

Energy consumption and carbon dioxide emission analysis for electric city buses

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Summary

This research presents a complete breakdown analysis of the energy consumption and carbon dioxide emissions for electric city buses. Different primary energy pathways for electricity are analysed in terms of energy efficiency and emissions. The energy losses for charging and bus operation are evaluated based on the simulations carried out in the Autonomie vehicle simulation software. Different types of driving cycles and operation conditions are used in simulations. The results show in detail the breakdown for the energy consumption and carbon dioxide emissions for the different energy pathways.

Keywords: energy consumption; carbon dioxide emissions, electric bus; energy efficiency; vehicle simulation

1 Introduction

Electricity for vehicle use can be produced in many different ways and depending on the pathway, usually called as well-to-tank (WTT) or well-to-pump (WTP), different amounts of energy is used and emissions produced [1]. The primary energy sources (coal, nuclear, natural gas, etc.) have an important impact on the energy efficiency and carbon dioxide (CO₂) emissions of the electricity production. Because geographical locations have different availability of primary energy sources, it is important to take into account the local electricity production when analyzing the energy efficiency and carbon dioxide emissions of electric city buses as it was shown in a recent research study in the USA [3]. In European countries, there is significant variability in CO₂ emissions due to differences between electricity generation pathways. This was shown in an extensive research by the European Commission [1] and by Eurostat [3]. According to the research studies, electricity produced from fossil energy sources has CO₂ emissions between 150–300 g/MJ. CO₂ emissions from renewable energy sources are minimal, and they could be even negative e.g. when biogas is used for producing electricity [1]. When defining CO₂ emissions of vehicles, emission values of electricity grid mix are often used. In a Spanish study [4], the grid mix CO₂ emissions were 104.5 g/MJ, and in another European study [5], the electricity grid mix CO₂ emissions were 138.0 g/MJ. The yearly average CO₂ emissions of the electricity production in Finland was 32.8 g/MJ in 2015 [6].

Electric city buses are getting more and more competitive with traditional diesel city buses because of their superior energy efficiency and zero emission operation [7]. The main reason for the success of battery electric buses are lithium based batteries and advanced charging technologies [8]. In the past, other type of battery technologies were used in city buses such as molten salt batteries [9] but modern electric city buses are powered by lithium-ion batteries [10]. Due to the flexibility of the electric powertrain, different design solution can be achieved as shown in [11] and [12]. The most typical powertrain solution is to use one or two electric traction motors directly connected via a differential gear to the wheels without a gearbox [13] or with a fixed reduction gear between the motor(s) and differential gear [14]. A full electric powertrain has very

high energy conversion efficiency, around 80–85%, depending on the powertrain design, operating cycle and conditions. The recent trend is to have a smaller battery pack (energy capacity < 100 kWh) and charge the battery during operation either in specific bus stops (opportunity charging) or at the end stations [14, 15]. This way the operation is not dependent on the battery capacity, and also, less investments are needed for expensive batteries. The charging efficiency depends on the power and it is usually better than 80%. High charging current increases the losses in the charging device and especially in the battery. Due to the high power acceptance of lithium-ion batteries, braking energy can be recovered in high efficiency which significantly improves the total energy efficiency of electric buses [11]. Despite of the technological advantages, battery electric buses still have higher lifecycle costs than diesel or hybrid city buses [7].

A typical operation of city buses includes rapid accelerations and decelerations between bus stops in city center or urban areas. Electric buses are much less impacted by the driving cycle than diesel buses because of the higher efficiency powertrain and possibility to regenerate braking energy [7]. The major challenges in the operation relates to the charging infrastructure and operating conditions. When operating in cold or hot ambient temperature, the energy consumption of the HVAC (Heating, Ventilation, and Air Conditioning) systems may be higher than the propulsion energy consumption [8, 10]. Because the electric powertrain does not produce a lot of waste heat [16], a significant amount of battery energy has to be consumed to the heating of the interior spaces in cold ambient conditions.

This research presents an exhaustive analysis of the energy consumption of electric city buses. Two different types of battery electric city buses were modeled and analyzed. The first bus type is suitable for operation with opportunity charging and the other one for overnight charging. Based on the simulation results, the energy consumption was evaluated in terms of powertrain, driving cycle, ambient conditions (temperature) and passenger load. The carbon dioxide emissions were also analyzed. First, the electricity production and generation pathways are described in European context. Secondly, the energy efficiency and CO₂ emissions of the different pathways were defined based on the recent statistical data. Based on the energy consumption values in operation, the total energy consumption and CO₂ emissions were calculated for different driving cycles.

2 Electricity production and pathways

Carbon dioxide emissions of electricity generation are heavily dependent on the electricity production pathway. There are substantial differences between countries and geographical regions in energy sources and CO₂ emissions. In this research, the focus is on Europe and a specific study was done for Finland. Figure 1 presents electricity production by energy sources in European Union (EU) 28 countries and in Finland [3, 6]. In Finland, very little electricity is produced by combustible fuels and a significant amount of energy is produced by nuclear power.

