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Ensuring sustainable development of urban public transport: A case study of the trolleybus system in Gdynia and Sopot (Poland)

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ABSTRACT

Electromobility is a vital tool in reducing the environmental impact of transportation. A technologically mature means of public transport is the trolleybus. Based on a case study of the Polish cities of Gdynia and Sopot, this paper explores the factors that influence the development of the trolleybus system. Recent developments of in-motion charging (IMC) technology are analysed what provides a new analytical framework for the trolleybus development, bringing the original path for the expansion of the electromobility in urban areas without overhead lines. The use of an economic model has made it possible to assess the total lifecycle costs of trolleybuses and to specify a threshold that makes it more cost-effective than diesel buses. Operational data allows for a simulation that reveals the minimal rate of catenary coverage of a route in terms of speed and two charging power values. Results indicate that after including external costs into the economic calculation, trolleybus transport is economically efficient, although the energy mix is an important factor. In-motion charging trolleybus can be seen as a compromise solution between capital costs and battery capacity and is recommended for cities already operating this system.

1. Introduction

1.1. The concept of sustainable development

The concept of sustainable development emerged in the 1960s following the discussion on the environmental impact of economic growth (Chen et al., 2019). In 1987 the report 'Our Common Future' of the United Nations World Commission on Environment and Development was published. The report defined sustainability as 'meeting the needs of the present without compromising the ability of future generations to meet their own needs' (UN, 1987).

Discussions about sustainable development were initially focused on reducing the negative impact of economic activity on the environment. Over the years, sustainable development evolved into a complex concept based on the three pillars, that is environmental, economic and social (Hassan and Lee, 2015; Zheng et al., 2014), and also scientific research and personal decision-making (Helne and Hirvilammi, 2015). Complexity and difficulty of its definition in clear terms are the reasons why sustainable development is structured with 17 Sustainable Development Goals set by the United Nations (United Nations. Economic and Social Council, 2020).

In political debate, sustainable development is regarded as a horizontal principle for transport, serious environmental, economic and social challenges.

1.2. Electrification of public transport in cities as a response toward environmental challenge

Although urban mobility has a local dimension, the consequences of inaction are European or even global in scope (European Commission, 2009, 2007) and must be dealt with taking into account transport, land use, real estate, environmental protection, and social policies (European Commission, 2013). The European Commission has singled out cities and local authorities as crucial stakeholders in the shift to low-emission mobility through urban planning, integrated land use, and sustainable urban transport

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Nomenclature

AC	alternate current
BEV	battery electric vehicle
BoB	battery on bus
CNG	compressed natural gas
CO_2	Carbon dioxide
DC	direct current
EV	electric vehicle
GHG	greenhouse gas
IMC	in-motion charging
kWh	kilowatt-hour
LCC	Life Cycle Cost
LTO	lithium-titanate
NCA	nickel-cobalt-aluminium
NiCd	nickel-cadmium
NMC	nickel-manganese-cobalt
PKT	Przedsiębiorstwo Komunikacji Trolejbusowej sp. z o. o., a trolleybus transport operator
$PM_{2.5}$	atmospheric particulate matter with a diameter of less than 2.5 micromenters
SO_2	sulphur dioxide
V	volt
ZKM Gdynia	Zarząd Komunikacji Miejskiej w Gdyni, Public Transport Authority in Gdynia

(European Commission, 2016). Therefore, adapting to climate change at the local level poses a strategic challenge for cities that aim to sustain or achieve a high quality of life for its citizens.

The development of public transport is one of many initiatives that decrease the negative impact on the environment and increase in urban sustainability and resilience (European Environment Agency, 2012). The electrification of public transport is a crucial element in improving energy efficiency (Lajunen, 2014), limiting emissions of harmful substances (at the local level), and reducing noise pollution (Ajanovic and Haas, 2016) and is redefining the public transport market (UITP, 2019a). Therefore, a significant motivation for the electrification of public transport is climate change mitigation (Nordelöf et al., 2019) since electric powertrains are highly energy-efficient, leading to lower levels of emissions and noise (Xylia and Silveira, 2018). The scale is dependent on local conditions and transit operating characteristics (Xu et al., 2015a), including local bus route characteristics (Gallet et al., 2018). The electrification of public transport fleets is growing faster than that of passenger cars, and market penetration in Europe is expected to reach 75% by 2030 (World Economic Forum, 2019).

In many cities, trolleybuses (often with trams) are the backbone of urban transport (Fitzová and Matulová, 2020; Kołoś and Taczanowski, 2016); their recent development is made possible by advances in battery technology.

1.3. Structure of the paper

The paper discusses different aspects of the evolutionary process of the development of trolleybuses using a case study of the Polish municipalities of Gdynia and Sopot.

