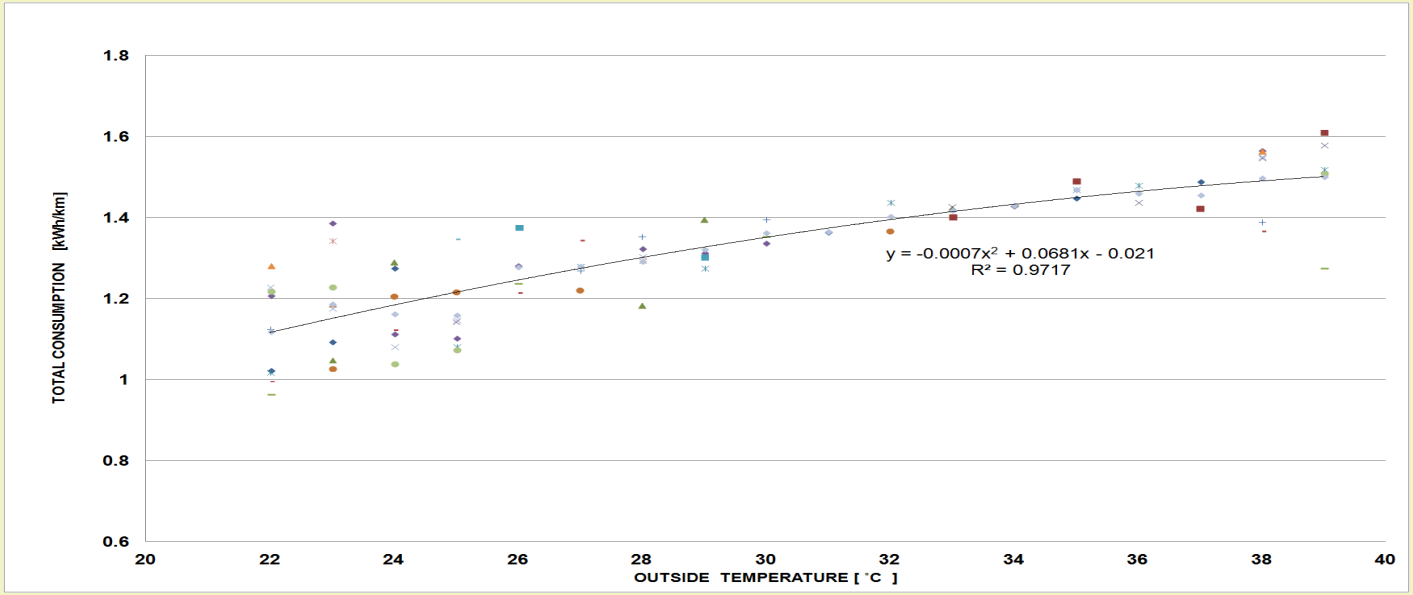
.Direction "A" '	Time [hh:mm:ss]	Outside temperature [°C]	SOC [%]	[kWh]	[kWh·km^{-1}]
Vuk monument	12:55:02	20	99		
Belvil	13:25:11	20	65		
Total consumpted energy				6.945	
Average consumption of E-bus					0.93
Average consumption of E-bus *					0.976

* with estimated losses of 5% in the filling phase

During July and August 2017, the change of SOC was recorded for the different dates, which the outside temperature was in the range of 22 °C to + 39 °C . Analyzing a sample of 75 measurements of total E-bus consumption (with calculated losses in the charging phase) expressed in kWh·km^{-1}, were in the range of 0.975-1.61 kWh·km^{-1}. Distribution of total consumption is presented in the next Figure .



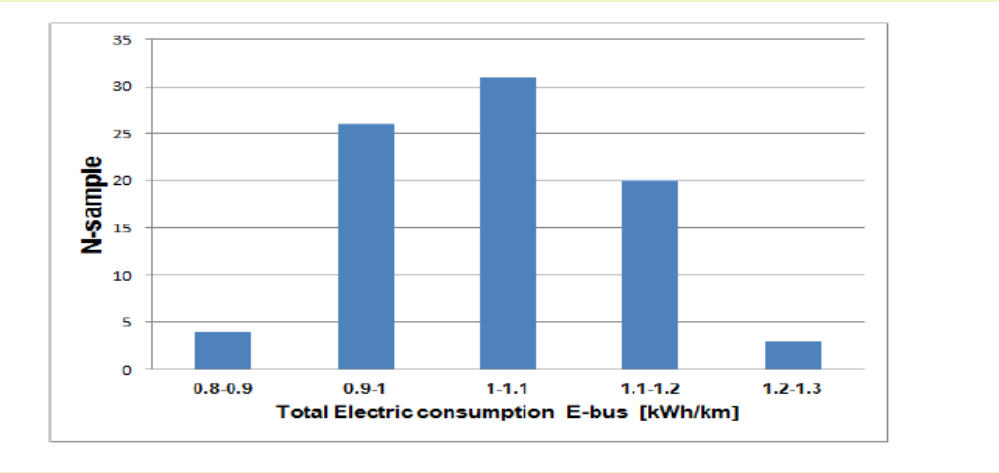
Distribution of total electricity consumption in the period July-August 2017 on the line EKO 1, direction "A"



