Is electric bus the only way?

Looking at hybrid trolleybuses as a path for more efficient electrification of public transport

Piotr Kargul
Aalborg University Copenhagen

AALBORG UNIVERSITY
COPENHAGEN

Aalborg University Copenhagen
A.C. Meyers Vænge 15
2450 Copenhagen SV

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Jesper Ole Jensen

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Piotr Kargul
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Abstract:

Electric vehicles in public transport, despite higher costs compared to ones with internal combustion engine, offer significant environmental and social benefits, and directly meet climate goals. Their implementation is therefore necessary and urgent. The remaining question is to select the most appropriate type of vehicle. Electric buses are gaining ground in the last time more and more implementation cases. However, due to operational limitations and thus increased costs, electric buses have difficulties in achieving the required scale of implementation. In turn, trolleybuses that do not have these limitations are associated with the need to build expensive traction infrastructure. Therefore, the concept of in-motion-charging and hybrid trolleybus has emerged. This paper examines their feasability and potential. Based on the experience of the considered network in Berlin-Spandau, the paper makes a critical discussion of the data found there. Considering both the economic viability in terms of lifecycle costs and environmental sustainability, it was possible to confirm that the hybrid trolleybus is a profitable solution and can be recommended for the default electrification of the public transport network.

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Problem formulation

In this first part of this report, introduction to the topic will be presented, which concludes in formulating research question.

Background

Currently observed climate changes pose possibly the greatest challenge for the world in the human history. Global consensus reached by majority of world countries, effected in, among others, Paris Agreement and its objective to keep the global temperature increase to well below 2°C, has clearly depicted need for drastically intensify ongoing efforts to reduce emissions of greenhouse gases (GHG), especially CO2, in order to slow down global warming effect, thus reduce detrimental impacts of the climate catastrophe. European Union has set binding goal of reducing its GHG emissions by at least 40% below 1990 levels by year 2030 (European Commission 2014) and announced an ambition to become climate-neutral by the year 2050 (European Parliament 2019).

Transport is one of the sectors identified as significant contributors to global GHG emissions, thus strong action measures are needed and public intervention is called.

In 2017, 27% of total EU-28 greenhouse gas emissions came from the transport sector, 22% excluding international aviation and maritime emissions (European Environmental Agency 2019). Emissions from road transport observed 23% increase in greenhouse gas emissions over 1990 levels and accounts for majority of emissions generated - almost 72%.

Moreover, with road transport the problem of air pollution and noise is associated. Exposition to, among others, NOx and PM pollution have significant health effect for citizens. OECD (2010) estimated that in EU-24, road transport share of economic cost of health impact from ambient air pollution 550.000 euro yearly. Noise from traffic can also have negative health effects, increasing the risk of cardiovascular diseases and being the main cause of sleep disturbance and annoyance in Europe corresponding to more than one million disability related life years. Those effects can be notably observed in urban areas, whereas concentration of both people and traffic takes place, exposing bigger parts of population to more intensified harmful impacts. As most of global population currently lives and will be living in cities, this presents as an important issue to tackle.

Most vehicles used in transport are powered based on internal combustion engines using fossil fuels, directly contributing to the CO2 emissions. As phasing out use of fossil fuels is primary cutting GHG emissions, the key solution to fossil-free transportation are electric vehicles (European Commission 2011). Electrifying transportation is therefore a fundamental mean of action towards reaching climate goals. It has to be noted, that reduction in GHG emissions comparing to diesel (petrol) vehicles will vary according to country owns energy mix. However, even in carbon-intensive european markets a significant positive climate impact of electric vehicles can be observed (Messagie 2014), portrayed on Figure 1.

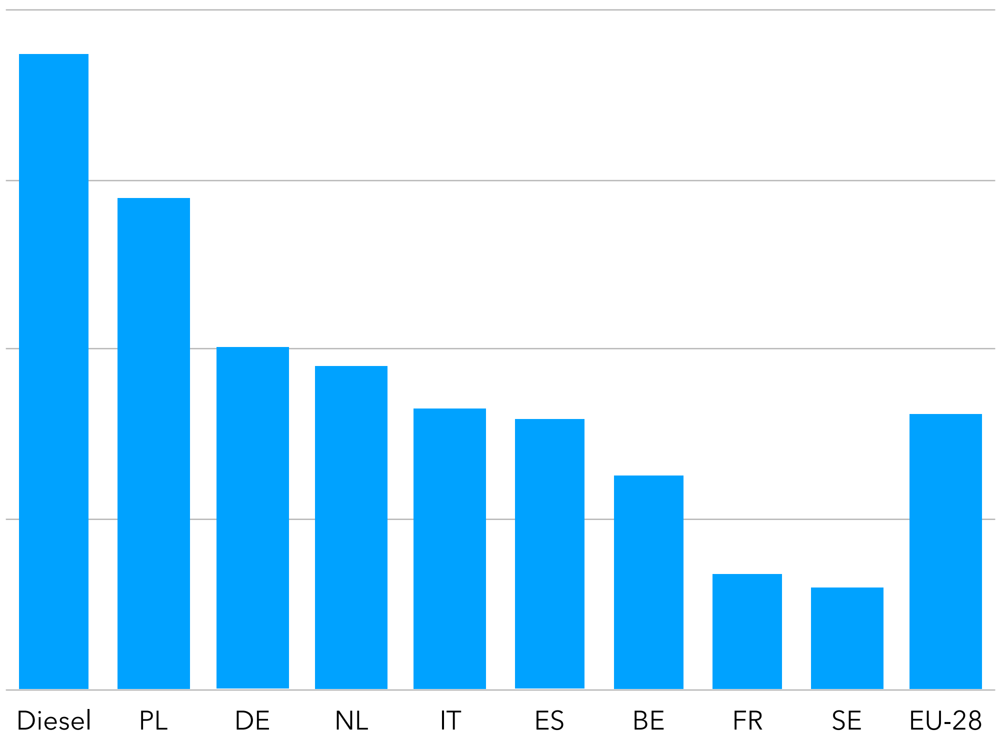


Figure 1. Electric vehicles' climate impact in different energy mixes (Messagie 2014)

Electrification of public transport

Public transport is a fundamental element in achieving sustainability in transportation. Although majority of GHG emissions are produced by cars (European Environmental Agency 2019), simple replacement of current diesel (petrol) cars by electric cars wouldn't solve other important in urban areas problems, such as congestion, space scarcity, etc.; a comprehensive sustainable urban mobility policy is needed. Also implementation of electric vehicle technology on a wide scale and in relatively short time as stipulated in climate ambitions, seems difficult in private road transport; it is the public transport which offers here much superior potential for considerable market penetration of full motor electrification (Mahmoud et al. 2016). Looking at the overall impacts, it would take roughly 100 electric cars to achieve the same environmental relief as can be gained from one 18 m electric bus. (Glotz-Richter, Koch 2016). This is especially true in context of urban buses; despite ongoing efforts to expand rail-bound transport systems such as trains, metros and trams, most of the collective transport system are and will rely heavily on buses. Bus is a primary mode of public transport in most towns and cities. For example, in England the number of journeys by bus accounts for 60% of all public transport journeys (UK Department for Transport 2018). In large metropolitan areas this share can be even higher, for example in Liverpool City Region it is 80% (Merseytraavel 2016). Looking globally, bus systems are accounting for 80% of all public transport passenger journeys worldwide (UITP 2010). Given the scale of use, it is instinctive to look at a context of the GHG emission. It is a fact that majority of buses driven globally use internal combustion engine as its propulsion system, and diesel is by far the most popular fuel used (UITP 2019). 50% of all bus fleets uses diesel, and further 22% uses diesel with some additives or biodiesel. Overview of propulsion systems used in bus globally is shown on a Figure 2.

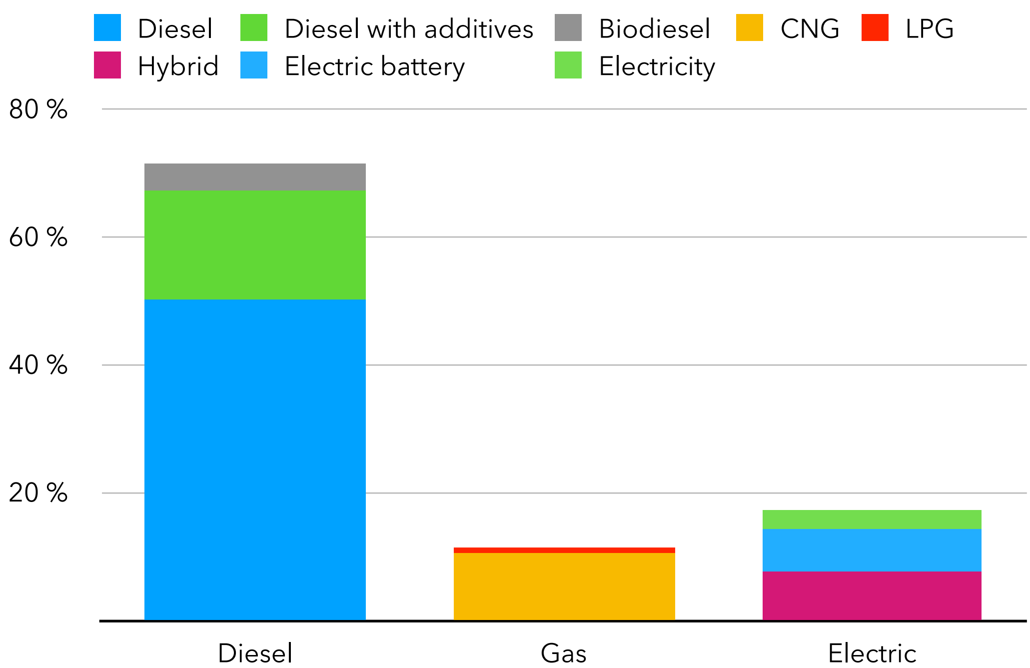


Fig. 2. Bus propulsion systems (UITP 2019)

In connection with propulsion system, carried emission standards are undesirable. Effective from 31.12.2012, current European emission standard for heavy-duty diesel engines is Euro VI; only 15% of buses uses this norm. Almost half of global fleets presents norm of Euro IV or lower (UITP 2019). This shows that buses has substantial role not only in terms of GHG emissions, but as well local pollution.