The structure of the paper is, therefore, as follows. The Research approach (chapter 2) includes the thesis, research questions and presents methods being used to answer them. Chapter 3 forms an overview of the trolleybus development, including an impact of the batteries and recent battery advancement developments of in-motion charging technology. In section 4, the case study site was thoroughly described, and the results of various research necessary for the goal of the paper were presented. Chapter 5 (discussion) and Chapter 6 (Conclusions) include results of the examination based on the results and literature review.

2. Research approach

This study explores the factors that influence the development of the trolleybus system in the municipalities of Gdynia and Sopot, located in the metropolitan area of Gdansk-Gdynia-Sopot in Poland.

The thesis is that economic, environmental, operational, social and technological conditions determine the evolution of trolleybuses toward increasing use of battery drives. This is further detailed through the following research questions:

- What is the possible direction of the evolution of trolleybus transport considering in-motion charging?
- Is the trolleybus significant independence from the catenary an important factor determining the efficiency of the transport system from the operational, environmental and economic point of view ?

Different research methods have been used to answer these questions, including case study analysis, marketing research, economic modelling based on Life Cycle Cost (LCC) and the simulation results on the catenary independent trolleybuses.

Case study analysis formulates the research background as it constitutes a type of intensive research (Swanborn, 2010) and enables the design of specific research questions to provide a range of evidence (Gilham, 2000). The analysis is in a real context (Yin, 2012) and timeframe, which is crucial in evaluating the transformation process of trolleybus systems. Although this study is focused on one local market, the economic, environmental, operational, social, and technological aspects reflect the complexity of the transition to electromobility at urban and metropolitan levels.

Life cycle cost (LCC) is commonly used to estimate the total costs of a given product according to its purchase, operation, maintenance and end-life (Islam and Lownes, 2019). An economic model based on the lifecycle cost approach and developed by the Electrification of Public Transport in Cities (ELIPTIC) project's team of authors is used to examine economic and environmental aspects (section 4.2.1). LCC methodology provides the economic and environmental comparability (Ally and Pryor, 2016; Harris et al., 2020; Mohamed et al., 2017; Simons and Bauer, 2015) of different alternatives for the electrification strategies that could be analysed in a model (Sánchez et al., 2013; Xu et al., 2015b). However, in a complex review of alternative fuel assessment studies for public transport buses in the U.S., investigating the end-of-life impacts was difficult because alternative fuel vehicles were in their initial phase of market operation (Tong et al., 2017). The analysis could be adapted for the whole public transport system or for particular lines, considering their specific features (Chang et al., 2019).

The model was improved and adjusted to specific Polish conditions within TROLLEY 2.0 project (TROLLEY 2.0, 2020). It allows for both financial and economic analysis and compares the range of solutions between trolleybuses and e-buses. It also enables input values representing local conditions such as the energy-mix or the existence of overhead networks along with an entire or part of a route to be predefined.

Social aspects (section 4.2.3) are discussed based on the results of marketing research partly focused on the trolleybus system in Gdynia in 2018 (conducted by the ZKM Gdynia – Public Transport Authority in Gdynia) and those conducted within TROLLEY 2.0 project (autumn 2019). The first research was devoted to examining transport behaviour, identifying modal splits, assessing residents' transport preferences, reasons for using particular means of transport, and quality of services. Research on transport behaviour is regarded as a baseline for the transport policy at each level (Bartosiewicz and Pielesiak, 2019). The random sample for in-house interviews included approximately 2000 residents (aged from 16 to 75) of Gdynia. The second research (conducted by the University of Gdansk) focused exclusively on trolleybus transport. Conversely, this research was quota-based; it included equally the residents of districts served by trolleybuses and those that are not. Personal interviews were conducted in places of highly populated areas (bus stops, parking, in front of shopping centres).

Technological aspects include simulations results within the ELIPTIC project for the trolleybus operator in Gdynia. The minimum technical requirements for the IMC power supply system are presented in section 4.2.4.

The results indicate a combination of different methods is needed to solve the complexity of the issue and to reflect its novelty.

The implementation of in-motion charging (IMC) technology in trolleybus transport, possible by technological advances in traction batteries, creates new opportunities for its use in urban areas without overhead lines. Therefore, this study contributes by providing:

- a new analytical framework for trolleybus development, bringing the original path for the expansion of the electromobility in urban areas without overhead lines;
- complex approach to the evolution of the trolleybus transport system, considering economic, environmental, operational, social and technological aspects;
- quantitative verification of the importance of renewable energy sources in IMC trolleybuses by using the LCC model;
- determination of the limit parameters for the IMC system (including minimal length of traction network per route depending on the parameters relevant to the operation of IMC trolleybuses);
- energy analysis of the IMC system based on real data from onboard recording systems (vehicle data logger systems).

3. The process of trolleybus evolution

3.1. Technical features of the trolleybus transport

The trolleybus is powered by direct current (DC) of between 550 V and 750 V (Fig. 1) network is divided into supply sections that are powered by traction supply cables (i.e. feeders) from substations that convert energy from the alternate current grid into DC power for the vehicles. One substation can provide power to as many as a dozen supplied sections.