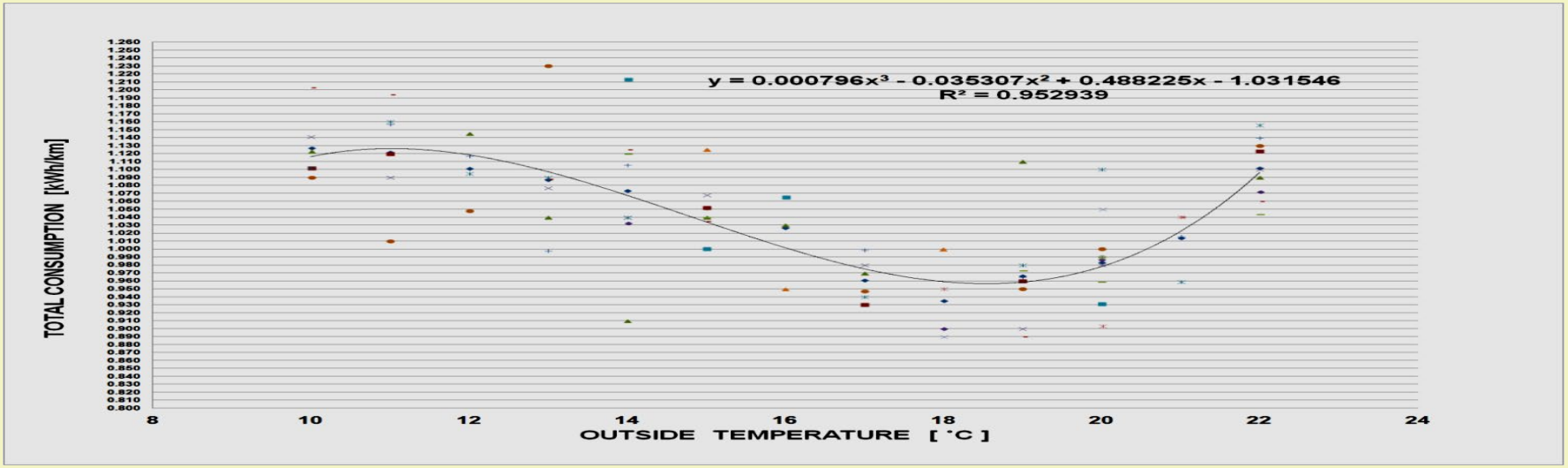
Electricity consumption E-bus, expressed kWh·km^{-1}, as a function of the outside temperature (summer period), direction "A"

TRANSITION PERIOD OF EXPLOITATION

During September, October and April 2016 and 2017, the change of SOC for different dates was recorded, the outside temperature was in the range of 10 °C to 22 °C . Analysis of a sample of 84 measurements total consumption of E-bus (with calculated losses in the filling phase) expressed in kWh·km^{-1}, were in the range of 0.890-1,230 kWh·km^{-1}. Distribution of total consumption is presented in the next figure [1].