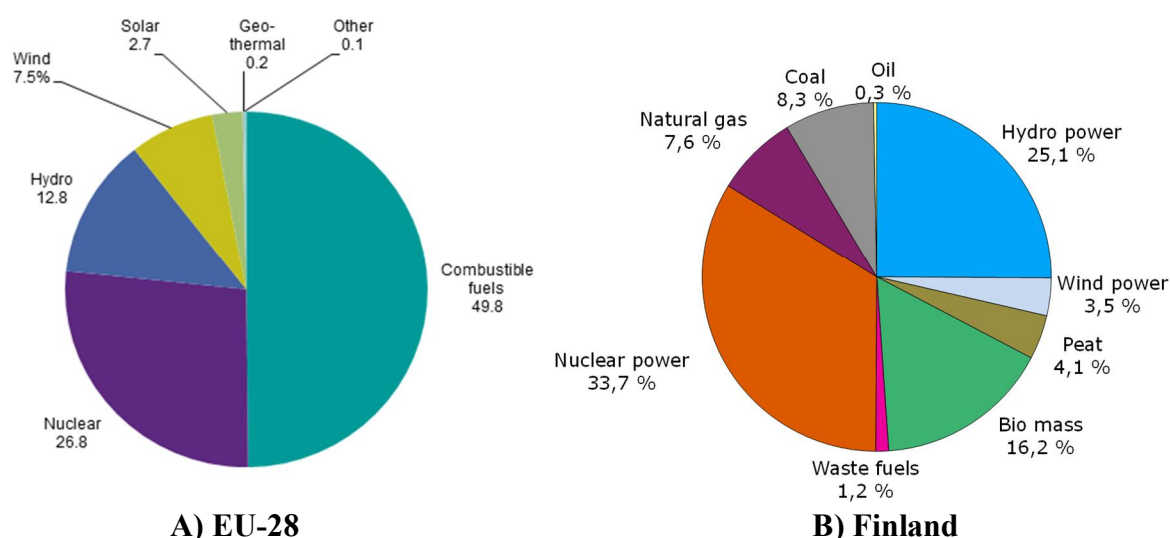


Figure 1: Electricity production by energy sources A) EU-28 countries [3], and B) Finland [6].

Figure 2 presents electricity production by energy sources for all EU-28 countries. It can be seen that many of the countries are still using a lot of conventional thermal energy sources for electricity production. The electricity generation pathways, total energy balances and carbon dioxide emissions were exhaustively studied in Well-to-Tank report by JRC (Joint Research Center) [1]. Figure 3 shows some of the typical electricity generation pathways as presented in [1]. The figure includes pathways for natural gas (GPEL1a/b/bC, GREL1), coal (KOEL1, KOEL2/2C), wind (WDEL1), and EU fuel mix (EMEL1). The descriptions of these pathway variants are given in Table 1 which also presents the energy balance and CO₂ emissions.

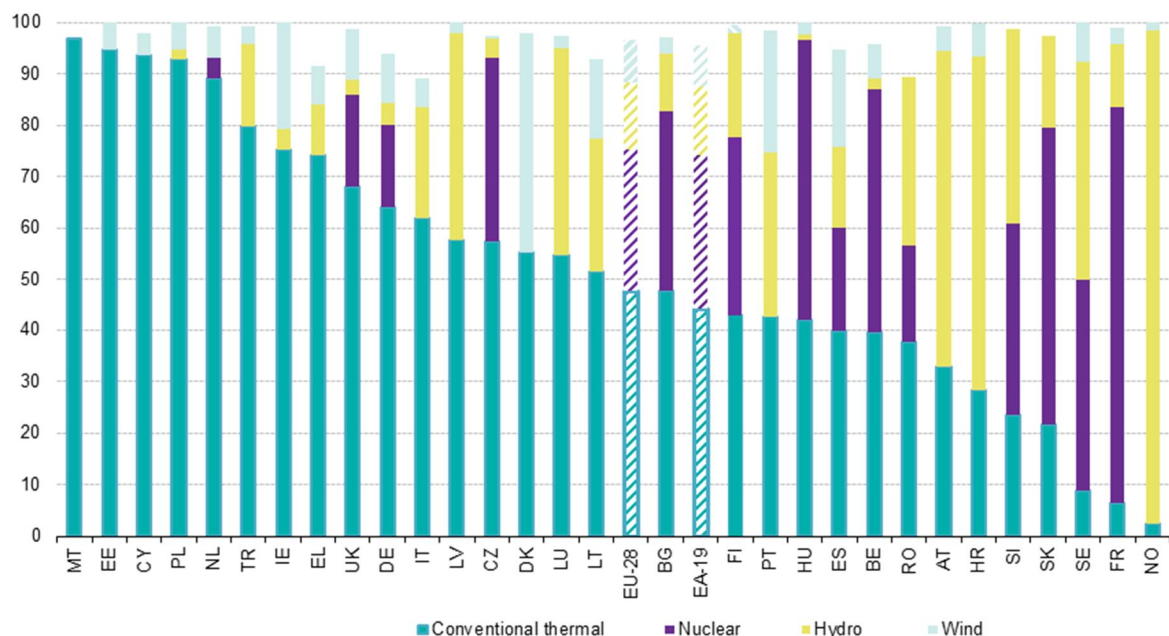


Figure 2: Breakdown of electricity production by source in EU-28 countries [3].