The network circuit is usually isolated from the ground, making it equivalent to an IT system in electric installations.

The trolleybus was the first means of electric mode of road transport but its operational restraints and inflexibility limited its use throughout the 20th century (Chen et al., 2015).

In many cities, the trolleybus constitutes a vital part of transport services (Fitzová and Matulová, 2020) but its development has been stunted by exogenous and endogenous factors. For example, trolleybus transport was hindered in the 1990s by difficult economic situations in many countries as a result of economic transformation (i.e. systemic), particularly in the former Soviet Union and Central Europe. Consequently, some systems could not withstand the financial distress and underinvestment that led to the degradation of their fleets and infrastructure. There was a noticeable trend against trolleybuses in favour of bus transport for its somewhat lower operating cost despite environmental concerns were ignored. The result of underinvestment can be seen in Russia, which has the most cities operating trolleybuses but whose fleets lack appropriate replacements (Ryzhkov, 2018).

Nowadays, the trolleybus is already operating in several European, American, and Asian cities with multiple powertrain options and designs (Alfieri et al., 2019). It is generally acknowledged as one of the most environmentally friendly electricity-based methods for public transport serving urban areas (Corazza et al., 2016a).

3.2. Battery development as a key factor determining evolution of trolleybuses

One of the main advantages of direct electrification is the delivery of electricity to the final user. The recent development of trolleybuses with traction battery accumulators allows for different pathways for further electrification (Connolly et al., 2014).

The use of electrochemical batteries that enable trolleybuses to travel a certain distance without power from the network is not a new solution. Trolleybuses produced as early as the 1950s were equipped with emergency battery power. Although interest in electrochemical batteries as a power source for EVs was on the rise in the first years of the 21st century, none of the used technologies proved to be satisfactory. Nickel-cadmium (Ni–Cd) batteries, despite their relatively low cost and proven technology, had a limited lifecycle for urban usage. Nickel-hydrogen proved to be superior in this scope but was more complicated in terms of road usage in traffic-oriented practice. It was only lithium technology that brought about a definite improvement; it was first utilized on a regular basis in Landskrona, Sweden, where hybrid trolleybuses were established in 2013 as a part of the Slide-In project.

Lithium-ion batteries combine technologies based on chemical compounds (Andwari et al., 2017). Among them, one of the most popular is the nickel-manganese-cobalt (NMC) cathode, which is characterised by high energy density, specific power, and an acceptable life span, making these batteries widely used in EVs and across industries.

The safest lithium-ion batteries, even when fully charged, are lithium-iron-phosphate batteries (LFP). They are stable regardless of temperature or tension (i.e. voltage) between electrode changes with a relatively small degree of battery depletion. Their strongest asset is high specific power that enables a discharge current to reach 20C and a relatively long life span. Its downfall, however, is the low density of collected energy. The link characterised by the highest energy density that reaches up to 300 Wh/kg is nickel-cobalt-aluminium combinate (NCA). Apart from its high energy density, it offers high nominal power, hence its implementation in Tesla EVs. Its low cycle durability of approximately 500 cycles constitutes its weakest point. Currently, the most promising lithium-ion batteries are lithium-titanate batteries (LTO). Their energy density is rather low compared to Ni–Cd batteries and they are the costliest among the discussed power sources. Their main asset, however, compensates for their cost and energy density: extremely high specific power that allows them to be depleted and charged by high voltage current. This is a significant feature for a power source in EVs. Their life span is decidedly greater than any other technology and amounts to at least 5000 cycles of charging and depleting. This value is increasing as technology develops. LTO batteries are currently installed on Solaris Skoda buses in Zlin, Czech Republic.

Currently, many cities with existing trolleybus infrastructure are integrating battery trolleybuses (Patella et al., 2018) that combine the advantages of the length of catenary and capacity of the battery. These operators benefit from their prior experience with electric

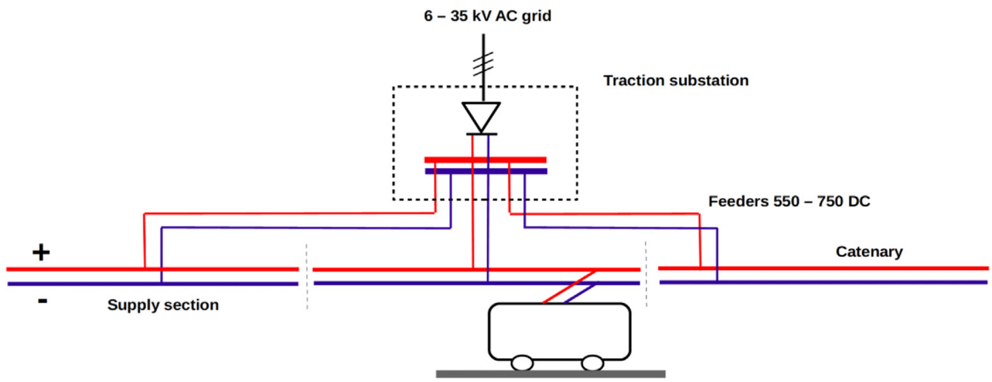

Fig. 1. An example of a trolleybus network powering system. Source: own work.

vehicles (EVs) - conventional trolleybuses fully dependent on catenary. According to Patella et al. (2018), 'this has gone some way to flattening the learning curve associated with the integration of IMCs in the network and connecting other EVs to the grid'.

