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FAST CHARGING ELECTRIC BUSES IN MARIBOR: A COMPARATIVE ANALYSIS OF SIMULATION AND REAL-WORLD RESULTS

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Abstract. This paper presents a study of the energy consumption of a full electric bus charged at a fast-charging station with pantographs in the city of Maribor. The results of simulated and real tests on the PT line 6 are compared and analysed. The partly electrified PT line 6 provides insights on comparison between simulated energy consumption and real-life energy consumption, charging time and reliability of charging. The results reveal that the simulation considered several important factors like real life turnaround time, driving cycle, regenerative braking, charging time, peak hour charging time, heating/cooling systems, full passenger load as important and critical to identify the appropriate concept for charging. Technical and operational errors were identified in real world, due to connectivity failures or driver errors in positioning the vehicle, which were not considered in the simulation. The real-world data and procedure for selection of the most appropriate charging technology represent a good basis for full electrified Public Transport in Maribor.

Keywords: energy consumption, electric bus, fast charging, simulation, real life data.

JEL Classification: Q42, O18, O33, L94.

Introduction

Several cities in the world are planning and implementing environmentally friendly buses to reduce costs, noise, respectively emissions of the current bus fleet and to increase the image of public transport. For the operation of local Public bus transport with environmentally friendly buses, several planning steps are needed to identify the best solution according to City characteristics, Public transport routes, and timetable. To select the most appropriate technology for electrification, an integrated view from energy and economy dimensions are needed. To support decision-makers, regarding the concept of charging (overnight vs. opportunity fast charging) and appropriate battery size for electric buses (small vs. large batteries) a technical framework for investments is needed. In general cities have different strategies of electrifying PT (Avenali et al., 2023; Papa et al., 2022; Teoh et al., 2018), where three different approaches are the most relevant to choose from:

- small batteries, high power charging;
- large batteries, low power – overnight charging;
- medium batteries, medium power charging.

Regardless the technology the general driver in favor of electrification is that electric buses can contribute significantly to meet EU air quality standards, as conventional buses are major source of air pollution in city traffic. There are different criteria to compare available electric technologies and it varies according to the local conditions of cities. Based on the different implemented projects and scientific literature, every electric technology has some pros and cons (Table 1) and it depends on the local public transport characteristics, which charging concepts is the most feasible. Moreover, most of the criteria are changing over time and it is very hard to say any constant facts for any technology. However, opportunity Battery Electric Buses [BEB] could be the most appealing choice with zero local emissions and a reasonable price tag (García et al., 2022).

To satisfy operational requirements, especially range limitations, Opportunity BEB requires optimal charging installations (Battaïa et al., 2023; Zhou et al., 2023). The Municipality of Maribor [MOM] follows different strategic documents to achieve objectives of sustainable mobility in the municipality. Testing and implementation of electric buses in in line with goals on increasing

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Table 1. Advantages and disadvantages of Batterie equipped buses

	Manual connection	Automatic connection		
	A (plug)	B (Pantograph on the mast)	C (Pantograph on the vehicle roof)	D (Pantograph underneath vehicle)
Advantages	Appropriate for routes with low daily run (up to 100 km)	Small batteries full charge (80–100%) can be achieved within 5–10 min. – minimal needs for maintenance on the vehicle Low-capacity batteries needed – Not heavy batteries	Appropriate for routes and Workshops with lower gauge Possiblities for upgrade to dynamic charging (Trolleybus)	less operating costs compared to gas powered counterparts Lower maintenance and manufacturing costs high efficiency of transfer, in the range of 80–95%.
Disadvantages	High capacity batteries can be very heavy and costly Total cost of ownership is higher than Automatic fast charging Overnight charging allows the bus to run only for 8 hours	requires a higher density of charging points along routes (every 10 km)	Higher operational costs, due to additional weight on the bus	Installation is costly Cannot operate during power outages Can run out of power in heavy traffic 55 Km/H speed limit

user-friendly Public Transport [PT] quality and image. On the other site, this measure also improves the quality of life with less emissions and noise.