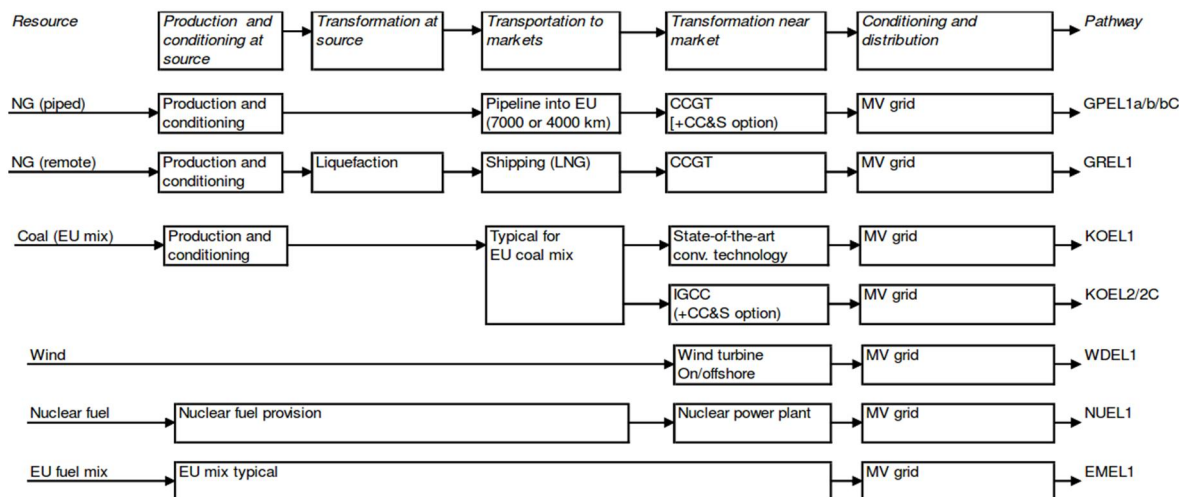


Figure 3: Electricity pathways from natural gas (NG), coal, wind, nuclear fuel and EU fuel mix [1].

Table 1: Energy balances and carbon dioxide emissions for different electricity generation pathways [1], [6].

Pathway	Description	Expended energy (MJ/MJ _{fuel})	GHG emissions (g CO _{2eq} /MJ _{fuel})
EMEL1	EU-mix (high voltage)	1.94	135.99
EMEL2	EU-mix (medium voltage)	2.05	141.13
EMEL3	EU-mix (low voltage)	2.24	150.11
KOEL1	Coal (hard), conventional	1.81	292.37
KOEL2	Coal (hard), IGCC ¹	1.54	262.36
KOEL2C	Coal (hard), IGCC + CCS ²	1.98	71.04
GPEL1a	NG, pipe 7000 km, CCGT ³	1.35	144.98
GPEL1b	NG, pipe 4000 km, CCGT	1.19	132.43
GPEL1bC	NG, pipe 4000 km, CCGT, CCS	1.71	44.67
GREL1	LNG, CCGT	1.39	141.62
NUEL	Nuclear	2.40	0.39
WDEL	Wind	0.12	0.00
FIMIX	Electricity grid mix in Finland	1.43	32.8

1) Integrated Gasification and Combined Cycle, 2) CO₂ Capture and Storage, 3) Combined Cycle Gas Turbine

3 Simulation models and parameters

3.1 Description of the simulation models

An electric city bus model was developed in the Autonomie vehicle simulation software [17]. There are two different configurations for the electric bus EV1) opportunity charging, and EV2) overnight charging. The EV1 configuration has smaller power-type battery (capacity of 77 kWh) which is being charged during operation. EV2 configuration has high-energy type battery with capacity of 373 kWh. The battery is charged overnight. These configurations were considered to be suitable for different type of operation. Figure 4 shows the powertrain layout of the electric bus in the Autonomie simulation software.

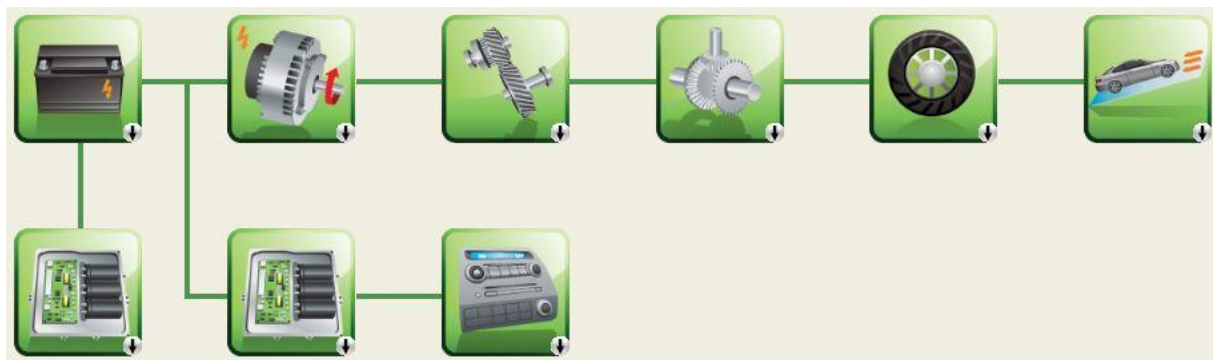


Figure 4: Powertrain layout. First row: Battery, Electric motor, Reduction gear, Differential gear, Wheels, Chassis. Second row: Charging device, Power converter, Auxiliary devices.

3.2 Model parameters

The general specifications of the electric bus models are presented in Table 2. The models are based on a lightweight, full-size city bus. The theoretical maximum speed of the bus is 100 km/h. Two different powertrain configurations are described in Table 3. EV1 is configured for fast charging operation and EV2 for overnight charging.

Table 2: General specifications.

Parameter	Value
Curb weight without batteries (kg)	9500
Gross vehicle weight (kg)	18000
Vehicle frontal area (m ²)	7.24
Drag coefficient	0.79
Rolling resistance	0.008
Wheelbase (m)	6.5
Front weight fraction	0.34
Centre of gravity, height (m)	1.0

Table 3: Powertrain technical data and simulation parameters of the electric bus configurations.