Presented numbers make it therefore apparent, that bus systems has to be one of the main areas of climate intervention; the potential scale of effects of electrifying bus systems seems significant. Electric vehicles are identified as crucial solution towards fulfilling fossil-free public transport, as well as, they can be considered a stepping stone towards full sustainability (Borén & Ny 2016; Robèrt, Borén, Ny, & Broman 2017).

Electric bus as a solution

The basic characteristic of electric vehicles is that the propulsion energy is derived from an electric traction drive system, that is using electric motor instead of an internal combustion engine. That means powering buses using electricity instead of diesel, providing a possibility to limit use of fossil fuels, thus significant environmental benefits, especially in terms of GHG emissions. The environmental benefits of electric powertrains are promoted as the main motivation for the electrification of mobility choices (Živanović, Nikolić & Stevic 2012). Several life-cycle assessment studies have found that life-cycle environmental impacts are lower from electric buses than from buses with internal combustion engines, particularly if they are powered by renewable electricity (Borén 2019). However, as indicated before, for EU market and its energy mix, electric vehicles can provide on average reduction in emissions by more than a half, comparing to diesel (Messagie 2014), see Figure 1 before.

Independent from electricity production, electric buses has zero local emissions. They drive is basically pollutant free (no emissions from propulsion system). This has remarkable importance in dense urban areas with increasing air pollution, especially along bus routes. Another significant benefit for local environment is significantly quieter work of an electric motor. That allows for noise reduction, which, again, is especially important in dense urban areas. Study in Karlskrona showed that an electric bus generates about 5 dBA less exterior noise during acceleration compared to a diesel bus, and 7 dBA less compared to a biogas bus (Borén 2019).

Apart from environmental and health benefits, electric traction offers also benefits from operational perspective. The engine configuration of this technology does not include any mechanical parts. That means slower wear-off of materials, benefiting with prolonged vehicle service time and lowered environmental burden, and reduced maintenance costs, comparing to traditional buses, even by 25% over 10 year operation period (Borén 2019). Lack of movable parts means also no vibrations during operation, contributing to noise reduction and more comfortable drive. Also electric braking reduces use of friction elements (prolonging use time) and possible usage of recuperation can reduce energy demand. Lastly, electric motor is characterised by favourable traction characteristic and higher energy efficiency comparing to diesel engine - same amount of energy used allows for performing more power in case of electric motor. Electric motor allows also overloading, which in turn enables higher acceleration and easier uphill performance.

Discussed advantages of electric buses over traditional (diesel) buses can be summed as follows (Varga, Iclodean & Mariasiu 2016, edited):

- reduction in GHG emissions, independence towards fossil fuels;
- lack of local pollutant emissions, zero emission operation;
- silent and vibration-free functioning, reduction of the noise pollution,
- high energetic efficiency, decreased energy use;
- lack of mechanical parts, lower maintenance.

Overall, electric buses are proved to provide substantial savings in societal costs and total cost of ownership when compared to diesel and biogas powered buses (Boren 2019).

Technology penetration

Electric bus is becoming more significant globally - UITP assess that currently around 17% of bus fleets are electric (2019). However this number includes different electric bus technologies, including:

hybrid electric vehicles, which use both electrical motor and internal combustion engine,

battery electric buses (BEB), which are powered autonomously from electricity that is stored in an on-board battery package,

and trolleybuses, which are also powered by electric motor, but electricity is supplied through a contact line from external electric sources.

Hybrid buses, for using internal combustion engine, cannot be regarded fully as electric vehicles. They have been proved not providing a significant reduction in GHG and cannot be considered viable long term solution for fulfilling climate objectives (Mahmoud 2016), therefore are not included in the course of this report. Presented in previous chapter, characteristics of electric bus technology are naturally true for both BEBs and trolleybuses, however for the purposes of this project, from now on in this report the term «electric bus» will be associated with BEB.

Although battery electric buses has been known for long time (Li 2016), only for last decade this category have received substantial attention. Thanks to the strong development of the electric power storing systems (batteries or capacitors) and increasing pressure on electrification of public transport due to ecological concerns, they has been the center of attention of the public transport operators and bus manufacturers (Varga, Iclodean 2015). In the last years, we therefore observe the rapid growth of the battery electric bus market. Quite remarkably, China has become the pioneer of operating electric buses reaching 57% share of its fleet. Noticeable penetration also can be observed in Romania (22%) and France with the UK (18%)

(UITP 2019). Interestingly high dynamics are reported in countries like Poland or Russia, where specific «boom» of electric buses can be observed. In Poland only from beginning of 2018 has introduced 183 electric buses; ending first half of 2020 with a total fleet of 269 vehicles. 435 further buses will be delivered by the end of 2022 (InfoBus 2020). In many cases however, those adoption cases, although serving, at least partially, its environmental and social health objectives, make little or none economic case, mostly due to technology limitations. Symptomatic in this context can be case of Moscow, which just recently phased out an entire fleet of trolleybuses in favour of battery electric buses, regardless of cost and at least doubtful environmental effect. Other Western European operators and authorities, notably from Germany and Czechia, are more reluctant with procurements of a larger scale. For instance, some bus operators in Sweden are hesitant to include battery electric buses in their fleets because of uncertainties regarding energy use, charging infrastructure, and initial costs for the new technology (Boren, Nurhadi, & Ny, 2016). Those are not unbiased reservations and limitation of battery electric buses will be covered in the following chapter.

Uncertainties and limitation of battery electric buses

Overall, main issues with electric buses can be identified as: low operational range, high cost of introduction and uncertainties connected to operation. Below those aspects will be discussed in detail.

Operational feasibility

The basis of functioning of electric buses is fact, that they do not have a continuous power supply nor they generate electricity onboard. Energy needed for operation is stored in the battery, which must be carried on the vehicles themselves. The energy density of batteries is rather low compared to diesel or hydrogen (Rogge, Wollny & Sauer 2015). Stored energy needs to be supplemented in course of operation by charging. There are two main charging methods popularised in the industry at the moment (Olsson at al. 2016):

overnight (slow) charging, performed in depots, this is slow charging (typically 40–120 kW) taking normally couple of hours using usually plug-in chargers;

opportunity (fast) charging, performed at the endpoints or at the bus stops using fast high power chargers (usually between 150 to 500 kW), recharging the bus during operation; charging takes usually from 30 seconds to dozen minutes, depending on applied power, and uses at large, conductive systems with automated pantographs.

Independence from the energy supply lines achieved by batteries, provide relatively large autonomy of operation, comparable to one of traditional diesel bus. However, said autonomy is limited by batteries. Capacity of batteries determines the operational range of electric buses (Živanović, Nikolić & Stevic 2012). For example, the reported battery capacity varies from 60 to 548 kWh, with the most typical capacity levels in the 200 - 300 kWh range (Gao et al. 2017). Range of diesel buses is typically much greater than 300 km - up to ca. 800 km. Electric buses cannot pass this level, achieving average range of 70 - 250 km, 25–65% less than that of diesel buses, which means that it is difficult to operate them continuously without recharging (Mahmoud et al. 2016). Using slow charging, amount of energy stored in the battery must meet amount of energy needed for electric bus operation. That requires large and heavy batteries to store enough energy. To illustrate that, Göhlich, Kunith & Ly (2014) indicate, that for chosen bus line in Berlin, the battery meeting required capacity, assuming using a Li-Ion battery with 110 Wh/kg specific power, would weight 6 tones! Such additional payloads are unacceptable for buses, as would drastically limit passenger capacity. In general then, currently available batteries are mostly not sufficient for whole-day service of an average bus line (Li 2016). Buses can only serve parts of expected schedule before they would need to come back to the depot for charging. This leads to much lower vehicle availability of electric buses, reported at 70% (Lajunen 2014). That means that more vehicles are required in the fleet to offer the same level of service, increasing significantly costs of service for public transport operators. Additional costs incurred, makes up not only cost for extra vehicles and energy, but also cost for employing additional drivers, which is usually very high. For example, in Sweden usually accounts for more than half of the total cost for bus traffic (Borén 2019).

Opportunity fast charging can possibly extend operational range of electric buses, allowing for more traditional operation consistent with that of a conventional diesel bus. That is achieved by continuously recharging the battery during service, essentially toping-up the energy. This is done at the charging stations on the route. Batteries needs to be designed to allow receiving high charging power, required to charge the battery over a short time period of time. Around 44% of electric buses in Europe uses this charging method (ZeEUS Project 2018). Opportunity charging requires less energy to be stored in the bus, which can reduce the battery capacity and therefore the weight significantly.

However, the bus schedule must provide sufficient charging times at charging locations. A lot of public transport systems has turn-around recovery time at the end of each route incorporated into timetables. This is to provide a robust timetable so that any unforeseen delay can be accommodated. Even if a bus arrives a bit late, it can still leave on time for the next departure. Milles and Potter (2014) present this as a window for opportunity charging. However, aiming for higher utilisation of the fleet and regularity of service, it is not possible to allocate this time for charging. For instance, Canadian public transport providers emphasised that recovery time is essential to deliver reliable service (Mohamed et al. 2018). Notably, lines with higher service frequency are characterised by short dwell times, largely not sufficient for charging. As electric buses cannot be used during the charging period (needs to be stationery), that electric buses needs additional operational time (De Filippo et al. 2014) compared to diesel buses. This will again mean that more buses are necessary in order to serve the same number of passengers (Varga, Iclodean 2015). Depending on a specific charge time causes that electric buses are relatively susceptible to traffic conditions. Any unforeseen delays can induce either difficulties with service reliability and keeping the schedule. Or, in case of not enough charging time, to problems with carried battery charge, which in effect can be not adequate to complete the service. Dependence on the available battery charge makes battery electric buses less flexible in comparison to conventional buses. Their operation rely heavily on access to charging infrastructure (Häll et al. 2019). That in reality hinders one of the biggest advantage of a battery bus over trolleybuses: independence from energy supply. In fact, this effects in fixed assignment of vehicles to the line, and make any temporal changes in service, diversions, etc. problematic.