There are four forms of public passenger transport in the MOM area: city bus transport, long distance buses, cable car and train. Marprom, which is a public company for city urban passenger transport (City bus and cable car), owned by the municipality of Maribor as the founder, currently covers the activity of passenger transport in MOM with 19 regular bus lines and 2 circular lines. Bus services are carried out in the area jurisdiction of MOM. The length of the lines is from 3 km to 21 km. Most of the transit lines are guided along flat, paved roads where there are no major slopes, except for line no. 20 Grušova.

21 city lines have 230 km of total length. There are 58 buses with a total capacity of 1.614 seats and 2.390 stands. Due to the annual investments in the modernization of the fleet, the average annual age of buses decreased from 11.3 years in 2014 to 8,2 years in 2022. Marprom operates 75 buses and has 162 drivers. On yearly level, 3.57 mio km are made. In year 2022 Marprom had 16 CNG buses (21,3%), 54 diesel buses (72.0%), 4 electric buses (5.3%) and 1 hybrid bus (1.3%). (Marprom Annual Report, 2022).

1. Route based energy consumption model – Technical feasibility

In last year's Maribor invested also in electric buses and charging infrastructure. The idea on electrifying PT bus fleet started in 2016 with Maribor's participation in European H2020 project Eliptic (Electrification of Public Transport and Cities, 2020), where a study entitled "Potentials for electrication Public Transport in Maribor" was elaborated. According to the recommendation from Eliptic project, the best way to start the electrification of PT is by electrifying individual lines and building multifunctional charging points, where several types of vehicles can be charged from one charging station (e.g., buses, battery trains, garbage trucks, cars, bicycles, the lower station of the cable car – the cable car). Regarding the charging technology and city terrain, line 6 in Maribor is the most suitable line for electrification.

Line 6 was chosen as the most suitable bus route for electrification due to:

- the route of the line and the final and the starting station will not change significantly in the future;
- the route line is guided through the center and the friendly zone (according to SUMP of Maribor);
- the final station is located at the lower station of the cable car, which enables the simultaneous use of a substation for multifunctional charging (lower stations of cable car, buses, passenger cars and bicycles). The test of grid stability showed, that there is no need to upgrade the current substation;
- the starting station is at the main bus station, which allows the simultaneous use of the charging infrastructure also for electric buses on other lines;
- possibilities of multifunctional charging at the main terminal (also for garbage trucks);
- the trajectory characteristics prevent charging only overnight (at a range of 150 km for 12 m electric buses, at least 3 more buses are needed to satisfy the current supply);
- the appropriate length of the route and the terminus times (stop times at the terminal and start station) enable fast charging;
- the highway brakes allow for lower consumption for electric buses due to regenerative braking;
- line 6 is among the busiest lines in the city (in 2015 the line is 1 – 652.593, line 6 – 528.910), which provides comfort to a larger number of inhabitants and tourists.

We developed a methodology where energy/technic and economy dimensions are integrated. Methodology includes a model for energy consumption and an assessment of the Total Cost of Operation [TCO] for different battery sizes and charging concepts on a selected PT route in order to define the best suitable charging concept. The developed concepts on choosing the best option for charging and selection of battery size considered charging profile and Battery degradation on a route (Zhou et al., 2022), cost effectiveness with resource assignment and robustness (Avenali et al., 2023; Chen et al., 2023), life cycle CO_2 footprint (García et al., 2022), location of charging and uncertainties (Abdelaty et al., 2023; Hu et al., 2022; Zhou et al., 2023). A mathematical model was developed with the aim of simulating the energy consumption according to different charging options in order to identify technical feasible solutions. The model was set up in 2 phases.

1.1. Phase 1 – Energy consumption in worst case scenario

The simulation of driving according to a standard or actual (measured) driving cycle is the basis for conducting a study of driving energy conditions in order to determine the energy consumption of an electric vehicle battery for the needs of the powertrain (S. Wang et al., 2023). The actual (measured) driving cycle was used to drive the bus along the route on line 6 – Vzpenjača (from the main bus station to the lower cableway station below Pohorje). The speed profile of the driving cycle consists of two components, the speed profile and the height profile (ascent) as a function of time (Hasan et al., 2023).