Configuration	EV1 (opportunity)	EV2 (overnight)
Battery chemistry and capacity	Titanate Oxide, 60Ah	Graphite/NMC, 200Ah
Battery cell specific energy (Wh/kg)	80	160
Battery module configuration	10 cells in series	7 cells in series
Battery pack configuration	8 modules: 4 in series, 2 in parallel	6 modules: 2 in series, 3 in parallel
Battery system configuration	7 pack in series	12 pack in series
Battery system specific energy (Wh/kg)	60	120
Battery capacity (kWh)	77.3	373.0
Battery system weight (kg)	1295	3106
Motor nominal power (kW)	170	170
Motor max peak torque (Nm)	1710	1710
Gear reduction	1.75	1.75
Final drive ratio	4.72	4.72
Tires	275/70/22.5	275/70/22.5
Bus curb weight (kg)	10795	12606
Load capacity mass (kg) / persons	7205 / 96	5394 / 72
Charging efficiency	0.82	0.87
Battery depth of discharge	0.75	0.9
Operating hours in a year	4000	Cycle dependent

The auxiliary power consumption was calculated based on the ambient temperature. The daily average temperatures of three different cities in Finland was used as reference. The temperature data was downloaded from an open data source provided by The Finnish Meteorological Institute [18]. The daily average temperatures shown in Figure 5 are measured from different geographical places in Finland; cities of Helsinki (south), Lappeenranta (east) and Oulu (north).

Figure 6A presents the estimated total auxiliary power consumption in function of the ambient temperature, and Figure 6B shows the ambient temperature impact on energy consumption in function of the average driving speed. The auxiliary power consumption in Figure 6A was estimated based on the recent literature [8, 15]. The constant power consumption is 5 kW without the HVAC system. The total auxiliary power consumption based on the ambient temperature can be calculated by using the estimated curve presented in Figure 6A. The reference simulations were carried out with 50% of the passenger load and in 15 °C of ambient temperature.

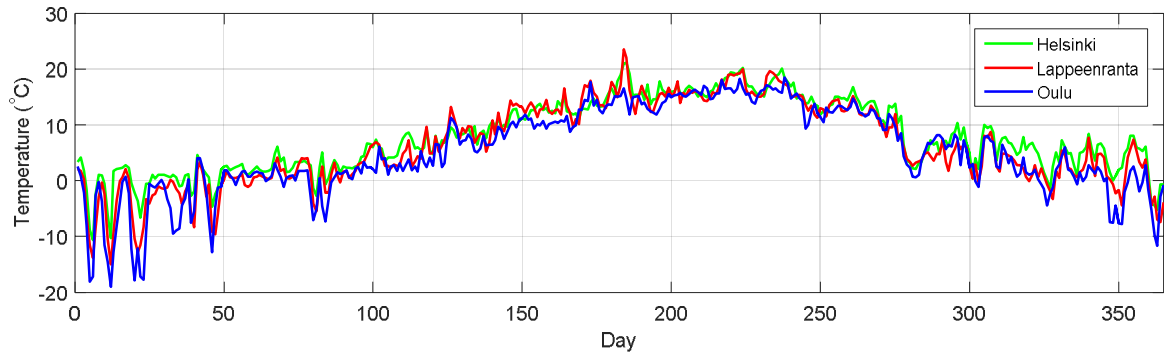


Figure 5: Daily average temperature of Helsinki, Lappeenranta and Oulu in 2015 [18].

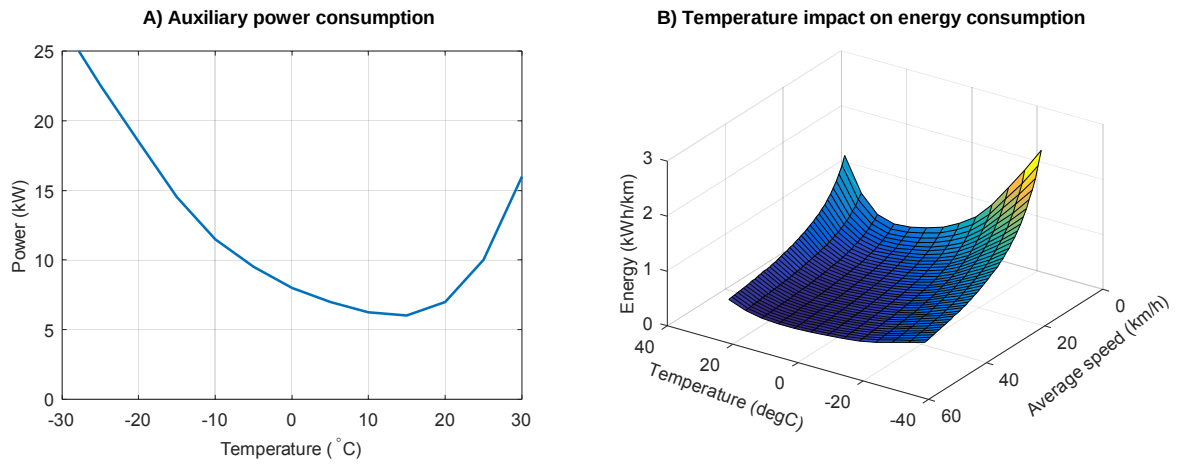


Figure 6: A) Estimated total auxiliary power consumption in function of ambient temperature. B) Temperature impact on energy consumption in function of the average driving speed.

3.3 Driving cycles

Six different driving cycles were used in simulations. Table 4 show the description of the cycles and Figure 7 presents the speed and elevation profiles of the cycles. Espoo 11 (E11), H550 and Line 51B (L51B) are measured cycles from existing bus operation lines and they also include elevation profiles. Braunschweig (BR) and Manhattan (MAN) are commonly used test cycles for city buses. Helsinki (H3) is an extra-urban cycle that is intended to represent the operation on roads that are external to the urban environment. The number of buses in a fleet was calculated based on a 10 minutes operating interval in the route.

Table 4: Description of the simulated driving cycles.