Energy consumption

The necessity of using high-capacity battery cells significantly affects the weight of the vehicle. Large batteries, in addition to limiting the passenger space inside the vehicle affecting the comfort of travel, noticeably add weight to the vehicle. Larger vehicle mass in turn results in higher energy consumption causing a significant increase of the amount of energy consumed from the batteries (Varga, Iclodean 2015). This effectively also affects the achievable operational ranges. With increasing electricity consumption originated by vehicle mass connects also limited passenger capacity – higher passenger occupancy also results in higher vehicle weight, posing risks in terms of available battery charge. Low tolerance of overloading makes electric buses difficult to deploy for service on high demand routes.

The electricity consumption is influenced also by other factors than the total mass. One of them is consumption by auxiliary systems (Varga, Iclodean 2015), that is mainly heating/cooling. Batteries alone do not tolerate well extreme temperatures, both cold and heat, affecting their performance and posing difficulties in use in specific climate conditions, like hard winters (for example Scandinavia, Russia) and extreme summer heatwaves (probably soon most of the world). But notable problem is use of said auxiliary systems for heating/cooling vehicle interior. Operating in cold climate conditions could increase the energy consumption significantly if the bus heating power is drawn from the battery (Lajunen 2018). For the extreme temperature case in Berlin (-17°C) the needed energy for heating increased consumption by almost half (Göhlich, Kunith & Ly 2014). Real-world measurement results shows that internal cooling (air condition usage) can significantly increase electric consumption. The gap between best and worst cases could be up to approximately 160% (He et al. 2018). This is especially important in the light of climate change, rising global temperature and more occurrences of severe heatwaves. Electricity consumption by heating/cooling system is seen as so considerable, that in many of electric buses they are powered by separate fuel-powered generators. That means that some of vehicles are not purely electric, using, most commonly, synthetic or bio- fuels. Interestingly, generators used for such systems are not obliged to meet emission norms, as those applies only to emissions from propulsion systems. An increased consumption results in the dependancy of operational range on the seasons and weather conditions. However, Tammi & Lajunen, in a recent research study, indicates that the average increases over a year of operation was only 10% (2016).

Last factor affecting energy consumption needed to be mention is a route configuration. Electricity consumption increases under acceleration or when climbing upgrades (Varga, Iclodean 2015). This proves difficulties in using electric buses for service in hard terrain conditions, e.g. in mountain areas.

Capital costs

Electric buses have significantly higher capital costs than traditional buses. High energy efficiency, paired with lower costs of electricity than diesel, can lead to those cost being counterbalanced by lower fuel and other operating costs (Miles & Potter 2014). However fuel cost are corresponding to smaller part of operating costs. - for operators in Canada it equals only for about 10% (Mohamed et al. 2018). High initial investment cost then, has been identified as a main problem of electric buses. That includes costs of procurement of vehicles, as well as an establishment of a necessary charging infrastructure.

Cost of a single battery electric bus vehicle can be from 2 to 3 times higher than a respective diesel powered bus. This make it an important hindrance in introducing electric buses in regular operation, especially for smaller operators, and without public financing can be considered as a major difficulty. The greatest part of costs are manifestly allocated to batteries, depending on their capacity. This will be true for a foreseeable future and, despite the fact that battery cell costs have been recently rapidly decreasing, batteries will remain the most expensive components of the vehicles for the next 10 to 20 years (Rothgang et al. 2015). Opportunity charging requires less energy to be stored in the bus, thus smaller batteries, which could significantly reduces the capital costs.

Due to technological advancement, substantial electrical power required and presence of multiple locations, the initial costs of the charging stations for opportunity charging are much higher than for the other charging methods (Lejunen 2014). Centrally located at the depot plug-in chargers for slow overnight charging, even in multiple instances, are cheaper and easier to provide. Using only depot charging however, limits operability of electric buses and makes route planning and timetables dependent on access to the depot. In this context, the importance of achieving certain level of public transport service, thus particular network route design might influence that the cost of charging infrastructure may not be a determining cost for choosing vehicles and battery size, and designing the charging system (Olsson et al. 2016). Local operating situation and requirements have important influence on the battery system design and charging concept choice of electric buses (Rothgang et al. 2015). Nevertheless, payback period of the charging infrastructure investment for electric buses is still very long (Wang et al. 2014). It seems preferable to carefully select routes for electrification and most applicable locations for charging, where they can be most used (for example those end points used by several lines) and the investment therefore justified (Xylia et al. 2017).

Technology reliability

Adoption of electric buses in regular operation is relatively new phenomenon. There is still need for reliable data concerning real-world performance of electric buses over longer periods of time. The successful implementation of electric buses is highly sensitive to operational context and energy profile (Mahmoud et al. 2016). Numerous trial studies might not be sufficient to provide enough insights for operators. In Canada, they have raise the demand for real-world operational data under a variety of network conditions, not proof-of-concepts calculated ones (Mohamed et al. 2018). They indicated that costs estimations must be carried out also at a network/ fleet level, not only for individual buses, due to the variations in operational features. What importance does it carry, can be shown by some real-life operation studies. The most common complaint heard may be the mismatch between the announced and actual operational ranges (Li 2016). In Shenzhen, China, the actual operational range of an electric bus resulted in about 180 km, compared to the announced 250 km (Sun 2012, as cited in Li 2016). Furthermore, in Chengdu operational range reported significant decrease after one year in operation (Shu 2012, as cited in Li 2016). Also He et al. (2018) indicates that actual service ranges would be significantly shorter than the declared levels, which are usually measured under impractical conditions (e.g. 40 km/h steady test). Energy requirements will largely vary between different bus lines and at different times of day (Gallet, Massier, & Hamacher 2018). Changing driving conditions, observed especially in large cities, will also lead to different achievable range. For example, the Chinese electric bus, BYD K9, that has been tested in Copenhagen, with only overnight charging, was showing a maximum range of 325km in light traffic and 250 km in heavy traffic (Hug 2015).

Some technical aspects have to be considered which introduction of electric buses. Owing to the high requirements on electric energy, electric buses could have a substantial impact on the electrical distribution system (Steen, Tuan 2017). Fast charging is characterised by many short-timed energy draw of a significant power, creating a lot of instantaneous peaks of demand, substantially higher than average. The high-power requirement and short charge time for flash and opportunity charging will result in an uneven charge profile for the charge station, and therefore stability of electrical grid. Overnight charging was found having less severe impact. From a utility perspective, a fast-charging electric bus can be less preferable option (Mohamed et al. 2017). In order to decrease grid impact of the chargers, investment in energy storage system at the charging stations can be justified.

Several considerations can also be raised regarding the batteries. On-board batteries must adapt to demanding cycling profiles that can severely impact their performance and lifespan (Carrilero et al. 2018). The capacity of a lithium-ion battery is not a constant value during its lifetime. It fades because of ageing processes, which are time and usage depended (Vetter et al. 2005). Industrial fast-charging affects the lifespan of lithium-ion batteries adversely because of the increase in the internal

resistance of the batteries, which in turn results in heat generation (Sebastian et al. 2020). The fast charging application causes an additional reduction of the usable capacity due to the voltage limitation (Rogge, Wollny & Sauer 2015).
Volume of batteries, which is significantly high in case of electric bus, means that their replacement and disposal costs are higher (Varga, Iclodean 2015). There are currently no effective method of utilisation or recycling batteries, especially considering using them on a high scale assumed by wide introduction of electric buses. Whereas production of batteries have significant degrading environmental effect, including high dependency on rare earth materials. Today's world is not prepared for a momentous increase in both battery production and disposal.

Electric buses, and in particular, their incremental components, i.e. batteries and chargers, are subject to rapid technological advancement. This means that technology used today, can be possibly considered dated in the near future. This has been identified as a large barrier for adopting electric bus in public transport (Mohamed et al. 2018). Within public transport operators there is common insistence on a stable technology which would stay current for the 12–16 years lifespan of bus operation.
Reassuming, electric buses are subject of several limitations and uncertainties, especially in terms of operational feasibility. Range anxiety have a significant role in slowing adoption of electric bus. Daily availability of vehicles, connected to charging time and range, is identified as important problem, comparing to traditional diesel buses. As cost is the main driver for the decision-making process in the transit context, high initial capital costs, both for the vehicles and accompanying charging infrastructure, is as well a key factor in moderate adoption of electric buses. Sensitivity to operational variation implies that a tailored technological configurations are essential to meet the operational demands of public transport service at a network level (Mohamed et al. 2018), making it impossible for a standardisation and a scale effect. Importantly, electric buses present also some technical difficulties, having as well effect on the environment.

What about trolleybuses?

Operational autonomy of electric buses, maybe resembling that of diesel bus, in connection with recent battery technology developments could have caused accelerated adoption of BEBs in the last years, as described earlier. Perhaps, this made common conviction that battery electric bus is the default solution for electrifying public transport. Zavada, Blašković Zavada & Miloš (2010) points out an unjustifiable neglect of trolleybus in the implementation for the public urban transport. Several studies conducted in that matter are surprisingly omitting trolleybuses. However, trolleybuses are still the most mature technology next to diesel bus [Berlin Spandau 1]. The trolleybus is a proven heavy-duty public transport technology, equaling and exceeding operational performances of diesel-propelled buses. It is present in over 310 cities worldwide and there are more than 40 000 trolleybuses in operation in the world (Korolkov 2015). Trolleybus might be perceived as an outdated technology, as its development stagnated due to larger growing popularity of diesel bus, achieved thanks to low fuel prices. However, since 1990 45 new trolleybus systems have been introduced globally, 27 in Europe. More are also currently studying possibility of its implementation, for example Leeds (United Kingdom), Verona (Italy) or Montreal (Canada). In Russia and Eastern Europe, the trolleybuses can have relatively similar status as the tram, in terms of the scale of operation and transported passengers (Tica et al. 2011).

Trolley-buses are electrical vehicles in which energy for its operation is supplied by continuous connection to overhead energy line. Line is under direct voltage of 600 or 750 V (Zavada Blašković Zavada & Miloš 2010), and vehicles are connected to it through catenary. Due to this fact, important technical characteristic of trolleybus vehicles is that they need to be equipped with two-stage isolation of the 600/750 V electric system for safety of passengers (Wołek & Wyszomirski 2013). Operation based on the connection to the overhead line restricts the buses to move along a fixed track. As trolleybuses are essentially a specific type of an electric buses using, instead of batteries, energy provided directly from contact line, all advantages mentioned in previous paragraph stays valid. Significant environmental benefits are positioning trolleybus as a potential solution for sustainability in cities, along the electric buses.