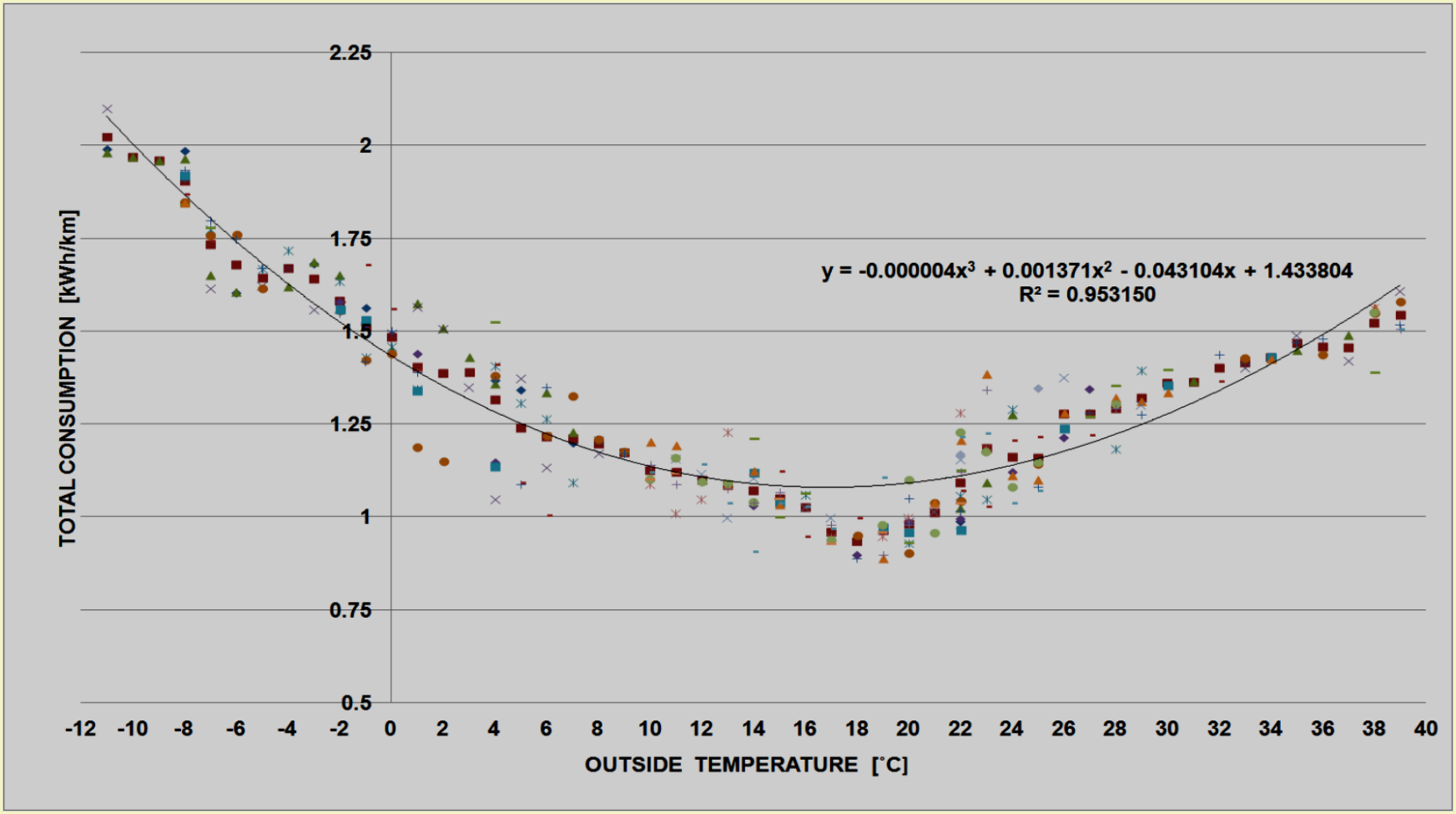


The average value of the treated sample is 1.045 kWh·km^{-1}, a standard deviation is 0.082 kWh·km^{-1}.



Electricity consumption E-bus, expressed kWh·km^{-1}, as a function of the outside temperature (transition period), direction "A"

If all the obtained results of measuring the total consumption of the E-bus during the summer, winter and transition periods were displayed in the function of outside temperature, the dependence which can be described by the function of the polynomial of the 3rd degree with the coefficient of correlation $R^2 = 0.953$, as shown in next Figure :



Electricity consumption E-bus, expressed $kWh \cdot km^{-1}$, as a function of the outside temperature, direction "A"(winter, transition and summer period)

Average consumption of E-Bus on an annual level, taking into account the different consumption during different periods of operation, can be shown in the next table [1] :

Energy consumption of E-bus in different periods of exploitation, direction "A"

Period of exploitation	Duration [months]	Average energy consumption of E-bus [kWh·km^{-1}]
Summer	4	1.289
Winter	5.5	1.520
Transition	2.5	1.045
Total	12	1.34

source:

[1] Mišanović S., Taranovic D.,Lukić J.,Pešić R.,Glišović J***., The impact of the system for heating and air-conditioning on the enerrgy efficiency of the electric drive bus (E-bus),*** 7th International Congress Motor Vehicles & Motors 2018, Kragujevac, 4-5 October 2018, Proceedings, ISBN 978-86-6335-055-7, pp.115-137