	BR	E11	H550	H3	L51B	MAN
Time (s)	1740	1548	3384	902	4283	1089
Distance (km)	10.9	10.2	28.7	10.3	16.1	3.3
Maximum speed (km/h)	58.2	58.4	74.9	71.7	59.0	40.5
Average total speed (km/h)	22.5	23.8	30.5	41.2	13.6	10.9
Average speed (km/h)	30.1	27.9	36.0	48.4	20.2	17.1
Stops per km	2.7	1.8	1.3	0.9	4.3	6.1
Aggressiveness (m/s^2)	0.235	0.152	0.206	0.195	0.281	0.306
Climbing gradient (m/km)	0.00	5.75	6.80	0.00	7.27	0.00
Descending gradient (m/km)	0.00	-5.83	-6.64	0.00	-7.26	0.00
Number of buses in a fleet	7	7	13	5	16	5

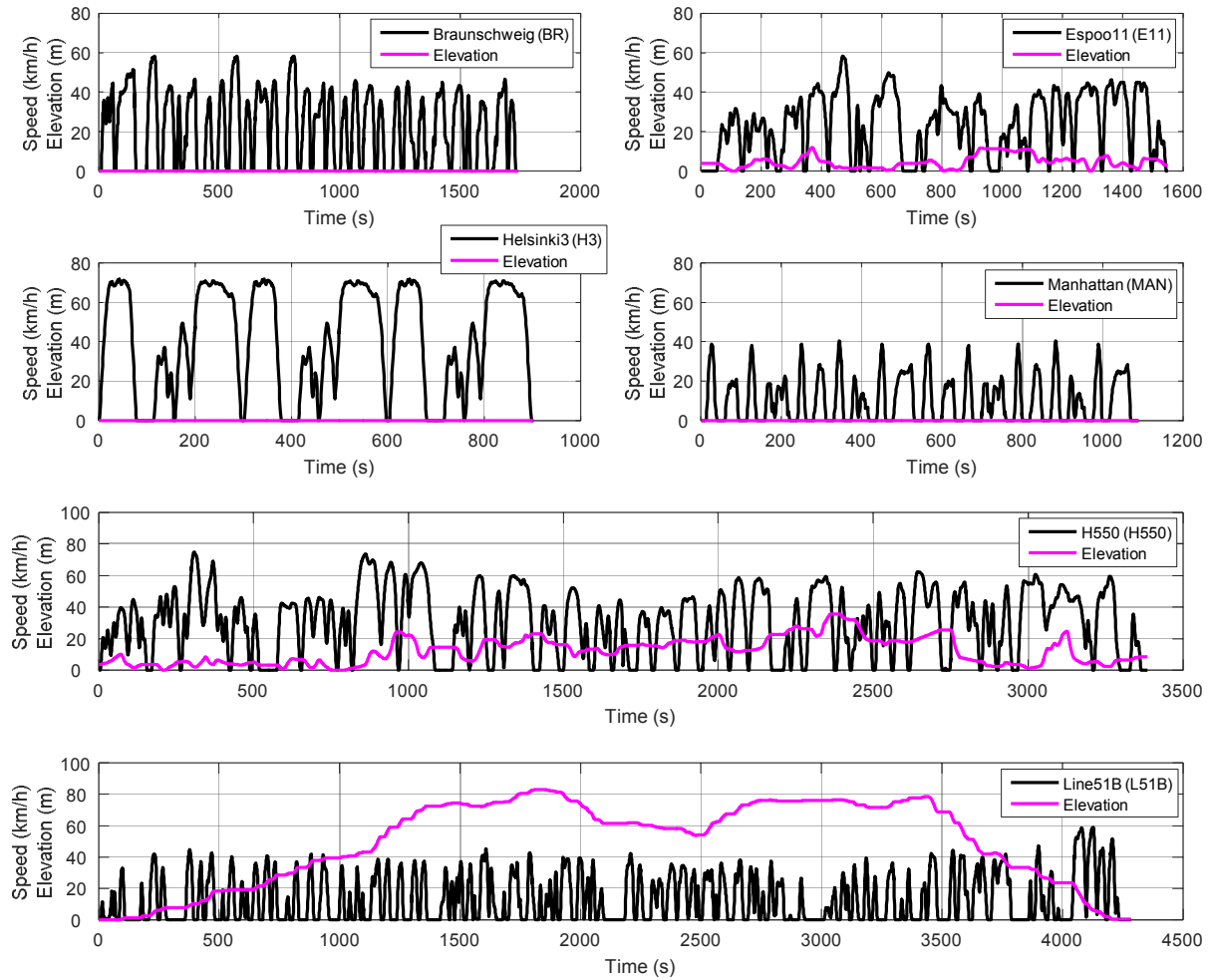


Figure 7: Speed and elevation profile of the simulated driving cycles.

4 Simulation results and analysis

4.1 Energy consumption in operation

The energy consumption of the electric buses was evaluated in different phases of the energy pathway. First, the electric bus consumption was analyzed by calculating the component specific losses based on the simulation results in different cycles. The reference simulations were done with 50% of passenger load and constant power of 6 kW for auxiliary devices (including HVAC systems). Figure 8 presents the distribution of powertrain losses for EV1 bus configuration. The consumption variation between different cycles is about 0.5 kWh/km which is quite significant; the increase in consumption between Espoo 11 and Manhattan cycles is more than 50%. The major part of the powertrain losses occur in tires, electric motor and auxiliary devices.