The behavior of the vehicle along the direction of travel is fully determined by the description of the magnitude of the forces in that direction. The drive unit generates a tractive force (traction force) Ft to move the vehicle forward over the entire drive train and wheels. During the movement of the vehicle, a drag force (rolling and air resistance), which opposes the movement or attempts to stop the vehicle, and a downward force occur. According to Newton's Second Law and the breakdown forces of resistance, the movement of a vehicle is determined by the following law:

$$m\frac{d}{dt}v(t) = F_t(t) - \left(F_r(t) + F_w(t) + F_g(t) + F_b(t)\right),$$

where are: $v(t)$ vehicle speed; $F_t(t)$ traction force; $F_r(t)$ rolling resistance force; $F_w(t)$ air drag force; $F_g(t)$ propulsion component to overcome gravity at uphill driving; $F_b(t)$ mechanical brake force; m the total mass of the vehicle in running order, including the inertia of all rotational parts, including the translational masses.

Based on these principles and the characteristics of the vehicle, a mathematical simulation model of the vehicle was created in MATLAB / Simulink. If all parameters are known, the model describes the behavior of the vehicle while driving very precisely. Such a system also makes it possible, by changing the parameters, to investigate special conditions that either do not occur frequently in real driving (e.g., the worst-case scenario "worst case") or are difficult to measure.

A review of the estimation methods of energy consumption for battery electric buses identifies simulations with real driving cycle data as one of the most appropriate methods for estimation of energy consumption (Al-Ogaili et al., 2021). We used the parameters of a typical commercial electric bus as a basis for the mathematical model of the vehicle. The propulsion system uses a lithium-ion battery and a synchronous PM electric motor with the associated electronic converter.

The analysis was performed based on driving in a real driving cycle recorded with a GPS device on line no. 6 – Vzpenjača:

- Mb AP – Vzpenjača Pohorje (l= 7,765 km, Δh = 54 m);
- Vzpenjača Pohorje - Mb AP (l= 7,765 km, Δh = –54 m).

The basic technical characteristics of the selected electric bus are as follows:

- l = 12 m,
- m = 15.000 kg (empty bus);
- M = 22.500 kg (including 100 passengers);
- nominal power of the traction motor P = 200 kW;
- regenerative braking Preg_max = 75 kW;
- heating mode: gas heater;
- cooling mode: air conditioner with heat pump max. electric power 10 kW, battery power.

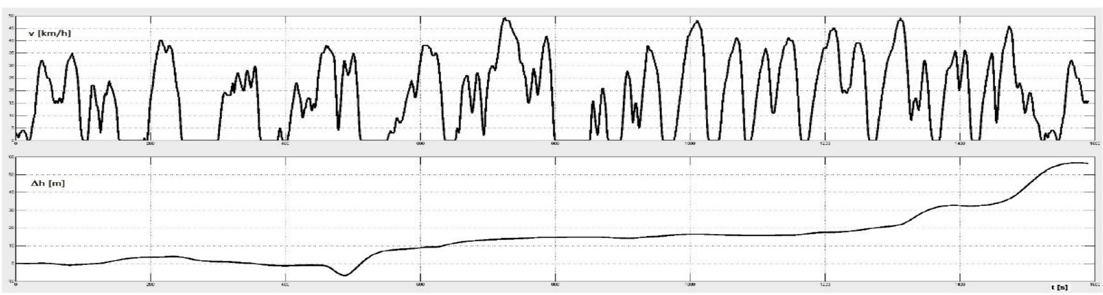

Figure 1. Driving cycle (upper curve, [km / h]) and altitude [m] of driving buses on line 6 (Vzpenjača) in the direction from the main bus station towards Pohorje

The goal of simulating driving according to the standard, or actual (measured) driving cycle is to determine the consumption of energy from the automotive battery for the needs of the drive assembly. The actual (measured) driving cycle for driving a bus on line 6 was used (from the main bus station to the lower station of the cable car under Pohorje). The vehicle energy is stored in two forms while driving, namely as kinetic energy depending on the driving speed and as potential energy relative to the ascent of the vehicle up to a certain height. As influence of data interpolation on the accuracy of electric bus driving cycle is important (X. Wang et al., 2023), the interpolation was done according to 1 second time interval of speed and altitude.