However, trolleybuses do not carry many of electric buses' disadvantages and limitations, having also edge over them in several aspects. Because trolleybus has a continuous access to electricity, operation of trolleybuses is independent to weather conditions. Diesel engines are susceptible to cold temperature, presenting largely higher fuel consumption until warmed up. Scandinavian countries or Russia observe issues with traditional buses in winter periods. In case of electric buses, operation of the electric motor does not depend on the temperature, however batteries must maintain a constant temperature to maintain capacity, as it is being use much quicker in loses capacity in low temperatures, or present risk of overheating in high temperatures. Analogically, operational capabilities in mountainous areas or in traffic aren't limited in trolleybuses - electric buses are in such conditions susceptible to higher energy draw, diesel buses to overloading the engine. This lack of risk of increased energy draw due to continuous connection to electricity cause also, that trolleybuses do not have to use any auxiliary fuel generators for heating / cooling, making them fully electric vehicles. Traditional trolleybuses do not have a battery on board, that means they do not have to be charged, which in connection to independence on temperature, terrain or traffic conditions leads to higher operational availability of rolling stock. Lacking batteries, trolleybus can have a significantly lower weight than electric bus translating to lower energy use. Absence of battery or engine, taking space inside the vehicle, provides also higher passenger capacity and increased comfort with spacious interior. Trolleybus is characterised by much longer lifespan comparing to the traditional bus. On average, lifecycle is from 15 to 22 years (Zavada Blašković Zavada & Miloš 2010), for example in Milan, Italy, based on operational data, it accounts to approximately 20 years (Tica et al. 2011) , which is about two thirds more than bus (typically 12 years). In terms of cost of fleet, trolleybus vehicles prices rate around 10-20 % higher than diesel buses. Including longer lifespan into the consideration, cost of vehicles can therefore, be considered as comparable in whole course of life of a vehicle.

Having described advantages of trolleybus, it is needed to remember that operation of trolleybus takes place only in connection to established infrastructure. The infrastructure necessary for the operation of trolleybus transport includes power supply connection and trolley line, including overhead wires and traction masts, and maintenance facilities (Wołek & Wyszomirski 2013). Looking at the infrastructure, trolleybus implementation costs are significant, and can vary largely, from as low as 1 mil. euro to even 20 mil. euro per km (Korolkov 2015). Taking that into account, introduction of trolleybuses usually present an economic case for routes with high passenger demand. Implementation is economically justified in the region of approximately 500 to 2500 carried passengers per hour (Zavada Blašković Zavada & Miloš 2010). When considered over a longer period, about 20 to 25 years corresponding to vehicle lifespan, it is apparent that the annual costs for trolleybuses electric bus systems are lower than the costs for diesel bus systems (Trolley Project n.d.).

In general, trolleybuses enjoy a high level of passenger satisfaction and are favourable among residents. Research showed that the trolleybus subsystem is much better received by customers compared to the bus subsystem (Tica and Busarčević, 2005). For example, survey in Salzburg show majority support for the development of the trolleybus network (41%) as well as the replacement of the existing bus lines with trolleybus lines (every third respondent). (Wołek and Wyszomirski 2013). Trial service in London showed half of respondents reacting positively to trolleybus technology. Same research revealed expectations that the trolleybus subsystem would derive more revenue than the bus subsystem for the same capacities and the same route by approximately 24 % (Tica et al. 2011). From Arnhem the experience is that the visibility of the trolley bus net and the low noise levels have contributed to increase the market share for public transport (Bjorklund et al. 2000). In this context, it is impossible to not mention discussions regarding overhead contact lines. Some experts call overhead wires as visual pollution, and claim as the main disadvantage of the trolleybuses in urban environment. However, an overhead contact line is a clear indication of a system to a public transport customer, confirming that the route is active. Visually detectable route network improves the accessibility of the urban public transport system (Tica and Busarčević, 2005).
Visual presence of the system in urban areas assures constant service, which will encourage ridership and allow urban development or revitalisation, increasing the value of the real estate along the line.

Summing up, trolleybuses offer the same range of advantages as electric bus in terms of addressing climate goals and providing significantly improved public transport service. At the same time it minimises operational risks connected to electric buses, assuming investment in necessary infrastructure. Capital investment in the trolleybus subsystem is substantial, and still higher than other technologies, however it might be compensated by longer lifespan and possible extra revenue, resulting of greater appeal and accessibility of the trolleybus system (Tica et al. 2011).

Combining electric buses with a trolleybus

Importance and urgency of addressing climate goals has shifted focus in public transport to electric vehicles, despite seemingly higher costs. Recent progress of battery technology, not only has accelerated wider adoption of electric buses, it also moved focus to addressing problem of autonomy of a trolleybus. For years trolleybuses had been equipped with auxiliary power units, mostly diesel engines or energy storage, allowing to operate small parts of route without a connect line. This was done where establishment of overhead wires proved problematic or economically unjustified, i.e. for example in historical city centres or in the fringe areas with low passenger demand. Independence from physically existing infrastructure, even partially, would significantly lower a barrier for introducing trolleybuses and put this system as superior, due to its operational capabilities. At the same time, from the other hand, important limitation of electric buses are connected with them operational difficulties, i.e. higher vehicle demand due to lower operational availability caused by limited range and capacity or increased timetable times. This has causes intensified efforts to minimise this effects and looking for other methods of charging, distinctly ones that wouldn't cause breaks in operation. That has lead to developing in-motion-charging technology, allowing to charge batteries of an electric bus during operation by using trolleybus overhead contact line. Or, in another words, having a trolleybus with batteries of capacity high enough to allow a notable autonomy. Combing two goals allowed to create cross between a traditional trolleybus and a battery bus, and in effect, hybrid trolleybus has emerged. As then categorisation of such system might be difficult, in literature it is assumed that a hybrid trolleybus is an electric vehicle that allows for 30 to 70% of operation without a catenary.

In general hybrid trolleybuses offers advantages of both systems, minimising their limitations, Comparing to trolleybus, they can offer extended operating radius to areas without overhead lines and lower suspect ability to traffic or energy conditions. Comparing to electric buses, they offer operational characteristics comparable to trolleybuses, without range anxiety or increased dwell time, influencing the costs. They are also more independent from energy demand, meaning conditions (temperature, terrain, traffic) has less influence. Naturally, there is still necessity for construction of energy supply infrastructure. However, those costs can be much lower comparing to trolleybuses, as overhead contact line is necessary on only part of the route. Flexibility of battery operation allows also to omit costly elements, such as problematic wire structures at junctions etc., lowering the cost further. Higher infrastructure costs can be as well compensated by lower vehicle demand and lower vehicle costs compared to overnight and opportunity chargers in electric buses. Hybrid trolleybuses vehicles, thanks to having significantly smaller batteries, are simply cheaper. Cost of fleet procurement is much lower comparing to electric buses. Moreover, in hybrid trolleybus systems less vehicle are needed since no breaks for charging are required. That means better fleet utilisation and lower costs of procurement and operation. In fact, this benefit significantly improve economical efficiency of the system. Bergk et al. (2016) indicates that additional costs occurred from just 3 additional minutes in dwell time of a line with 10-minute interval equals to 92 000 euro per year comparing to hybrid trolleybus. Using smaller batteries also means relatively lower environmental impacts connected to their production and utilisation. This may even eliminate the need of battery replacement during a vehicle lifetime.

Research question

Above consideration show directly that hybrid trolleybus could possibly provide more beneficial solution for electrifying public transport. Therefore, this has lead to formulating the following research question:

Can a hybrid trolleybus present a sustainable solution for electrifying public transport in cities better than the electric bus?

That should include therefore:

- is it economically viabale, that is present better economical case than electric buses.
- are there differences in an environmental impact?
- and finally which solution offers easier and faster implementation, thus realising climate goals.

Presenting a research question concludes this introductory part of the report.

Problem investigation

Methods

The considerations presented in the introductory part of this report already present possible answers to the questions posed. However, in order to test this possible hypothesis, the case of considered hybrid trolleybus network in Berlin-Spandau was analysed.

This has been done based on the desk research. As a main source of data, the feasibility study «Feasibility of hybrid trolleybus operation in Berlin-Spandau» (BMVI 2019) was used. The study carried out for the BVG and the Berlin Senate to examine and assess the technical and economic feasibility of a hybrid catenary bus system for Berlin Spandau is an important part of this ongoing transformation process. The study was funded by the BMVI as part of the federal mobility and fuel strategy. Additionally, insights from other cities using hybrid trolleybuses will be presented.

Analysis

Structure of the remaining part of project report will be the following: Firstly, cases of implementation of hybrid trolleybuses will be analysed in connection with presenting achieved learnings. Secondly, investigated hybrid trolleybus case of Berlin-Spandau will be presented in more detail, followed by presenting and critically analysing economic calculations data from the feasibility study. Lastly, results will be discussed based on other literature.

Electric buses and hybrid trolleybuses in cities with a trolleybus network

Gdynia (250.000 inhabitants) is one of the 3 cities in Poland operating trolleybuses on their public transport network (Wołek, Hebel 2019). In Gdynia (and in Sopot, as its agglomeration), an overhead network covers 42.7 km of routes, including the city centre, thus allowing hybrid trolleybuses to be introduced as a transport mean for new residential developments. From 2015, Gdynia systematically expands its trolleybus operation outside of a catenary network using vehicles with auxiliary battery units. Notably, this has increased significantly in 2019 and total vehicle-kilometres without catenary covered by trolleybuses counted 8.17% of the total supply (Wołek et al. 2020). This year, Gdynia has introduced another trolleybus route with off-catenary operation. At this new line 32, more than the half of a route is operated without the overhead line. This can be achieved thanks to newly procured hybrid trolleybus vehicles, which are equipped with batteries of capacity 87 kWh. This has allowed to replace a traditional bus line, operating with diesel buses before. Significantly expanding electric operation did not involved considerable investment, apart from fleet acquisition and minor network addition/adjustment.