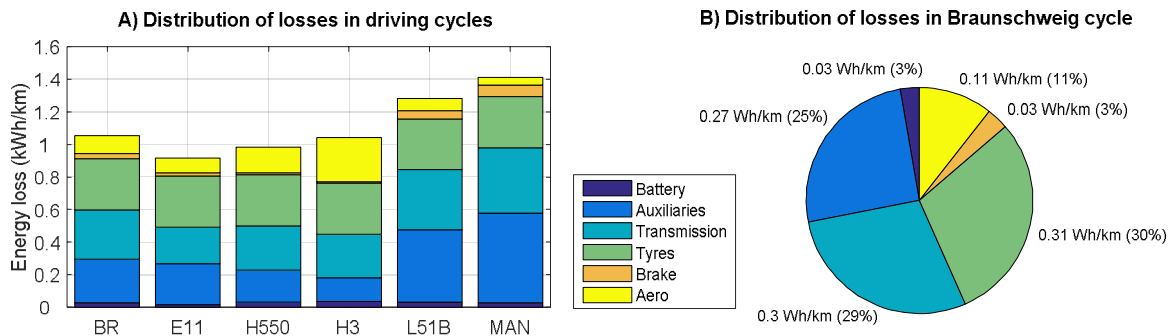


Figure 8: Distribution of powertrain losses for EV1 (opportunity charging).

Figure 9A shows the energy consumption for the EV2 bus configuration in two units: kilowatt-hours per kilometer and kilowatt-hours per hour of operation. It is important to analyze both of these units because it clarifies the differences between driving cycles. The energy consumption can be high for a distance (Manhattan) but it is not necessarily high for an hour of operation. This connects the energy consumption to the actual operation service which is usually done as service hours and not as a driven distance. Figure 9B presents the operating time and range for EV2 in each driving cycle. Because the EV1 configuration is charged during operation e.g. at the end of the route, its service operation is not limited by the operating range. Similarly to the results of the energy consumption, the operating time actually indicates the possible service hours in a given driving cycle for EV2 in Figure 9B. The operating range varies from 225 to 350 kilometers and hours of operation from 7 to 20 hours per day.

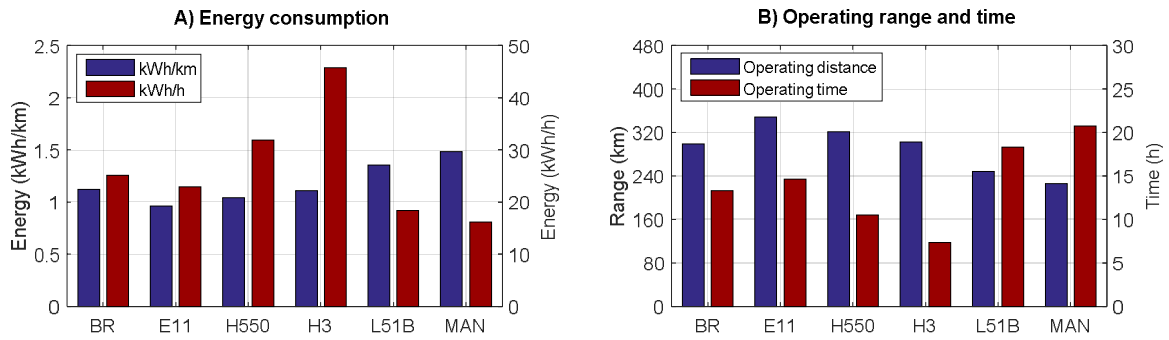


Figure 9: The reference energy consumption and operating range for EV2.

Figure 10 presents the passenger load impact on energy consumption as watt-hours per kilometer per ton of passengers (Wh/km/ton). In this case, one ton (1000kg) roughly equals 13 passengers. It can be seen that the load impact also depends on the driving cycle or more precisely on the driving style. In Figure 10B, it is shown that the energy consumption increase is actually more dependent on the type of driving than driving cycle itself. More aggressive driving increases the impact of passenger load on the energy consumption. This can be explained by the fact that when driving aggressively, higher power levels (higher acceleration levels) are used in acceleration which decreases the operating efficiency of the powertrain. In high deceleration levels, regenerative braking is limited due to the torque limitations of the electric motor.

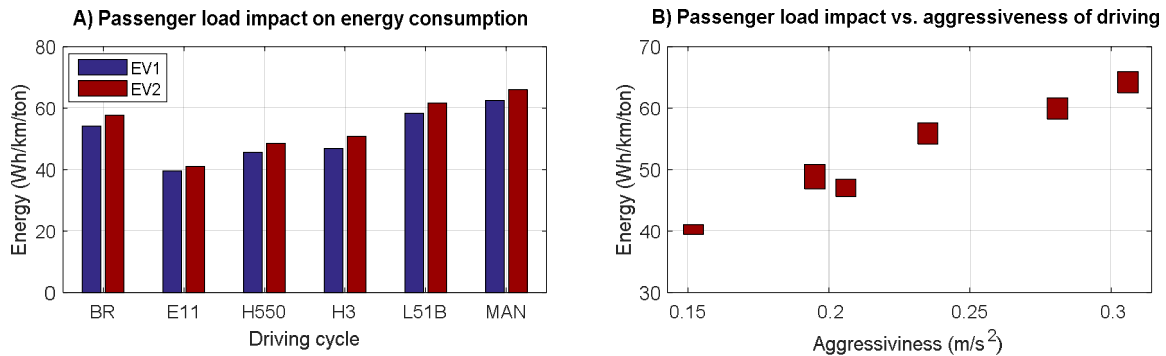


Figure 10: Passenger load impact on energy consumption.

Figure 11 presents the yearly average energy consumption which was calculated based on the daily average ambient temperatures of Helsinki and Oulu (Figure 5). The red error bars show the daily consumption variation. On average, the energy consumption increase due to the ambient temperature changes was around 10% in comparison to the reference energy consumption (ambient temperature of 15 °C). It can be seen in Figure 11 that there is only a slight difference in energy consumption between the bus configurations EV1 and EV2.