3.3. In-motion charging trolleybuses

Using new power sources to make trolleybuses more flexible and partially independent from the catenary was tested as part of the TROLLEY project ('TROLLEY Project', 2013). Practical findings were implemented in 2015 within the CIVITAS DYN@MO project in Gdynia, with the first use of catenary-based trolleybuses with lithium-ion batteries on short sections without catenary ('CIVITAS DYN@MO project', 2016). This line was received positively among the general public when it entered regular operation. Further development of trolleybus-related issues was undertaken as a part of the ELIPTIC project of Horizon 2020 (2015–2018) with a general aim of optimising existing electric public transport infrastructure and rolling stock (ELIPTIC Project, 2018). The project mainly targeted three topics (integrating electric buses into already operational infrastructures, regenerating or upgrading electric public transport systems, and implementing multi-purpose infrastructure) (Corazza et al., 2016b) and focused on three trolleybus systems, Gdynia, Szeged, and Eberswalde. This included further development of battery-dependent trolleybus operations. A central focus of the TROLLEY 2.0 project (2018–2020) is the deployment of the in-motion-charging technology in trolleybus transport operations. Research, tests and implementation are conducted in Arnhem (Netherlands), Eberswalde (Germany), Gdynia (Poland) and Szeged (Hungary). (TROLLEY 2.0, 2020).

IMC trolleybuses usually use smaller batteries compared to electric buses (Gao et al., 2017) and can recharge while in motion through catenary (Bartłomiejczyk and Połom, 2016). One of the most important features of trolleybuses (and e-buses as well) is their ability to recover energy through regenerative braking, thus increasing energy efficiency (Gao et al., 2017). Recuperating braking energy reduces the energy loss in the braking resistors of trolleybuses (Bartłomiejczyk and Połom, 2016). However, what positively distinguishes trolleybuses is the increase in the use of regenerative braking energy achieved by an accumulation in supercapacitors or a change in topology of the power supply system to facilitate flow (Hamacek et al., 2014).

Currently, IMC trolleybuses are regarded as part of the modern electromobility concept and are the most technologically ready, fully electric means of public transport receptive to further innovation that can be categorized as:

- development of auxiliary power, especially batteries;
- energy efficiency improvements derived from recovered energy through regenerative braking;
- multi-use of power systems, making it available for other users (i.e. electric buses, electric cars, pedelecs).

In conclusion, 277 trolleybus systems are operating globally (UITP, 2019b), among which IMC vehicles are gradually being further developed. Trolleybuses are an effective tool in developing transport policy following the principles of sustainable mobility. The implementation of IMC technology, made possible by technological advances in traction batteries, creates new opportunities for its use in urban areas without overhead lines.

4. Results of the case study analysis

4.1. Process of development of trolleybus transport in Gdynia and Sopot

Trolleybuses in Gdynia (population 247,000) and Sopot (population 37,000) are operated by PKT Gdynia sp. z o. o. (PKT), which is owned entirely by the city of Gdynia. The Public Transport Authority in Gdynia (ZKM Gdynia) is solely tasked with organizing transport for both cities and four other municipalities on the Baltic coast. The trolleybus system forms an integrated network that serves both cities and has been gradually developed over the years. The board employs six other bus operators (two of which are municipal and four privately owned).

The development of trolleybus transport in Gdynia and Sopot has undergone several stages:

- inauguration in Gdynia (1943) and Sopot (1947);
- expansion (until 1971);
- decline (between 1972 and 1978);
- revitalisation (from 1979 until 1997);
- reorganisation (between 1998 and 2004);
- development through innovation and green technologies (between 2005 and 2014);
- regular service partly without catenary (from 2015).

The trolleybus network was developed in the post-war period and expanded from Gdynia to Sopot; at that time, environmental issues were marginal. The decline of its trolleybus transport was the result of the difficulty in obtaining new rolling stock since it was not produced nationally. The energy crisis spurred by an increase in the price of oil led to its revitalisation in the late 1970s.

One of the visible effects of Poland's political and economic transformation that began in the early 1990s was an increase in the number of passenger cars, which forced public transport systems to compete but also stressed the importance of greening the whole transport in the city.