Similar plans for extending electric operation using existing trolley network were decided in Pilsen, Czech Republic, which is an interesting example case. The city (170.000 inhabitants), one of 13 in Czech Republic with trolleybus system and known for its brewery, already has achieved level of electrification of its public transport network, mainly thanks to trams (36%) and trolleybuses (29%) (Kohout 2018). As part of ZeEUS project (ZeEUS 2018), city has carried out a trial operation of opportunity charged electric bus. Results has confirmed mentioned in the introduction of this report limited operational range of electric bus, mainly due to heating in winters and traffic conditions (too short time for charging). Learnings also indicated high requirements for energy supply and negative impact of peaking demand on the energy grid, increasing energy price. That resulted in higher energy consumption per km comparing to a trolleybus (2,5 kWh/km and 2,03 kWh/km respectively), when including losses in substation and infrastructure (Kohout 2019). Those learnings has lead to a decision for expanding trolleybus operation instead of electric buses, and introducing hybrid trolleybuses. In 2021, trolleybus line 11 will be extended to take over the route of a bus line 35, almost doubling in length. This will be done without any infrastructure investment, proving hybrid trolleybuses as a mean for easy and rapid electrification of public transport. Kohout (2018) provides an overview of possible extent of such electrification, providing only few new catenary lines.

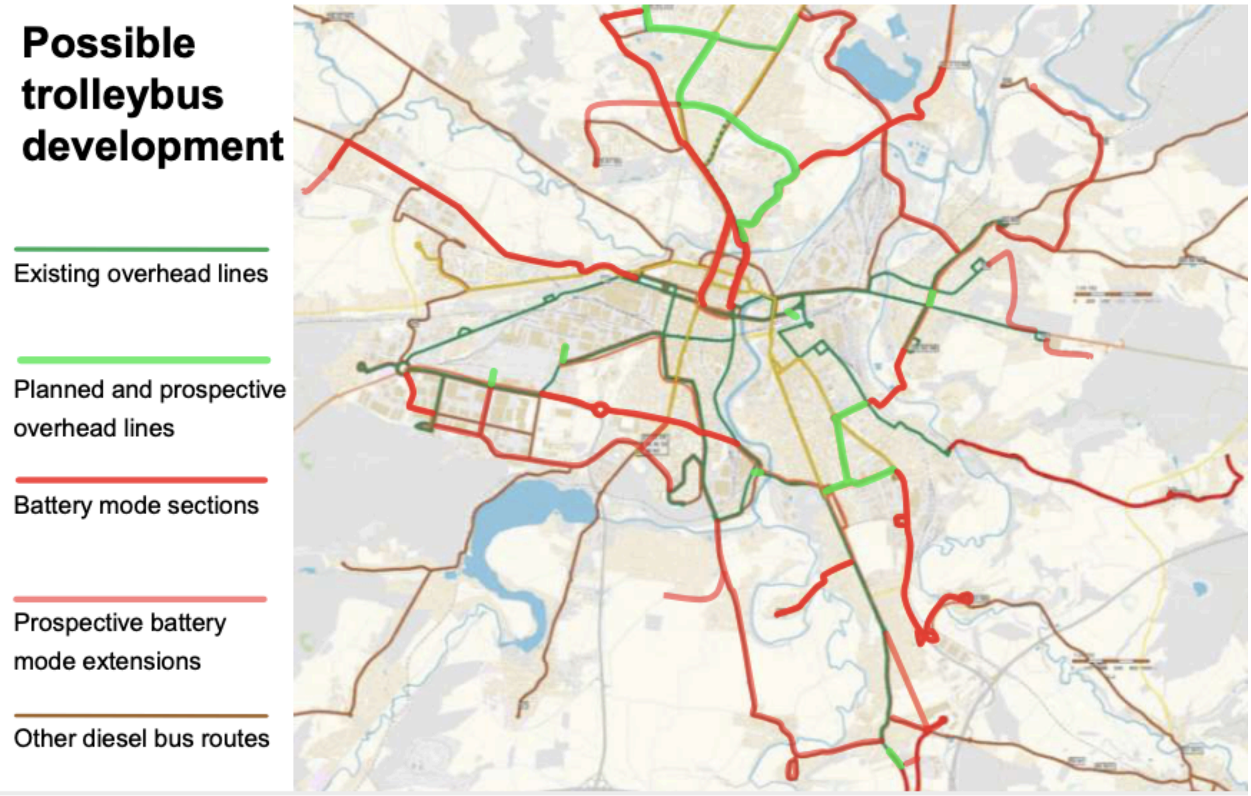


Figure. Possible electrified routes in Pilsen thanks to introducing hybrid trolleybus (Kohout 2018)

Based on Gdynia as a case study, Wołek et al. (2020), constructed a model for calculating life cost for 3 typical insensitivity of operation (as a daily mileage). Result shows that using in-motion-charging vehicles allows to achieve lesser financial costs over diesel buses already for distances approx. 190 km/day. For battery electric bus, this is true only for distances from 270km/day. That means, that electric vehicles can have for typical service (exept peak-only).

Figure 9. Annual lifecycle financial costs for different type of buses assuming existing catenary

Considering the above, it is evident that for cities already operating trolleybus system hybrid trolleybus are the chosen solution, offering reduced costs, increased operational parameters and better utilisation of infrastructure. Hybrid trolleybus allows those cities to meet climate goals quickly, with minimised or none investment in infrastructure.

Hybrid trolleybus as a new system - considered implementation in Berlin-Spandau

Although providing important insight, considerations presented in a previous chapter cannot answer research question of this project, as number of cities with functioning trolleybus systems is limited. Therefore main part of investigation is based on possible hybrid trolleybus implementation in Berlin–Spandau (Germany). As indicated in methodology chapter, this is based on the feasibility study conducted in relation to research performed for BMVI. Further, reader of this report, will receive more detailed information about considered network in Berlin–Spandau.

Economic comparison of different bus systems for network in Berlin-Spandau

The costs incurred for the development, production and disposal of a product over the entire life cycle are referred to as life cycle costs. In the life cycle cost analysis, the relevant investments and operating costs are taken into account in a specified period.
In the present analysis, the life cycle costs include the investment, maintenance and operating costs over a specified period of use. For the hybrid trolley bus and the technology alternatives, the investments are first compared. This is followed by the presentation of the annual costs. Then the net present value and the annuity are calculated. Net present value and annuity are key figures in dynamic investment calculation.
To allow comparisons, later cost will be expressed as well per place-km. Place-km is unit determining level of service, that is offered passenger places in kilometres of transport service performed.

Fleet

To determine costs of fleet acquisition cost, number of vehicles and unit price is required. For lifecycle cost calculation, this has to be related with assumed vehicle service life, also determined in the following subsections.
Vehicle prices
Prices of vehicles can represent a relatively wide price range. The actual price from procurement data shows that unit price for articulated hybrid trolleybus situates

between 500.000 to 800.000 euro. For calculations BMVI (2019) assumes a value of 760.000 euro was assumed. Unit prices for other types of vehicles has been determined based on BVG procurement experience. The following table shows comparison of unit prices for an articulated vehicle.

Vehicle type	Cost of vehicle (excl. batteries) [€]	Cost of batteries [€]	**Cost of vehicle incl. batteries [€]**	Cost difference
Diesel bus	350.000	-	**350.000**	*ref.*
Electric bus with depot charging	588.000	246.000	**834.000**	+ 138%
Electric bus with opportunity charging	580.000	253.000	**833.000**	+ 138%
Hybrid trolleybus	760.000	72.000	**832.000**	+ 138%

It can be seen, that prices of different vehicles technologies are very similar. What is notable, that battery costs are very significant in case of electric buses. Assumed high cost of hybrid trolleybus (vehicle alone), apart from technical differences in circuit safety, can be explained by its relative novelty and rather small market offer in Germany. Nevertheless, this value seems in line of data from recent vehicle deliveries, taking into the account expected scale effect for large order for Spandau. For example order for 16 articulated hybrid trolleybus yielded price ca. 900.000 euro per vehicle including batteries. It is expected that prices can decrease slightly in the following years. Costs of batteries is directly depend on required capacity, showing an advantage of hybrid trolleybus.

Number of vehicles

The bus network in Berlin - Spandau for operation today require 187 diesel buses. That includes different types of vehicles: standard bus, that is with length of 12 m, articulated bus (length around 18 m) and double-deckers, that is vehicles having 2 storeys (decks). Service concept for hybrid trolleybuses assumes 2 types of vehicles: articulated vehicle and bi-articulated vehicles with increased passenger capacity and the length of 24 m.

For the electric buses, similar vehicle types as in diesel bus operation are assumed. Double-decker diesel bus requirements in the study was assumed to be covered by articulated vehicle due to market unavailability of electric vehicle of this type. Currently there are fully electric double-decker buses available on the market and in a regular service. The highest implementation is observed in London, UK. Number of vehicles requirements for electric buses are increased comparing to traditional bus.

This is due to operational limitations caused by batteries, mainly time needed for charging as explained in the introduction of this report. BVG assumes that requirements should be increased by 10% for bus with opportunity charging and by 20% for depot charging. This is a general assumption, as real numbers will differ depending on routes and timetables. The increase can be even in range of one third, as reported by some operators, even in case of opportunity charger. For example, municipal public transport company in Radom (Poland), MPK, in order to introduce electric buses on the line 1 had to provide 8 vehicles. For diesel operation only 6 buses were needed (33% increase). According to information provided by company, although electric bus exhibit lower energy/fuel costs (1 PLN/km, comparing with 1,6PLN/km for diesel), induced increased drivers cost can pose financial difficulties in network-wide adoption of electric buses.
Overall, the Spandau bus network has an additional vehicle requirement of 18 electric vehicles for opportunity charging method and 36 for overnight.

Identical number of vehicles as for diesel buses is found for hybrid trolleybuses. Moreover, it needs to be noted that types of vehicles are different, as hybrid trolleybus variant is based on planned expanded public transport offer, thus number of offered passenger capacity is higher.
10% of vehicle requirements for a fleet reserve is taken into the account in all categories. Overall vehicle requirements for network in Berlin - Spandau is presented in a table below.