The example of energy consumption when driving a bus applies to the "worst case": complete bus with 100 passengers, journey from Maribor to Vzpenjača (distance 7.77 km and 55 m gradient), constant cooling capacity 10 kW, in this case the distance driven from Maribor bus station to Vzpenjača amounts to a total energy consumption of 19.2 kWh.

The graph (Figure 2) shows all components of the energy consumed when operating a bus on the Mb - Vzpenjača (for worst case):

- ΔW – total electricity consumed from the battery (red);
- W_{pogon} – traction energy used to drive the vehicle (blue);
- W_{pot} – potential energy used to overcome the climb (green);
- $W_{aircond}$ – energy used to cool and heat the vehicle (brown).

Table 2 shows the values of the energy consumption of the electric bus in both directions, from the bus station "to" to Vzpenjača, and in the opposite direction. There is also a simulation with different values of the operating power of the refrigeration unit, from 0 kW, 5 kW to 10 kW. It turns out that the energy consumption for the same route can be very variable, from 0.89 kWh / km under the most unfavourable conditions to 2.47 kWh/km.

Table 2. Energy consumption per different power of air conditioning/heating

Aircondition power $P_{AirCond}$ [kW]	Energy consumption (Line 6, direction: Maribor – Vzpenjača)		Energy consumption (Line 6, direction: Vzpenjača – Maribor)	
	[kWh]	[kWh/km]	[kWh]	[kWh/km]
0	14.79	1.9	6.94	0.89
5	17	2.18	9.15	1.18
10	19.21	2.47	11.36	1.46

1.2. Phase 2 – Technical feasibility on a daily basis

In order to select the optimal configuration of the system components with the aim of effectively driving the vehicle in public transport, a full-day simulation of 14 round trips with associated stops and battery charging was performed.

An analysis of the amount of energy in a battery set during the ride and the all-day charging was performed under the following assumptions: An analysis of the amount of energy in a battery pack during the journey and the all-day charging was carried out with the following assumptions:

- Real driving cycles were used for the simulation (bus tracking was recorded with the GPS device),
- the measured stops are realistic, measured under different conditions,
- The stops at both end stations are used to charge the battery,
- both pantograph filling stations are installed at both end stations,
- In the simulation it is possible to calculate different values of the power of the Ppoln charging station, the size of Wbat_max and the initial
- State of charge of the Wbat_Start of the battery,

The simulation was carried out for a typical all-day cycle with a bus on line no. 6 – Vzpenjača, consisting of 14 return trips 14 × [(Mb AP – function) + jam + (function – Mb AP) + jam],

The study was carried out for the worstcase scenario, i.e., a realistically measured daily driving cycle with few successive load failures was chosen, the maximum number of passengers and the increased cooling consumption (10 kW) were considered.

The graph in Figure 3 shows an example of driving an electric bus in a timetable without delays with normal stops and consequently efficient charging. The energy/charge of the battery is therefore at a high level (between

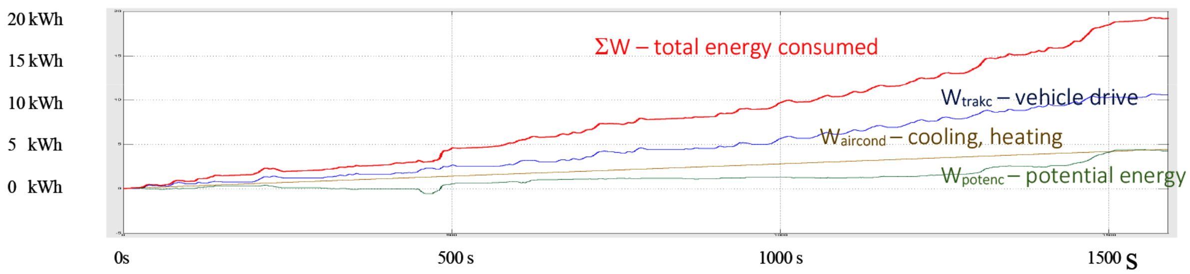

Figure 2. An overview of the energy consumption by component when driving from the Mb – Vzpenjača