ECOLOGICAL EFFECTS ON THE LINE EKO 1

One of the main reasons for introducing E.buseva the line EKO 1 are the environmental effects compared to diesel buses. This relates primarily to:

- smaller level of noise, compared to a diesel bus

- "O" emission of harmful gases. Comparison of the emissions of harmful gases of one E.bus and diesel buses on the line EKO 1 for annual mileage 60 000 km, present in next tables:

Line EKO 1 : Consumption of electricity and diesel fuel

Typ of bus	Average of Consumption
E-bus	1.34 kWh/km
Diesel bus	0.44 L/km

Comparison of the emissions of harmful gases of one E.bus and diesel buses on the line ECO 1, for annual mileage 60 000 km

Pollutant	E-bus	Emissions of diesel bus (Euro 4)	Emissions of diesel bus (Euro 5-EEV)	Emissions of diesel bus (Euro 6)
	(kg/year)	(kg/year)	(kg/year)	(kg/year)
CO	0	147	147	147
CxHy	0	45.2	24.3	12.75
NOx	0	342.1	195.7	39.2
PM 10	0	1.96	1.95	0.95

•Better CO_2 emissions, WtW (Well-to-Wheel) at E.bus compared to a diesel bus

In Serbia, 70% of electricity is produced from coal and 30% from hydro potential, which gives LCA factor 774 t / MWh (774 g / kWh). LCA ("life cycle assessment) emission takes under consideration all emissions of the supply chain (exploitation, transport, processing etc.)

On the example of the EKO 1 line for a diesel bus with a consumption of 44 L / 100km, CO2 emissions, WtW (Well-to-Wheel) can be calculated as:

$$CO_{2\ WtW} = m_{co2} \cdot 1.2$$

$$m_{co2} = m_f \cdot g_c \cdot 44/12$$

m_{co2} - mass of carbon dioxide generated by burning fuel (830 g/L)
m_f - the mass of fuel burned (830 g/L)
g_c - (0.85 kg C / kg fuel) ratio of the amount of carbon in the fuel
44 - molar mass of carbon dioxide CO2
12 - molar mass of carbon C
1.2 - emission factor CO_2 during the production and transport of diesel fuel

Emissions, CO_2 WtW (Well-to-Wheel) for an electric bus can be calculated:

$$\mathbf{CO_{2\ WtW} = LCA \cdot C_{e\text{-}bus} \cdot 1.05}$$

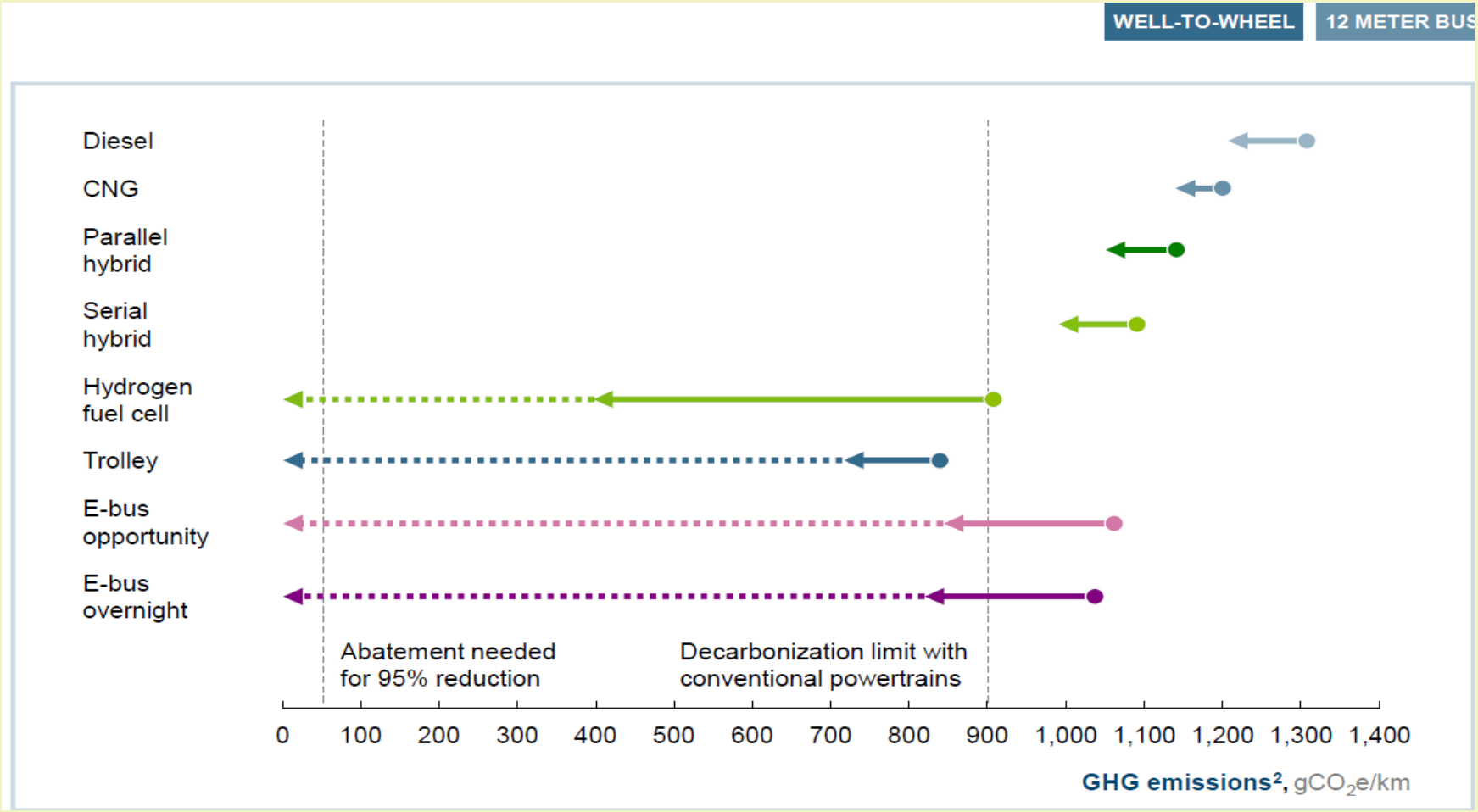
LCA - "life cycle assessment (774 g/kWh)
$C_{e\text{-}bus}$ - E.bus consumption (kWh/km)
1.05 - loss factor of electricity during charging

Table , shows the values of CO_2 emissions for E.bus and diesel bus on the line EKO 1 in Belgrade.

Type of bus	Consumption	Emission of CO2 (g/km)
E-bus	1.34 (kWh/km)	1089 (g/km)
Diesel	0,44 (L/ Km)	1365 (g/km)

Conclusion is that the emission of CO_2 , for E.bus about 25.3% lower in comparison with the diesel bus.

Similar results came in a survey carried in some European cities, as presented in next Figure [2] According to this study, CO_2 emissions for diesel buses amounted to about 1350 g/km while E-bus had a emissions of about 1050 g/km.



source :

[2] Urban buses: Alternative powertrains for Europe, A factbased analysis of the role of diesel hybrid, hydrogen fuel cell, trolley and electric powertrains, november 2012

CONCLUSIONS:

The operation of the heating and air conditioning systems for electric buses are of high importance to the energy efficiency of the vehicle. Unlike buses with diesel drive where the impact of these systems is not as pronounced, buses on electric power are had a large variations in electricity consumption at different period of the exploitation.

In the case of exploitation of electric buses in Belgrade, the consumption of electric energy in the winter increase by 45.4% in the summer period by 23.3% compared to the transition period when these systems are not used or used at a lower intensity.

The practice has shown, when are outside temperatures between 17 °C and 19 °C, the energy efficiency of buses on an electric drive are highest since at these temperatures heating and air conditioning systems are not used. The heating and air conditioning systems installed in the E-Buses which used in Belgrade, fully meet all the required performance in terms of thermal comfort in accordance with the defined recommendations.

Knowing the performance of the heating and air conditioning system from the aspect of thermal comfort and electricity consumption is important from the aspect of system selection and dimensioning of the required capacity of the electrical energy storage system for electric buses in order to realize the planned autonomy of vehicle movement at the working day level.

In summer period of operation when the air conditioner is intensively used, often open side windows in the passenger compartment allow hot air flow, which reduces the efficiency of the air conditioning system as well as the energy efficiency of the E-bus.

In winter conditions, the biggest problem is unplanned congestion on the streets, with the heating system, is operated at full capacity. In such situations, it is necessary for the driver to switch off the heating system in order to prevent the excessive discharge of the battery or supercapacitor and to prevent the risk of stopping the E-bus on the route.

E-bus has a "0" emission of harmful gases observed at the local level and a more favorable CO_2 emission observed at the national level.

Thank you for your attention

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