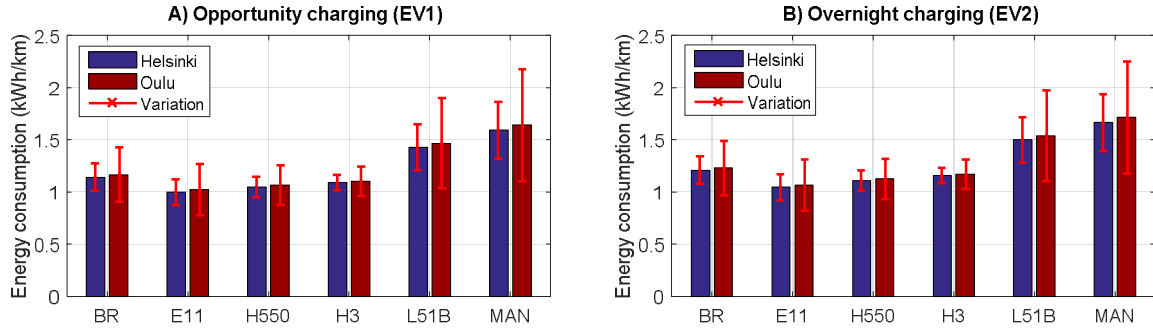


Figure 11: Yearly average energy consumption for EV1 and EV2.

4.2 Total energy consumed

The yearly consumed energy per one electric bus (EV1) and a fleet of buses is presented in Figure 12. The number of buses in fleet was calculated based on the cycle time and operating interval of 10 minutes (Table 4). It can be seen that the energy consumed in higher speed cycles (H550 and H3) is much higher than the other type of driving cycles for an individual bus. Figure 12B shows the differences of consumed energy between driving cycles in fleet operation. The longer operating routes (H550 and L51B) have more buses in the fleet which increases the amount of consumed energy.

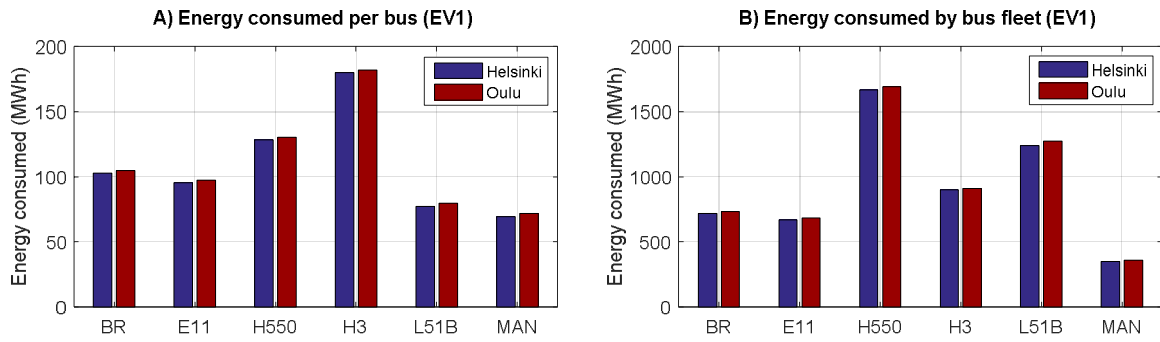


Figure 12: Bus and fleet specific yearly energy consumption.

When considering the total energy consumption of electric buses, the different phases of the energy use during bus lifecycle are taken into account. The energy consumed in bus manufacturing, maintenance, material production and end-of-life (referred as Bus) was calculated from [4]. Figure 13 shows the total energy consumption of one bus for EV1 in each driving cycle divided into four different phases: Bus, Well-to-Tank, Charging and Tank-to-Wheel. The different energy generation pathways were described in Table 1 with corresponding energy consumption values.

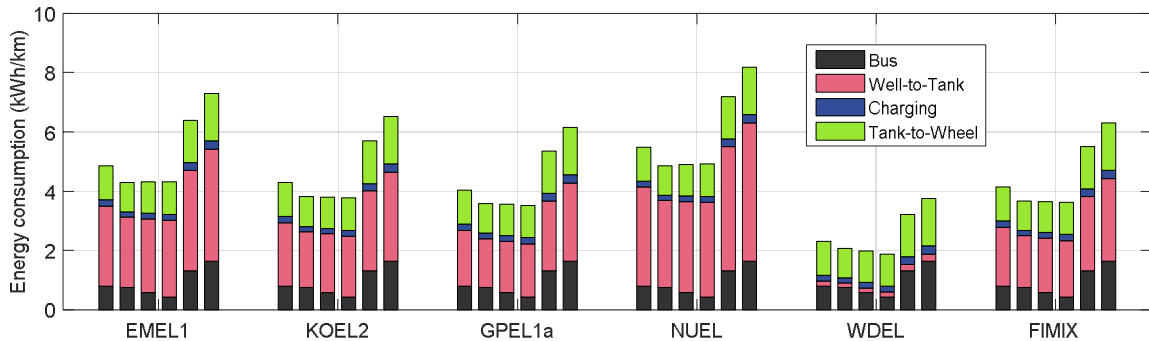


Figure 13: Total energy consumption distribution: different phases of bus lifecycle (EV2).

Except wind energy pathway, all other electricity production pathways have major share of the total energy consumption. On average, the bus manufacturing phase has slightly higher energy consumption than bus

operation (TTW). It should be noted that due to the different distances driven in each operating route during service life, the share of the bus manufacturing phase varies between routes.