Vehicle requirements	Diesel bus	Electric bus with depot charging	Electric bus with opportunity charging	Hybrid trolleybus
Bi-articulated vehicle	-	-	-	74
Articulated vehicle / double-decker	177 (116 / 61)	211	194	113
Standard vehicle	10	12	11	-
Total	**187**	**223**	**205**	**187**
Increase		+ 20%	+ 10%	+ 0%

Table. Vehicle requirements for network in Berlin - Spandau

Expected useful lifespan

For calculation of costs in the perspective of a lifecycle, data about expected useful lifespan of vehicles (and batteries) is needed. Based on operation of trolleybuses, corresponding lifespan of 16 years has been determined for hybrid trolleybuses. This is conservative approach, since the service life of the trolleybus vehicle is technically possible for 18 - 20 years (Zavada, Blašković Zavada & Miloš 2010). The lifetime of the diesel buses corresponds to the experience of BVG from today's operation and equals 10 years. For the electric buses, BVG assumes a useful life of 12 years. This seems like an agreed assumed value in the industry. The battery life is assumed to be 6 years for all electric bus types. This is presented in the table below.

Type of vehicle	**Expected lifespan**
Diesel bus	10
Electric bus with depot charging	12
Electric bus with opportunity charging	12
Hybrid trolleybus	16
Battery	6

Table. Expected lifespan of vehicles

Fleet costs

Based on above assumptions and unit prices the calculation of a fleet costs for network in Berlin Spandau has been done. This is presented in the following table:

Vehicle type	Cost of vehicle fleet [€]	Cost difference	*Cost of vehicle fleet per place-km [€]*
Diesel bus	70.750.000	ref.	*0,0449*
Electric bus with depot charging	183.474.000	+ 159%	*0,1249*
Electric bus with opportunity charging	168.466.000	+ 138%	*0,1119*
Hybrid trolleybus	188.144.000	+ 166%	*0,1113*

Table. Fleet acquisition costs

Costs has been determined as highest in case of hybrid trolleybuses, however offered passenger capacity is the highest - in comparable values per place-km, hybrid trolleybus offers the lowest cost. Yet, costs of electric buses with opportunity charging is relatively close.

Infrastructure

Crucial for this analysis is determining investment costs for infrastructure. Infrastructure required for bus operation is:

in case of electric buses: charging infrastructure,

In case of hybrid trolleybus: connect line (traction wires + masts) and energy supply, incl. traction substations.

Substations are the most significant element of costs and its number is depended on required total power of a system. Construction of substation alone is estimated to 600.000 euro per MW. For the overhead connect line, cost will directly depend on the length of network under traction. Costly elements are switches and crossings, although impact of the cost of these elements can me minimised with hybrid trolleybus. In general, with a mast spacing of 31.5 m, investments of almost 500.000 euro per km of bi-directional line (4-wires) result for the pure catenary.

No infrastructure investments are required for the diesel bus.

Establishing new trolleybus network is expected to carry significant initial cost, as this has been identified as major obstacle to wider adoption of trolleybus systems worldwide. As hybrid trolleybuses allows for traction to be installed only for a part of network, this can offer reduction in those cost in comparison to trolleybuses. In Berlin–Spandau, there are 2 main concepts of installing traction line: scenario 1 with 84% of network with connect line, and scenario 2 with reduced traction line share to 63%. Both scenarios are considered in calculations. As the feasibility study offers detailed dimensioning of the network, cost calculation can be considered relatively precise, even taking safe assumption regarding unit prices and tolerance.

Therefore overview on cost of infrastructure is presented in the following table:

Costs [€]	Diesel bus	Electric bus with depot charging	Electric bus with opportunity charging	Hybrid trolleybus	
				Scenario 1 (84%)	Scenario 2 (63%)
Charging infrastructure	-	12.248.000	26.181.000	1.416.000	1.705.000
Overhead connect line	-	-	-	26.279.000	22.314.000
Masts	-	-	-	39.940.000	29.939.000
Energy supply	-	-	-	49.136.000	49.871.000
Others	-	1.715000	3.819.000	20.330.000	17.499.000

Total (incl. other costs)	0	12.248.000	30.000.000	137.101.000	121.328.000

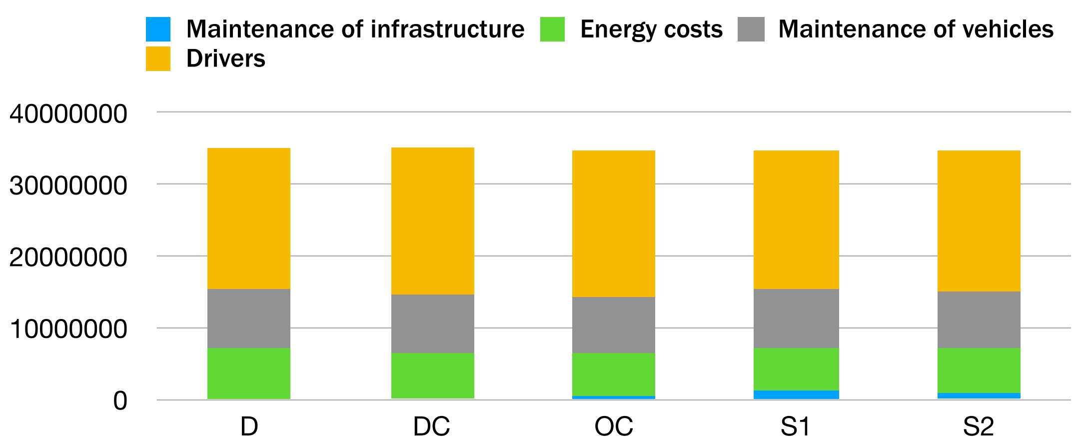
Lowest infrastructure investments for network in Berlin-Spandau are required for electric buses with depot charging, while opportunity charging will more than double this costs. However, costs for charging infrastructure are in completely different order of magnitude than traction infrastructure. Infrastructure costs for hybrid trolleybus in scenario 1 is around 4,5 times higher than for electric opportunity bus.

Sum of capital cost (fleet + infrastructure)

Looking together at costs of investment in fleet and infrastructure make out capital costs that must be incurred initially. Result shows that costs of electric buses are similar. High number of additional vehicles required in case of depot charging, has been offset by the lower costs for the charging infrastructure. Investment in hybrid trolleybuses are certainly higher, however the difference is of different scale than looking at infrastructure costs alone. For example, scenario 1 will incur initial investment costs higher by 64% comparing to opportunity charged bus. Data is presented in the table below.

Costs [mil. €]	Diesel bus	Electric bus with depot charging	Electric bus with opportunity charging	Hybrid trolleybus	
				Scenario 1 (84%)	Scenario 2 (63%)
Total	**70,750**	**197,436**	**198,466**	**325,244**	**309,472**
				+ 64 %	+ 56 %

The following chart present structure of capital costs for different types of systems.



Annual costs

As lifecycle costs include also operating costs, those are presented in the following section. Annual costs were divided into two categories:

- maintenance of infrastructure,
- operational costs, which includes:
  - energy costs,
  - Maintenance of vehicles,
  - costs for driving stuff.

It can be expected, that electric vehicles (electric buses and hybrid trolleybuses) will have lower operating costs due to higher energy efficiency and lower electricity price comparing to diesel. Price of electricity was assumed as 0,15 euro per kWh. Maintenance and operating costs estimates was either assumed and calculated accordingly or provided by BVG based on their experience.

The following table provides an overview of the annual costs in different categories. For comparison taking into the account differences in offered passenger capacities, each cost has been expressed in eurocent (0,01 euro) per space-km.

Annual costs [€ per year]	Diesel bus	Electric bus with depot charging	Electric bus with opportunity charging	Hybrid trolleybus	
				Scenario 1 (84%)	Scenario 2 (63%)
Maintenance of infrastructure					
Charging infrastructure	-	145.000	444.000	56.000	62.000
Trolley infrastructure	-	-	-	1.090.000	933.000
Sum	**0**	**145.000**	**444.000**	**1.146.000**	**995.000**
per place-km [0,01€ per year]	*0*	*0,0099*	*0,0295*	*0,0678*	*0,0589*
Operating costs					
Energy costs	7.331.000	6.329.000	6.028.000	6.091.000	6.091.000
— per place-km	*0,4652*	*0,431*	*0,4005*	*0,3604*	*0,3604*
Maintenance of vehicles	8.145.000	8.022.000	7.640.000	8.035.000	8.035.000
—per place-km	*0,517*	*0,546*	*0,508*	*0,475*	*0,475*
Drivers	19.500.000	20.475.000	20.475.000	19.500.000	19.500.000
— per place-km	*1,237*	*1,394*	*1,36*	*1,154*	*1,154*

Sum (incl. others)	**35.631.000**	**35.607.000**	**34.861.000**	**34.281.000**	**34.281.000**
— pe place-km	*2,2610*	*2,4245*	*2,3161*	*2,028*	*2,028*
Overall costs	**35.631.000**	**35.752.000**	**35.305.000**	**35.427.000**	**35.276.000**
— per place-km	*2,261*	*2,4344*	*2,3456*	*2,0958*	*2,0869*

As this shows, annual costs for all analysed technologies are characterised only by small differences. However, in terms of offered passenger space, it can be clearly seen that hybrid trolleybuses due to increased capacity, offer much lower operational costs. Even after including costs of infrastructure maintenance, which is the highest for this type of vehicle, hybrid trolleybuses still accounts for the lowest overall annual costs.

Financial result and profitability

After presenting all financial calculations, it is necessary to refer it to lifecycle in order to determine profitability of variants. A period of 30 years is assumed for this. This represent a typical period used for assessing investments into infrastructure expansions. The feasibility study has provided financial results in terms of values for net present value (NPV) and yearly annuity. NPV shows all expenditures (payment flows) over an assessment period expressed in present value. Residual values at the end of the period are included. Annuity presents the average annual cash flows, also expressed in present value. For its calculation assumptions of interest rate (3%) and inflation (1%) was taken.

Following table present financial results of different bus technology variants for network in Berlin-Spandau.