The 1998 Act on the Transport Policy for the City of Gdynia constituted the city's first legislative attempt to prioritize the development of green trolleybus transport (Gdynia City Council, 1998). The PKT was formed that same year and took over the trolleybus rolling stock from the former municipal bus and trolleybus operator.

Joining the European Union accelerated the process of the quantitative and qualitative development of the trolleybus transport in Gdynia and Sopot (Wołek and Hebel, 2020). In 2005, PKT took part in a first EU-funded project to extend the catenary, purchase new rolling stock, and build a new depot, opening a new chapter in the development of trolleybus transport in the cities. PKT introduced trolleybuses equipped with nickel-cadmium batteries in 2010, marking the beginning of a series of actions aimed at freeing trolleybuses from the traction network. Trolleybuses powered by lithium-ion batteries were introduced in 2015 (Table 1). This stage provided regular service on lines that are partly independent of the traction network, giving trolleybuses electric bus-like features. PKT also simultaneously pioneered the conversion of used buses into trolleybuses. Consequently, the company was able to add 33 low-floor vehicles at relatively low cost quickly.

In 2019, trolleybuses in Gdynia and Sopot covered 5.383 million vehicle-kilometres (Fig. 2), accounting for 30.64% of the total urban transport supply in Gdynia and 13.24% in Sopot. Trolleybuses provided services on 16 trolleybus routes, 14 of which were annual and two seasonal. They also provided regular services on one bus route, replacing partly diesel vehicles. One of the seasonal lines was served by historical vehicles. Of the 96 vehicles owned by the trolleybus operator, 60% were equipped with lithium-ion batteries, enabling them to cover the distance up to 15 km independent of the catenary. The newest trolleybuses with LTO batteries delivered in 2019 can operate without catenary up to 35–50 kms in moderate weather conditions. The implementation of the described innovations has significantly decreased the unit energy consumption in recent years (Fig. 2).

4.2. Results

4.2.1. Economic and environmental aspects

To verify the efficiency of the trolleybus network development, this research used a lifecycle cost model created as a part of the TROLLEY project ('TROLLEY Project', 2013), extended and developed within the ELIPTIC project (Wołek et al., 2018) and adjusted to specific conditions for Poland within TROLLEY 2.0 project (TROLLEY 2.0, 2020).

The initial model compares diesel buses with four low-emission alternatives including hybrid, compressed natural gas (CNG), trolleybus, and battery electric vehicles (BEV, e-bus). The model compares the cost components — both internal and external — that differentiate the choices while omitting the rest (i.e. costs related to drivers). Each modelling output is equal to the total lifecycle costs for three typical daily distances:

- 150 km per workday, representing urban peak-only service (equivalent to 37 500 km/year, assuming 250 days of service per year, 'low-intensity mileage');
- 250 km per workday, representing typical urban service (62 500 km/year, 'medium-intensity mileage'), which is similar to assumptions of Tong et al. (2017);
- 350 km per workday, representing intensive service such as suburban or express service (equal 87 500 km/year, 'high-intensity mileage').

Typical daily mileage per workday is not synonymous with the average daily mileage, which is always lower because of breakdowns and lower mileage during weekends. In a summary of the extracted assumptions from other studies, daily mileages ranged from 140 to 450 km per day (Stempien and Chan, 2017).

The model can be easily adjusted for local conditions and issues. The full set of model assumptions has been described in Wołek et al. (2018). The model has been updated for this analysis to include additional variants for a public transport line:

- (1) diesel bus service;
- (2) 'classic' trolleybus service with network construction costs along an entire route and without batteries;
- (3) BEVs with mixed and overnight charging - the most promising BEV solution as shown by the ELIPTIC project findings (ELIPTIC Policy Recommendations, 2017) and Pelletier et al.'s (2019) analysis of 12-m vehicles because of the optimal trade-off between battery costs and operational capabilities resulting from the battery capacity;
- (4) BEVs charged from overhead trolleybus networks - IMC trolleybuses or so-called 'trolleybus without catenary' - a solution that can be used only in cities with existing trolleybus infrastructure that run buses along the trolleybus network to connect to stations with no overhead network. In these cases, although BEVs may be introduced without investment in infrastructure, vehicle costs increase due to the battery component. Similarly, overhead network wear increases slightly, resulting in some additional costs.

Considering the cash flows of operators (Fig. 3), the classic trolleybus service in which full network construction costs must be covered is not a competitive solution. Using BEVs charged from an existing overhead network as a complement is an optimum solution for typical services. Further, using an existing trolleybus network instead of financing new chargers moves the break-even point against diesel buses from approximately 270 km/day to about 190 km/day, meaning BEVs are recommended for all but typical peak service. The difference in total costs between variant (1) Diesel and, (3) BEV is nevertheless very slight and amounts in case of high mileages are 0,17€/km, and in case of medium mileages are 0,09€/km, which are both in favour of variant (3). Classic trolleybus (2) increases costs compared to Diesel (1) by 1,08€/km and 0,60€/km, respectively (Fig. 3).