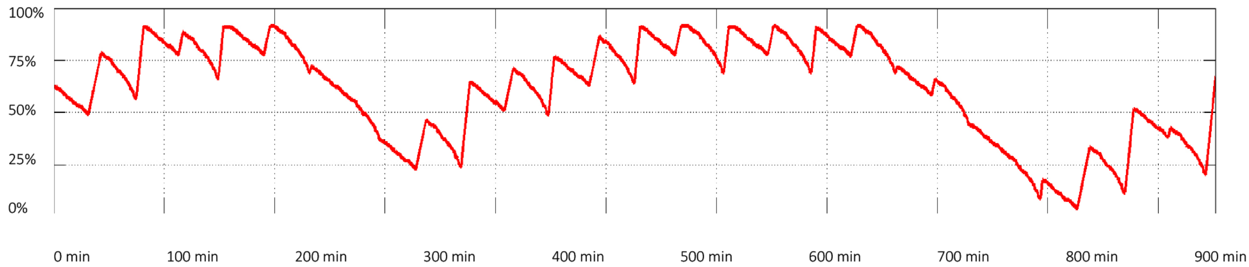

Figure 3. An example of simulation results with amount of energy in 100 kWh battery with 200 kW fast charging on both end of the route and real-life turning data

80% and 100%), which ensures a high level of driving safety.

Many (several dozen) simulations have been performed to analyze the appropriate battery size and performance of the charging station. Below are some examples of the results of the most unfavorable simulations. In the worst case, they differ in the combination of battery size (energy content in kWh) and charging station power kW.

The results of the simulations show that for the existing schedule the different technical solutions are feasible:

- Large batteries with no fast charging (4 diesel buses are to be replaced with 7 overnight charging buses with battery capacity over 450 kWh).
- Medium batteries with medium charging (4 diesel buses are to be replaced with 4 e-buses with minimal battery capacity of 150 kWh and minimal charging capacity of 2×150 kW).
- Small batteries with fast charging (4 diesel buses are to be replaced with 4 e-buses with minimal battery capacity of 100 kWh and 2×200 kW fast charging).

2. Route based energy consumption model – Economic feasibility

The charging station must be able to transfer enough power to replace all the energy consumed by the battery during the charging process. The results showed different consumptions, when considering basic vehicle characteristics (weight, air resistance, rolling resistance, power traction, Tyre pressure), PT route characteristics (hilly terrain, driving cycle), changing factors of power for regeneration, power for heating, passenger load, electric heating, low temperatures). Different conditions provide the possible range of consumption on line 6 from 0.5 kWh/km in optimal conditions and relatively high consumption was calculated in extreme conditions (2.4 kWh/km). 9.55 kWh was calculated consumption for one run up (Maribor AP – Maribor Vzpenjača) and 4,4 kWh for one return (Maribor Vzpenjača – Maribor – AP) on line 6 on normal days. Results show, that the heating system can increase the consumption up to 30%, which was also researched by Chiriac et al. (2021) and Čulík et al. (2021). The following TCO parameters were considered when calculating the costs of replacing diesel buses with electric buses (Jefferies & Göhlich, 2020; Kim et al., 2021; López et al., 2022):

- vehicle costs (acquisition costs, annual inflation rate, discount value, option co-financing),
- battery costs (cost, inflation rate, expiry date, discounted value, co-financing),
- costs of the charging station (costs, inflation rate, discount value, ratio between the number of electric buses and the number of charging stations, the additional costs of modernizing the charging station, preparation of documentation, construction works),
- Costs of energy consumption (Based on the simulation we considered 1.6 kWh/km for TCO calculation. electricity price, forecast price increase),
- other costs (maintenance),
- technical parameters (average consumption kWh/km), battery efficiency, charging efficiency station).