4.3 Carbon dioxide emissions

Carbon dioxide emissions were analyzed for six different electricity generation pathways which were described in Figure 3 and Table 1. The CO₂ emissions from bus manufacturing were calculated based on the values presented in [4]. Figure 14 presents the distance specific CO₂ emissions for the different pathways and driving cycles. The Well-to-Wheel phase produces the major share of the carbon dioxide emissions in the fossil fuel based electricity generation pathways EMEL1, KOEL2 and GPGL1a. Because the larger battery in EV2 increases the CO₂ emissions of the bus production and the operation range of EV2 is limited in routes BR, E11, H550 and H3, its distance specific CO₂ emissions are slightly higher in comparison to EV1.

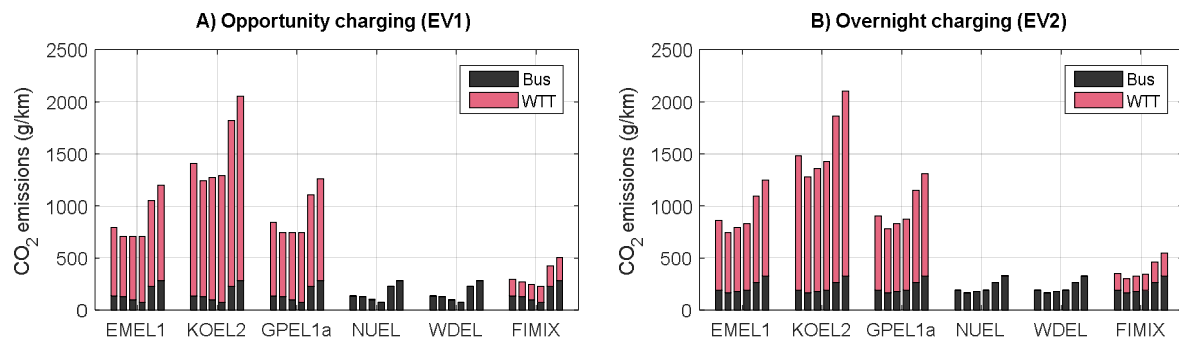


Figure 14: Carbon dioxide emissions from the bus manufacturing and electricity generation.

Figure 15 shows the total carbon dioxide emissions produced in yearly basis for the different electricity generation pathways and driving cycles. Figure 15A presents the bus specific CO₂ emissions and Figure 15B fleet specific emissions. It can be seen that there are about the same differences between the pathways as in Figure 14. The emissions are much higher in the longer routes (H550 and L51B) due to the size of the bus fleet.

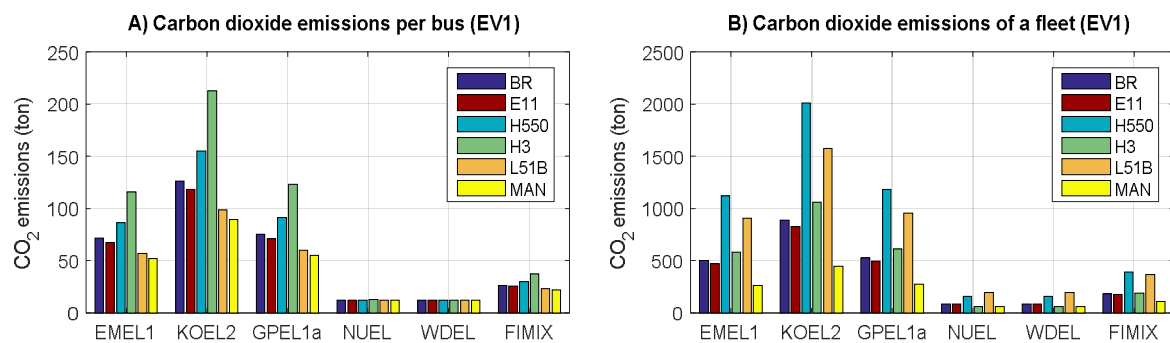


Figure 15: Yearly carbon dioxide emissions.

5 Discussion and conclusions

Electric city buses are considered to be a relevant solutions for energy efficient and emission free public transport. Recent research studies have shown that electric buses have far superior energy efficiency than any other bus technology and they do not produce any emissions in operation. When analysing the global energy efficiency of electric buses, the primary energy sources of the electricity have to be taken into account. Especially in the case of carbon dioxide emissions, the energy pathway is in crucial role as there is no emissions produced in bus operation.

This paper presented an exhaustive analysis of the energy consumption of electric buses in the different phases of the lifecycle. It was shown that there are significant differences in distance specific energy consumption between different operation routes. The evaluation of passenger load indicated that also the driving style has important influence on the energy consumption. The ambient temperature was taken into

account in the calculation of the yearly average energy consumption. It was observed that, on average, the impact of the variation in ambient temperature (cities of Helsinki and Oulu in Finland) was around 10 percent.

The total energy consumed in operation depends on the operating route characteristics. In higher speed cycles, the yearly distance is higher which leads to overall higher amount of total energy per year. The differences between operating routes were observed in fleet operation. The energy consumed in the electricity production was higher for the fossil fuel based pathways whereas it was very low for the wind energy pathway (WDEL).

The carbon dioxide emissions are heavily dependent on the electricity generation pathway. The CO₂ emissions during Well-to-Wheel phase of the lifecycle are multiple times higher in the fossil fuel based pathways (European grid mix, coal and natural gas) than the CO₂ emissions due to the bus manufacturing.

Acknowledgments

The authors would like to acknowledge the technical and financial support from the ECV-eBus project which is partly financed by the Finnish Funding Agency for Technology and Innovations (Tekes).

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