In an economic analysis, taking external costs into account, Fig. 4 shows only a slight change, with very small difference remaining among variants (1), (3) and (4). Thus, the power-generation mix supersedes (International Energy Agency, 2019; Wang et al., 2015); it determines emission levels (especially CO_2, PM2.5 and SO_2) and willingness to pay for the reduction of local emissions.

In Poland, the local energy-mix is not favourable (only 20% of the energy is produced using zero-emission technologies) and poor air quality and dense urban environments have increased the willingness to pay for reduced emissions and noise levels. For a typical 250-km service per day, the economic lifecycle costs are basically the same for a diesel bus (1) and a BEV (3) with opportunity charging. Nonetheless, a BEV that is charged from an overhead network (IMC trolleybus) (4) is more efficient than a diesel bus (1) for most mileages. Even in peak-only service, it is economically neutral.

Moreover, an increase in local renewable energy production would improve the competitiveness of EVs since charging during operation (i.e. IMC) significantly lowers emissions compared to diesel buses because the share of renewables, especially solar energy, in the electricity mix is at a maximum during daylight (Rupp et al., 2019).

Table 1
Research and investment projects in trolleybus transport in Gdynia and Sopot since 2005

Period	Source of co-funding, project	Total investment [million EUR]	Rolling stock [trolleybuses]	Infrastructure
2005–2007	European Regional Development Fund (ERDF)	13.5	10	Construction of the depot. Construction of trolleybus catenary with a new loop
2010–2013	ERDF	25	28	Construction of 4 and upgrading of 5 substations. Construction of power dispatch management centre in one of the substations. Upgrading of catenary between Gdynia and Sopot
2010–2013	ERDF (Central Europe Program, TROLLEY project)	0	0	A temporary experimental super capacitor installed in one substation to increase efficiency of energy recuperation
2012–2016	7th Framework Program (CIVITAS DYN@MO project)	0.37	2	A permanent super capacitor installed in one substation to increase efficiency of energy recuperation
2015–2018	H2020 (ELIPTIC project)	0.1	0	Highly advanced dual power supply system software installed in the network. Feasibility studies for further extensions of trolleybus transport
2017–2020	ERDF	17.5	30 vehicles and 21 Lithium battery sets to replace Ni–Cd batteries in older vehicles	No infrastructure development planned
2018–2020	Electric Mobility Europe (TROLLEY 2.0 project)	0	0	Research on the in-motion-charging trolleybuses.
2019–2020	Non-emission public transport (within priority program Green Investment Scheme), part II, GEPARD	3.38	6	Short extension of trolleybus network. Replacement of 6 diesel buses with trolleybuses.

Source: own study based on (CIVITAS DYN@MO project, 2016; ELIPTIC project, 2018; TROLLEY Project, 2013; TROLLEY 2.0, 2020) [1 EUR = 4 PLN].

This can be also illustrated in our model (Fig. 5) - if we assume 100% green energy and call new variants respectively (2A), (3A) and (4A) - no-emission energy brings up to €15 000–20 000 lower yearly emission costs, compared to the current, real energy-mix assumed in Poland. It also changes main conclusions – BEVs charged from overhead trolleybus networks (4A) are the most efficient solution even at low mileages. Further, BEVs with mixed and overnight charging (3A) start to be more efficient than Diesel buses (1A) at a typical daily mileage of 170 km/yearly mileage of 42 500 km. At a medium mileage, the total economic cost of a battery trolleybus (3A) is 0,30€/km lower, compared to Diesel (1A) and at high mileage – 0,39€/km.

The modelling outcome presented above changes if trolleybus network construction is a sunk cost. Therefore, using an existing trolleybus network instead of new opportunity chargers is much more viable economically and increases benefits while decreasing the break-even point in comparison to diesel buses.

However, trolleybus network costs can be avoided only in the short run since the periodic exchange of overhead infrastructure is needed even though the infrastructure's lifetime cycle is much longer than that of a vehicle. Thus, although the costs of renewals are usually lower than those of construction, the lifecycle cost level will increase toward what is called a 'classic trolley' scenario.

The model considers the entire technical infrastructure, including network, substations, switches, and depot that a trolleybus transport operator has at its disposal. The lower energy costs and longer lifecycle of a trolleybus compared to a diesel bus is reflected in the results. Lifecycle costs of EVs in public transport, including charging devices, are an important consideration as they have significant impacts on capital costs (Lajunen, 2018).