	Diesel bus	Electric bus with depot charging	Electric bus with opportunity charging	Hybrid trolleybus	
				Scenario 1 (84%)	Scenario 2 (63%)
NPV for 30 years period [milion €]	-966,988	-1.262,127	**-1.233,066**	-1.268,052	-1.251,613
Annuity [€/year]	-43.058.000	-56.201.000	**-54.907.000**	-56.464.000	-55.732.000
Annuity per place-km [0,01€/year]	*-2,732*	*-3,827*	*-3,648*	***-3,34***	***-3,297***

Analysing the results it has been shown electric bus with opportunity charges presents the most satisfying financial results over 30 year period. Diesel bus, despite presenting highest profitability due to minimum investment (renewal) costs, was presented here only as a reference, and it not taken into the account when comparing technologies.

In relation to offered passenger space, battery trolleybus shows a significant cost advantage. As a result of this project-specific life cycle cost analysis, it could be determined that yearly annuities calculated per offered space-km can be up to 22% cheaper than for electric buses. The main reasons for this are:

- very high offered capacity and high efficiency due to service with bi-articulated vehicles,
- lower vehicle requirements and the lower mileage of the hybrid trolleybuses, thanks to higher operability (no additional charging times)
- longer lifetime of the vehicles
- lower costs of battery changes due to their significantly lower capacities.

Therefore, it can be concluded that from an economic point of view, that the hybrid trolleybus presents highest profitability in relation to space-km, and thus is recommended for the traffic volume investigated in Berlin–Spandau.

Discussion

Costs assumption

Presented in a previous section results of profitability analysis are achieved under condition that assumptions used are realistic. It needs be pointed out that, since the data are based on a technical feasibility study, no fundamental errors in the assumptions should be expected. For some assumptions, they have been simplified or generalised, so the actual values could be slightly different. This applies in particular to the assumed operability of an electric bus, energy efficiency and costs for hybrid trolleybus. In the opinion of the author of this thesis report, on the basis of examples from the literature, this could result in showing even greater advantage of hybrid trolleybus. However, without detailed real life operational data under comparable operating conditions, a more detailed analysis will not be possible.

The key element influencing the calculation result for Berlin-Spandau is the assumed high capacity of the public transport offer, due to the use of bi-articulated buses. It is difficult at this moment of this thesis project to estimate how the results for the use of the identical transport offer would change in comparison with the use of this type of rolling stock. Infrastructure costs would remain the same, but the cost of purchasing rolling stock, maintenance and operating costs would change accordingly. Therefore, it seems that the presented comparative method in relation to place-km can be considered sufficient.

Dimensioning of a traction system

An important issue that may affect the obtained results is the assumed ratio of the network under the catenary. Infrastructure costs directly depend on it, having a significant impact on the final financial result. The issue of optimizing this ratio is a question that is reflected in the literature (Bartłomiejczyk 2017, Wołek 2020). Bartłomiejczyk (2017) proves that on average, a 50% share under the catenary should be assumed. It allows a smaller share (min. 33%), provided that the conditions for the minimum charging time under the network and the availability of emergency chargers at the end points of the line are met. However, this data may be out of date due to technological developments. For example, Knorr-Bremse, a producer of power systems for trollleybuses, has developed the latest charging standard in motion - IMC500, which allows for the drawing of up to 500 kW of power from the overhead contact line. According to the manufacturer's claims, this would reduce the sections under the cable to approx. 20% (Knorr-Bremse 2019).

Batteries

Another question that can be discussed is developement of battery technology. Paradoxically, the batteries that are the basis for the operation of electric buses are now also the cause of their limitations. Technological breakthrough in this field, which would significantly improve their parameters, leading to increased availability and reduction of battery costs. It could also mean eliminating the limitations of electric buses that are associated with batteries. Until now, battery technology was expected to develop significantly at a rapid pace. In Bergk at al. (2016) in a comparative life cycle cost analysis, such an assumption caused the authors to argue the advantage of hybrid trolleybuses over electric buses only until 2025. After that time, the assumed technological development, would make battery buses show higher profitability. However, it must be unequivocally stated that these assumptions do not cover the observed level of battery development today. The dynamics of this sector has slowed down and there is no significant increase in capacity. It is reflected in the prices also adopted for the study for Berlin-Spandau. Boren (2019) indicates that no further decline in prices in relation to 2018 prices should be assumed, due to the increase in demand and limitations in their production.

However, considering the possible increase in battery density, announced by Tesla, it should be said that it will not have a revolutionary impact on the battery market for public transport. There are still important parameters, e.g. time lost on charging, which may indicate the legitimacy of considering a hybrid trolleybus.

The last issue under discussion is the ease and speed of implementation. This is a difficult question to resolve. It has been shown that in the case of the existing trolleybus networks, the use of a hybrid trolleybus allows for the electrification of a significant part of the public transport network in a very short time. Taking into account the long-term financial profit, it can be concluded that creating new networks, even to a limited extent, should have a major advantage. However, it should be remembered that the initial costs associated with the creation of an overhead contact line are significantly higher than for an electric bus. Similarly, the scope of works and their complexity seem to be greater. This issue should be examined more broadly from the organizational point of view, however, due to the very local character of the conditions, generalization would be difficult.

Conclusions

To answer research question, in the course of this project has been indicated that hybrid trolleybus can present a better sustainability solution.

Based on the example of the Berlin-Spandau, it has been proven that a hybrid trolleybus is both a viable and a cost-effective solution. The use increases the use of the rolling stock, reduces the demand for rolling stock and the work of drivers. Even taking into account the infrastructure costs, the result in terms of the passenger capacity offered indicates significant gains in relation to the electric bus.
In terms of sustainability, it should be noted that a hybrid trolleybus offers the same local benefits in the form of no emissions and reduced noise. In a broader sense, however, it can represent a reduced impact on the environment, mainly due to the reduction in the demand for batteries. As a result, the emissions related to the production and disposal of batteries are significantly reduced, and the reduced power consumption, less load on the power grid and stability are also important in this aspect. The reduction potential for CO2 relative to diesel is also correspondingly higher. In terms of implementation, a hybrid bus may still be a more difficult to implement solution, however, the remaining advantages favor a preference for this type of vehicle.

Perspective

In the current literature, the issue of hybrid trolleybuses is not widely discussed, and in the context of the development of electromobility in public transport and meeting the climate criteria, the consideration of this project seems to be very relevant. In particular, it may be interesting to directly compare the costs of using a hybrid trolleybus on the new network and present the results of a study to an English-speaking audience in Berlin.

However, basing this project on a case study exclusively for Berlin makes it difficult to apply the results directly to other cities. For example, it would be interesting, at least

from the author's perspective, to try to estimate Copenhagen, which at the end of 2019 introduced articulated electric buses for regular service (Kopenhagen Kommune).
Regardless, it seems important, at least roughly, to define such a comparison for another network with different operational parameters. This would help in a broader assessment of hybrid trolleybuses and the irrefutable results. At present, it should be shown that the study affects networks with very high passenger demand. This confirms the thesis of Berg et al. 2016 that, In comparison with other electric buses, the battery assisted trolleybus is the most cost-effective bus system for high capacity lines. We know that an electric bus can be the most suitable solution for a low demand network (.). However, it would be important to carry out a broader analysis and try to determine for which network parameters a hybrid trolleybus is a better solution. The starting point for the discussion could be the electrification strategy developed by the Zurich public transport operator (VBZ, n.d.).

Nevertheless, a hybrid trollley bus seems to be a beneficial solution for the electrification of public transport in cities, and should be considered when implementing such projects. This report concludes.

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References

European Commission (2014). *2030 Framework for Climate & Energy*. Commission communication on a policy framework for climate and energy from 2020 to 2030 - COM(2014) 0015

European Parliament (2019). Resolution of 14 March 2019 on climate change – a European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy in accordance with the Paris Agreement. Text adopted P8_TA(2019)0217. Available at: https://www.europarl.europa.eu/doceo/document/TA-8-2019-0217_EN.html

European Environmental Agency (2019). Greenhouse gas emissions from transport in Europe. Indicator Assessment | Data and maps. Retrevied from: https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-12

OECD (2014), The Cost of Air Pollution: Health Impacts of Road Transport, OECD Publishing, Paris, https://doi.org/10.1787/9789264210448-en.

European Commission (2011). Roadmap to a single European transport area (Final), European Commission, Brussels. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/ ?uri=CELEX:52011DC0144&from=EN

Messagie, M. (2014). Life cycle analysis of the climate impact of electric vehicles. Journal of Life Cycle Assessment, 2014, 14.

Glotz-Richter, M., & Koch, H. (2016). Electrification of public transport in cities (Horizon 2020 ELIPTIC Project). Transportation Research Procedia, 14, 2614-2619.

UK Department for Transport (2018). Bus statistics. Retrieved from: https://www.gov.uk/government/collections/bus-statistics

Merseytraavel (2016). Liverpool City Region Bus Strategy. Changing the way we do bus. Merseytravel/Liverpool City Region, April 2016

UITP (2010). Buses today and tomorrow, (press materials). Retrieved from: https://www.uitp.org/sites/default/files/Buses%20today%20and%20tomorrow.pdf

UITP (2019). Global Bus Survey. Statistic brief. May 2019. Retrieved from: https://www.sustainable-bus.com/wp-content/uploads/2019/07/Statistics-Brief_Global-bus-survey-003.pdf

Borén, S., & Ny, H. (2016). A strategic sustainability analysis of electric vehicles in EU today and towards 2050. International Journal of Environmental, Chemical, Ecological, Geological, and Geophysical Engineering, 10(3), 207–215. http://doi.org/waset.org/Publication/ 10003726

Robèrt, K.-H., Borén, S., Ny, H., & Broman, G. (2017). A strategic approach to sustainable transport system development - Part 1: Attempting a generic community planning process model. Journal of Cleaner Production, 140, 53–61. (Systematic Leadership towards Sustainability), doi:10.1016/j.jclepro.2016.02.054

Boren, S., Nurhadi, L., & Ny, H. (2016). Preference of electric buses in public transport; conclusions from real life testing in eight Swedish municipalities. International Journal of Environmental, Chemical, Ecological, Geological, and Geophysical Engineering, 10(3), 255–264.