The basic TCO – Total Cost of Ownership method must be used for the basic driving of a diesel-powered bus in an electrically powered bus.

Based on the Total Cost of Ownership methodology (EUR/pkm), which took into account the number of busses, the initial investment (battery, infrastructure, purchase of new vehicles), the annual kilometres travelled, occupancy rate, maintenance costs and other costs (energy, environment, noise), we compared a diesel-powered bus and an electric bus. The calculation used examples combining the size of the batteries and the power of the chargers:

- Example 0: Diesel drive (current state);
- Example 1: 100 kWh battery, 200 kW charger;
- Example 2: 150 kWh battery, 150 kW charger;
- Example 3: 200 kWh battery, 150 kW charger.

We used the following equation to calculate TCO:

$$TCO = \frac{\left(sum\ of\ the\ costs\ over\ a\ period\ of\ 12\ years\right)}{\left(number\ of\ km\ traveled\right)\times\left(maximum\ number\ of\ passengers\right)\times\left(occupancy\ factor\right)}.$$

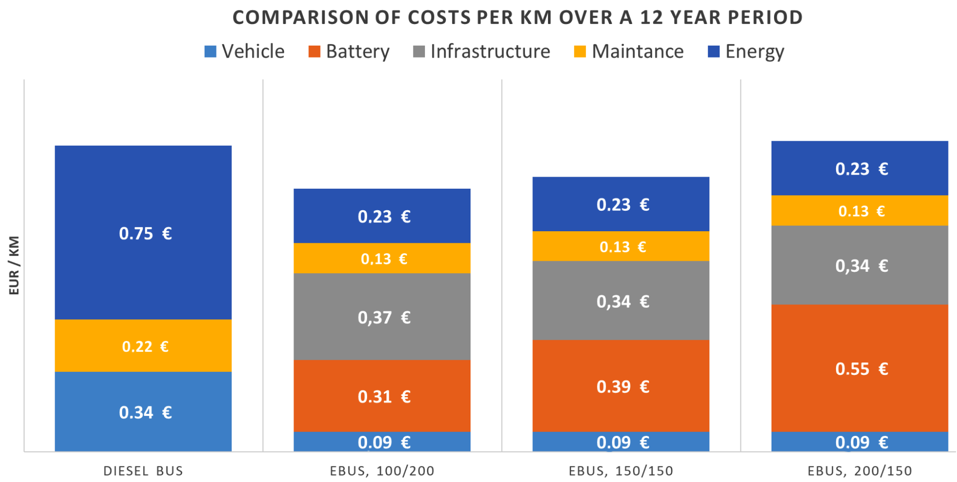

Figure 4. Comparison of costs per km (Deliverable D.T1.2.1. EfficienCE, n.d.)

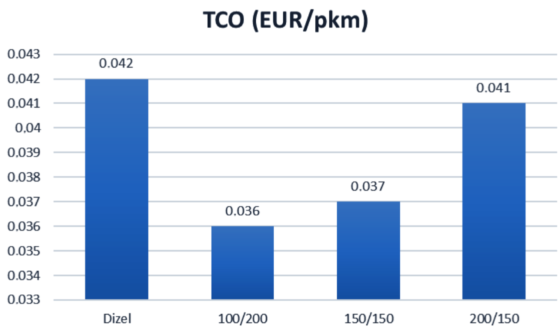

Figure 5. Comparison of TCO (€/pkm) (Deliverable D.T1.2.1. EfficienCE, n.d.)

According to the methodology, the total operating costs are as follows:

- Present situation: diesel bus – 0,042 EUR/pkm;
- Example 1: 100 kWh battery, 200 kWh fast e-charger, purchase of five electric buses and three chargers – 0,036 EUR/pkm (14,3% improvement compared to the current situation);
- Example 2: 150 kWh battery, 150 kWh charger, purchase of five electric buses and three chargers – 0,037 EUR/pkm (11,9% improvement compared to the existing situation);
- Example 3: 200 kWh battery, 150 kWh charger, purchase of five electrically powered buses and three chargers – 0,041 EUR/pkm (2,4% improvement compared to the existing situation);

Depending on the different charging technologies, the opportunity charging at the end and at the beginning of line 6, as well as over-charging in workshops was identified as the best option.