Although the environmental advantages are strongly sensitive to the national energy-mix and local conditions (i.e. topography, population density, transport network, weather conditions), some findings indicate that trolleybuses are one of the best alternatives when modernizing a public transport fleet. EVs are more efficient under the 'well-to-wheel' approach as they rely on power generation (Köhler et al., 2009) and open research for further development of sustainable transport (Robèrt et al., 2017). In the 'well-to-wheel' approach, electric transport is locally emission-free regardless of a country's energy mix. A comparative 'well-to-wheel' lifecycle assessment of fuel chains indicates trolleybuses (and biogas buses) represent one of the best options for future public transport in Kaunas, Lithuania (Kliucininkas et al., 2012). Similarly, an analysis conducted for the city of Tychy (Poland) showed that novel solutions for traction design and vehicles equipped with traction batteries and generation systems can have a significant impact on energy savings and, therefore, on decreasing greenhouse gas emissions (Borowik and Cywiński, 2016). A comparative analysis of solutions for alternatively powered trolleybuses in Lublin, Poland, indicates that electrochemical batteries are advantageous in the long term (Hołyszko and Filipek, 2016).

4.2.2. Operational aspects

Electric buses are more than five times greater than IMC trolleybuses in range, which is a considerable advantage. However, this advantage only exists when there is limited or no existing overhead network. In Gdynia and Sopot, an overhead network covers 42.7 km of routes, including the city centre, thus allowing zero-emission IMC vehicles to be introduced in new residential developments. IMC trolleybuses allow for parts of an overhead network to be

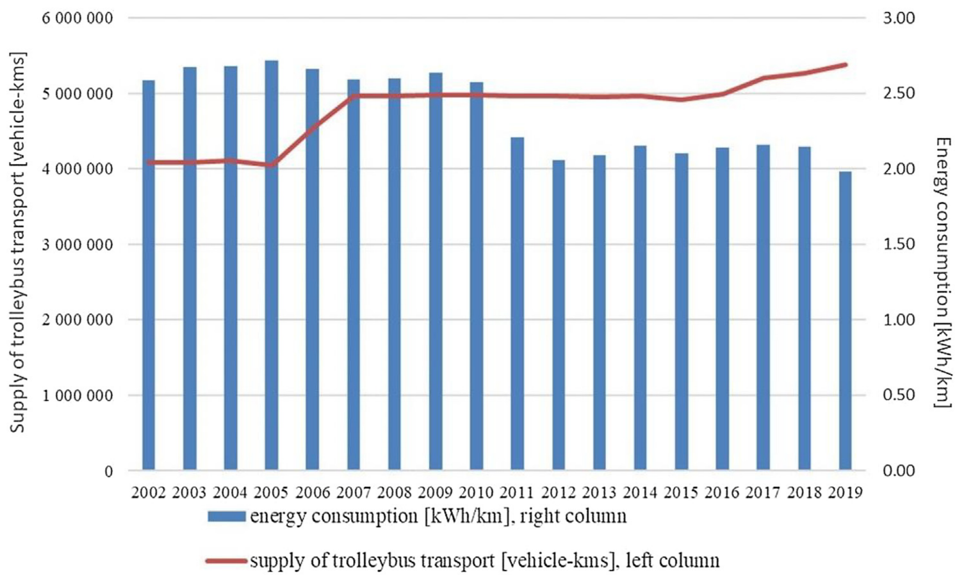

Fig. 2. Annual supply of PKT in Gdynia and energy usage per unit in the years 2002–2019. Source: own study based on (TROLLEY 2.0, 2020; ZKM Gdynia, 2020). Note: Total energy consumption, including heating and air conditioning, for 12 m-long vehicles.

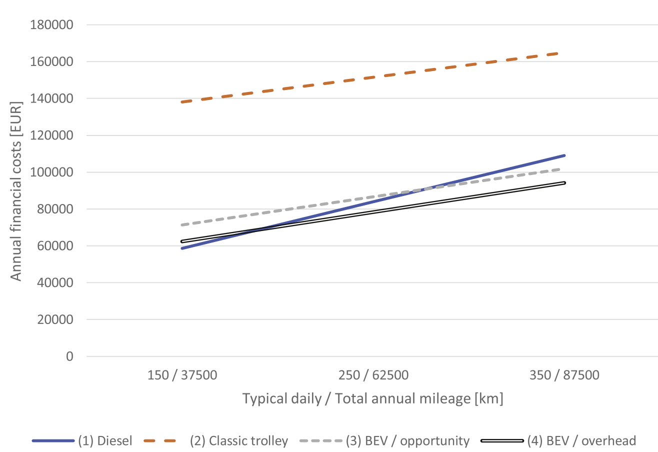

Fig. 3. Annual financial costs of operating an urban transport line assuming technology variants. Source: own work based on the (ELIPTIC Project, 2018; TROLLEY 2.0, 2020).