Li, J.-Q. (2016). Battery-electric transit bus developments and operations: A review, International Journal of Sustainable Transportation, 10:3, 157-169, DOI: 10.1080/15568318.2013.872737
Borén, S. (2019). Electric buses' sustainability effects, noise, energy use, and costs. International Journal of Sustainable Transportation, 1-16.

Mahmoud, M., Garnett, R., Ferguson, M., & Kanaroglou, P. (2016). Electric buses: A review of alternative powertrains. Renewable and Sustainable Energy Reviews, 62, 673-684.

Varga, B. O., Iclodean, C., & Mariasiu, F. (2016). Electric and hybrid buses for urban transport: energy efficiency strategies. Springer.

Živanović, Z., Nikolić, Z., & Stevic, Z. (2012). The application of electric drive technologies in city buses. Intech open science, 165-203.

Varga, B., & Iclodean, C. (2015). Electric buses for urban transportation: assessments on cost, infrastructure and exploitation. Fascicle of Management and Technological Engineering, (1), 253-258.5

Infobus (2020, 25 August). Polski rynek autobusów elektrycznych w I połowie 2020 r. Infobus.pl. Retrevied from: http://infobus.pl/polski-rynek-autobusow-elektrycznych-w-i-polowie-2020-r-_more_126555.html

Olsson, O., Grauers, A., & Pettersson, S. (2016). Method to analyze cost effectiveness of different electric bus systems. In Proceedings of the EVS29 symposium, Montreal, Quebec, Canada.

Rothgang, S., Rogge, M., Becker, J., & Sauer, D. U. (2015). Battery design for successful electrification in public transport. Energies, 8(7), 6715-6737.

–> [Hug, V. (2015). Copenhagen trial with 12 m b.y.d k9 electric buses. Gothenburg, Sweden: Nordic Electric Bus Initiatives.]

–> [Rothgang, S., Rogge, M., Becker, J., Sauer, D.U., 2015. Battery design for successful electrification in public transport. Energies 8 (7), 6715e6737. https://doi.org/ 10.3390/en8076715.
]

Wang, X., Gonzalez, J.A., 2013. Assessing feasibility of electric buses in small and medium-sized communities. *Int. J. Sustain. Transp.* 7, 431e448. https://doi.org/10.1080/15568318.2012.667864.

Wang, N., Li, Y., Liu, Y., 2014. Economic evaluation of electric bus charging infrastructure. In: IEEE 17th International Conference on Intelligent Transportation Systems. Qingdao, China. https://doi.org/10.1109/ITSC.2014.6958138.

Göhlich, D., Kunith, A., & Ly, T. (2014). Technology assessment of an electric urban bus system for Berlin. WIT Trans. Built Environ, 138, 137-149.

Mohamed, M., Farag, H., El-Taweel, N., & Ferguson, M. (2017). Simulation of electric buses on a full transit network: Operational feasibility and grid impact analysis. *Electric Power Systems Research*, 142, 163–175.

Mohamed, M., Ferguson, M., & Kanaroglou, P. (2018). What hinders adoption of the electric bus in Canadian transit? Perspectives of transit providers. Transportation Research Part D: Transport and Environment, 64, 134-149.

Gallet, M., Massier, T., & Hamacher, T. (2018). Estimation of the energy demand of electric buses based on real-world data for large-scale public transport networks. Applied energy, 230, 344-356.

Sun, Y. (2012). About the half of battery-electric buses suffered from the short operational range. Retrieved from http://www.find800.cn/news/ diao/kediao/ 120919/23446.html

Shu, M. (2012). An electric bus costs about 2.8 million rmbs, but its batteries are degraded gradually [in Chinese]. Retrieved from http://www.find800.cn/news/diao/ kediao/120831/22992.Html.

ZeEUS Project (2018). *ZeEUS eBus Report #2. An updated overview of electric buses in Europe.* Available online at http://zeeus.eu/uploads/publications/documents/zeeus-ebus-report-2.pdf.

Lajunen, A., (2014). Energy consumption and cost-benefit analysis of hybrid and electric city buses. *Transport. Res. C-Emer.* 38, 1–15.

Lajunen, A. (2018). Lifecycle costs and charging requirements of electric buses with different charging methods. Journal of cleaner production, 172, 56-67.

Tammi, K., & Lajunen, A. (2016). Energy consumption and carbon dioxide emission analysis for electric city buses. In 29th World Electric Vehicle Symposium and Exhibition (EVS29) Curran Associates, Inc.

Gao, Z., Lin, Z., LaClair, T. J., Liu, C., Li, J. M., Birky, A. K., & Ward, J. (2017). Battery capacity and recharging needs for electric buses in city transit service. *Energy,* 122, 588-600.

Xylia, M., Leduc, S., Patrizio, P., Kraxner, F., & Silveira, S. (2017). Locating charging infrastructure for electric buses in Stockholm. *Transportation Research Part C: Emerging Technologies*, 78, 183-200.

He, X., Zhang, S., Ke, W., Zheng, Y., Zhou, B., Liang, X., & Wu, Y. (2018). Energy consumption and well-to-wheels air pollutant emissions of battery electric buses under complex operating conditions and implications on fleet electrification. Journal of Cleaner Production, 171, 714-722.

Steen, D., Tuan, L. A. (2017). Impacts of fast charging of electric buses on electrical distribution systems. CIRED-Open Access Proceedings Journal, 2017(1), 2350-2353.

Carrilero, I., González, M., Anseán, D., Viera, J. C., Chacón, J., & Pereirinha, P. G. (2018). Redesigning European Public Transport:

Impact of New Battery Technologies in the Design of Electric Bus Fleets. Transportation research procedia, 33, 195-202.

Rogge, M., Wollny, S., & Sauer, D. U. (2015). Fast charging battery buses for the electrification of urban public transport—a feasibility study focusing on charging infrastructure and energy storage requirements. Energies, 8(5), 4587-4606.

Vetter, J.; Novák, P.; Wagner, M.R.; Veit, C.; Möller, K.-C.; Besenhard, J.O.; Winter, M.; Wohlfahrt-Mehrens, M.; Vogler, C.; Hammouche, A. Ageing mechanisms in lithium-ion batteries. J. Power Sources 2005, 147, 269–281.

Sebastian, S. S., Dong, B., Zerrin, T., Pena, P. A., Akhavi, A. S., Li, Y., ... & Ozkan, M. (2020). Adaptive fast charging methodology for commercial Li−ion batteries based on the internal resistance spectrum. Energy Storage, e141.

De Filippo, G., Marano, V., & Sioshansi, R. (2014). Simulation of an electric transportation system at The Ohio State University. Applied Energy, 113, 1686-1691.

Miles, J., & Potter, S. (2014). Developing a viable electric bus service: The Milton Keynes demonstration project. Research in Transportation Economics, 48, 357-363.

Häll, C. H., Ceder, A., Ekström, J., & Quttineh, N. H. (2019). Adjustments of public transit operations planning process for the use of electric buses. Journal of Intelligent Transportation Systems, 23(3), 216-230.

Korolkov, S. (Ed.) (2015). How to build and operate an efficient trolleybus system. UITP 2015.

Zavada, J., Blašković Zavada, J., & Miloš, K. (2010). Conditions for implementing trolleybuses in public urban transport. Promet-Traffic&Transportation, 22(6), 467-474.

Schuchmann, A. 2005. Trolleybus Systems: Business Case (Investment and operating costs) [CD], in: UITP-Bus Committee, 2th Trolleybus meeting.

Tica, S.; Busarčević, D. 2005. Elements for defining policy of trolleybuses traffic development [CD], in: UITP-Bus Committee, 3th Trolleybus meeting.

Tica, S., Filipović, S., Živanović, P., & Bajčetić, S. (2011). DEVELOPMENT OF TROLLEYBUS PASSENGER TRANSPORT SUBSYSTEMS IN TERMS OF SUSTAINABLE DEVELOPMENT AND QUALITY OF LIFE IN CITIES. International Journal for Traffic & Transport Engineering, 1(4).

Wołek, M., & Wyszomirski, O. (Eds.) (2013). The trolleybus as an urban means of transport in the light of the Trolley project. Wydawnictwo Uniwersytetu Gdańskiego, Gdańsk.

Bjorklund, S., Soop, C., Rosenqvist, K., Ydstedt A. (2000). New concepts for trolley buses in Sweden. KFB-Rapport 2000:70. Kommunikationsforskningsberedningen. [*Swedish Transport and Communications Research Board]*.

Trolley Project (n.d.) Take-up guide for the Replacement of urban Diesel buses by Trolleybuses.

Bergk, F., Biemann, K., Lambrecht, U., Pütz, R., & Landinger, H. (2016). Potential of In-Motion Charging Buses for the Electrification of Urban Bus Lines„„. Journal of Earth Sciences and Geotechnical Engineering, 6(4), 347-362.

Bartłomiejczyk M. (2017). "Practical application of in motion charging: Trolleybuses service on bus lines," 2017 18th International Scientific Conference on Electric Power Engineering (EPE), Kouty nad Desnou, 2017, pp. 1-6. doi: 10.1109/EPE.2017.7967239

Wołek, M., & Hebel, K. (2019, September). Strategic planning of the development of trolleybus transportation within the cities of Poland. In Scientific And Technical Conference Transport Systems Theory And Practice (pp. 141-152). Springer, Cham.

Wołek, M., Wolański, M., Bartłomiejczyk, M., Wyszomirski, O., Grzelec, K., Hebel, K. (2020, pre-proof). Ensuring sustainable development of urban public transport: A case study of the trolleybus system in Gdynia and Sopot (Poland), Journal of Cleaner Production, https://doi.org/10.1016/ j.jclepro.2020.123807.

TROLLEY 2.0, 2020. TROLLEY 2.0 project [WWW Document]. URL https://www.trolleymotion.eu/trolley2-0/

Bundesministerium für Verkehr und digitale Infrastruktur (BMVI) *[Federal Ministry of Transport and Digital Infrastructure]* . (2019). Wissenschaftliche Beratung des BMVI zur Mobilitäts- und Kraftstoffstrategie: Machbarkeit eines Hybridoberleitungsbusbetriebs – „Berlin-Spandau“.