3. Comparison of simulation and real-world data

In June 2022 2 fast chargers with power 150 kW and 300 kW were installed on the start and the end of the route 6 in Maribor (Figure 6). Additionaly 212 m e-buses with LTO battery capacity 77 kWh were full functional.


Figure 6. Opening ceremony of introduction of e-bus fast charger in Maribor (June 2022)

The main goal of replacing two diesel buses with electric buses with fast charging equipment was to lower the emissions and also cost for operation. Table 2 represents the comparison of simulated data/KPI, that was calculated before implementation, Real situation with diesel buses and measured data/KPI after implementation of partly electrified route 6 in Maribor.

When comparing real-life data with simulated data several Key performance indicators were estimated as in reality, while indicators on disruptions of charging connectivity were neglected. Nonetheless, the comparison of simulated and real-life data shows the similarities between real life data used for the mathematical model and real-life data from the measurements in the field.

In the category of energy, the proposed concept in simulation with 100 kWh batteries and 2 *200 kW power of fast charger was realised with a little different configuration, due to the manufacturer's specifics and availability of the technology on the market. Municipality of Maribor decided to prepare two different tenders, one for fast chargers and one for e-buses, due to ensure multifunctional and multimodal charging of fast chargers (suitable for different manufacturers of e-buses and in the future also suitable for garbage/delivery trucks).

In regard to consumption the selected solution of e-buses in real life does not include electrical heating, therefore the energy consumption is comparable with

Table 3. Comparison of simulated and real-life data

Category	Indicator	Unit	Simulation	Real -situation zero – diesel bus	Real – with fast chargers
Energy	Battery size of buses	KWh	100	–	77
	ower per Fast charger	KW	2×200 kW	–	150/300 kW
	Energy consumption per bus (average)	KWh/km	1.6 (for cost comparison) 1.4 (worst case – no heating)	3,9	1,2
Operation	Dwell time of a bus (average at the end stop)	Seconds	426	426	323
	Charging time (average time)	seconds	320	–	255
	Number of bus charges	Number/day	29	–	29
	Pasenger capacity of a PT mode	Number	100	32 + 72 (104)	(32 + 72) 104
	Reliability of charging equipment	% of failures per day	–	–	11.1%
Environment	Emmisions	CO_2 (t/year) per route	192	380	
Costs	Energy consumption cost per bus (average)	€/km	0.23	0.75	0.22

the simulated. The main challenge in real life represents the timetable, as in morning and afternoon peak hour, the charging on some end stops is not possible, due to keeping the timetable. Additionally, the conversion factor for a diesel bus: 1 litre of diesel equals 10.96 kWh was considered. By implementing a fast-charging station and purchasing two buses, Maribor saved 340 000 kWh (10 month in operation) and reduced the energy consumption of the entire vehicle fleet by 1.7% since their introduction.

In the operation category errors due to charging process in the e-bus were not considered in the simulation phase. Most of the errors occurred during the charging process, which is due to the wrong placement of the bus under the charging station. Other errors were identified in communication failures between fast charger and e-bus. In the implementation period (June 2022), there were the most errors, 22.3%, due to the need to calibrate the contact slide.

Based on calculation the full electrified bus line 6 will produce yearly 190 t less Co2 emissions than line 6 with 4 diesel buses. Noise emissions were reduced by 30%, while energy costs were reduced by up to 70%. ROI for the fully electrified Line 6 is planned for 8 years. Based on the pilot project and calculations, Municipality of Maribor expects to increase the number of electric buses from 5% to 50%, decrease TCO for 25%, decrease the noise and emissions of PT by 20% and increase RES IN PT to 25% till 2030.

Conclusions

The comparison reveal that the simulation considered several important factors like real life turnaround time, regenerative braking, charging time, peak hour charging time, heating/cooling systems, full passenger load as important and critical to identify the appropriate concept for charging. Especially implementation of real-life driving cycle with real life turnaround time in the simulation was identified as crucial regarding minimal technical feasibility for the battery capacity and fast charger power. According to ideal condition with no delays in traffic and within optimal weather conditions, where no heating is needed, a very small battery of 20 kWh on buses would satisfy the needs for this route. As, due to traffic conditions in peak hours, the buses do not start their departure according to the timetable, the fast charging in these periods is not possible, the simulation showed, that there is a need for bigger battery capacity to maintain the minimum 20% threshold of the battery. Real life energy charging revealed that the fast charging at the fast-charging station begins when the amount of energy in battery is lower than 74% according to manufactural requirements in order to prolong the battery lifetime.

In city bus transport the neglected area represents the regenerative braking. According to simulation the regenerative braking represents the savings with potential energy and braking at junctions and stops. 47 % more energy is consumed on the uphill route in comparison to the downhill route. Although hysteresis effect is to be considered, there is a potential of approximately 5 kWh per route to be regenerated from regenerative braking. In real life this measure is to be upgraded with eco driving skills of the drivers and technological support of driver's deceleration/regenerative braking with monitoring/warning systems. The regenerative braking affects the most in full passenger load situation, as higher mass of the vehicle effects on bigger regenerative power.

Regarding charging time, the simulation considered the manufacturers data on connection time and time for lowering the pantograph, when starting the charging process and time for stopping the charging and lifting the pantograph. In real life the charging time was not identical as technical and operational errors were identified, due to connectivity failures or driver errors in positioning the vehicle. These errors were not considered in the simulation.

Additionally different heating and cooling consumption alternative were simulated. As heating of the buses can represent up to 40% of energy consumption in very low temperatures, an e-bus with no heat pump was procured to fulfil the energy consumption needs of the buses on PT Route 6.

The real-world data and procedure for selection of the most appropriate charging technology represent a good basis for full electrified Public Transport in Maribor. Based on the experience from route 6, Maribor plans to electrify half of its bus fleet till 2030. The proposed methodology can be transferred to other routes, where electrification and fast charging is needed. Electrification is to be in line with the new route network plan, which is under development. In order to lower consumption of e-buses and to increase the PT image also measures for prioritization of bus traffic in junctions. Alternative concept for the future is also consideration of testing/introduction of in motion charging of local and regional busses through a hybrid trolleybus network and integration of charging with railways. Maribor has the plan to establish mobility and logistic hubs in combination with modern energy and mobility concepts (RES (photovoltaic), e-car sharing, e-bike (cargo) sharing, e-vans sharing, etc.) in order to achieve maximum potential of local energy production (Dougier et al., 2023). As electric bus transport represents managerial change in monitoring, managing, operating and maintaining, future management measures include intelligent monitoring, change management, innovative procurement processes, legal measures for the sale of electricity from public facilities to private users, data management (urban data platform). Additional risks that were identified during implementation of fast chargers are:

Technical risks related to compatibility/interoperability between different technology providers (not all interoperability standards are available (e.g., between fast chargers and e-buses).

Operational risks due to delays (e.g., detours due to construction, peak hour) or long boarding times for passengers. Charging e-buses with opp fast chargers requires on-time operation of the buses according to the timetable. If operation is delayed, there is a serious risk that the bus will not be charged with enough energy to operate for the entire day. Measures that impact on-time performance, reliability, and faster PT service (e.g., bus priority, open boarding) must be considered in parallel with electrification implementation.

Legal/implementation risks exist related to the sale of electricity from PT to private users. An additional risk is the need for environmental impact studies (e.g., hybrid trolleybuses charged through the rail network), which may prove too complex and lead to higher technical (standard) requirements, which in turn may lead to higher costs or cancellation of the investment.

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Contributions

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Disclosure statement

Authors declare that there is no competing financial, professional, or personal interests from other parties.

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