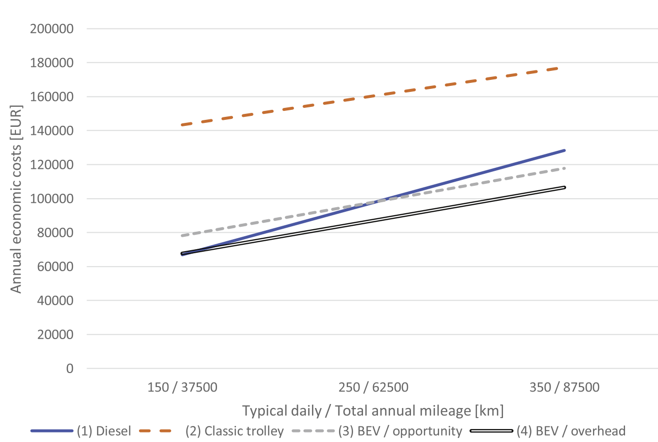

Fig. 4. Annual economic costs of operation of a line (including externalities) under technology variants – assuming real Polish energy-mix. Source: own work based on the (ELIPTIC Project, 2018; TROLLEY 2.0, 2020).

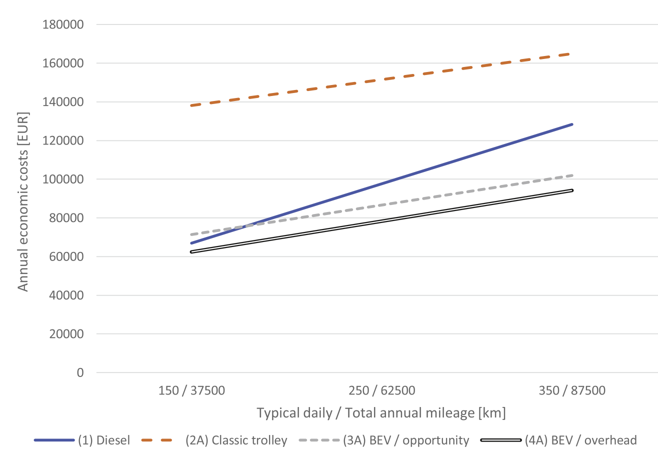

Fig. 5. Annual economic costs of operation of a line (including externalities) under technology variant – assuming using 100% green energy. Source: own work. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

removed from areas where they are deemed to be unnecessary, either because of local architecture or planning for city development.

By the end of 2019, five trolleybus lines in Gdynia and one in Sopot were partly operating without catenary. Moreover, since 2019 trolleybuses have partly replaced diesel buses on one 'conventional' bus line; on this line, trolleybuses from Gdynia to Sopot partially operate without catenary. The total vehicle-kilometres without catenary covered by trolleybus transport increased significantly in 2019 and accounted for 8.17% of the total supply (Fig. 6).

Trolleybuses need dedicated lanes on the streets of Gdynia and Sopot. Otherwise, their susceptibility to traffic congestion will negate their emission advantage. Their future operational efficiency strongly depends on an integrated transport network (with priorities given to public transport vehicles) that is in the process of development in Gdynia and Sopot.

4.2.3. Social aspects

The evolution of trolleybuses that determined the change of their share in the supply of public transport within Gdynia underwent additional social valuation in the light of the results of periodical, representative market research into the preferences and transport behaviour. The research analysis of the attitude of inhabitants towards the development of trolleybus transport was related to the share of trolleybuses in the public transport of Gdynia's supply (measured in vehicle-kilometres). Results presented in Table 2 support the conclusion that between the years 2000 and 2018, the percentage of inhabitants who would have liked to have seen trolleybus transport substituted with bus transport declined, while the share of those who opted for an unchanged balance between buses and trolleybuses - increased. The results of this research corroborate those completed as part of the Trolley 2.0 project in 2019. They show that 59.6% of inhabitants support further development of trolleybus transport despite being conscious of the fact that this form of transport incurs higher operational costs.

Even though particular features of trolleybuses were highly rated by the inhabitants who took part in research during the Trolley 2.0 project, the findings obtained did not confirm the influence of trolleybuses on the quality of life within cities. In relation to a cross-section of five vehicle features trolleybuses scored highly (7.95–8.19 on a scale between 1 and 10) (Fig. 7). More than 19.6% of inhabitants saw the ecological factor of trolleybuses as the main feature of these vehicles and 8.3% would consider paying a higher fare to travel on a trolleybus on account of its eco-friendliness.

4.2.4. Technological aspects

Although electrochemical batteries have made it possible for electric buses to service routes throughout the day without the need to recharge, challenges including risk mitigation, operational capabilities, and cost reductions remain (Mohamed et al., 2018). An alternative solution, especially for cities with an existing traction network, is IMC, also known as Slide-In (Bergk et al., 2016). The length of the line must be long enough to charge the battery with the energy needed to travel the section without traction. This is mainly a problem from a technical point of view, but also a scientific issue. The urban transport system is characterized by the influence of road congestion, which results in variability of energy consumption for traction purposes (Bartłomiejczyk, 2019). Moreover, energy consumption for non-traction purposes (heating, air conditioning) can also vary widely (Bartłomiejczyk and Kołacz, 2020). Consequently for example, the total energy consumption of a standard trolleybus can vary between 1 kWh/km and 4 kWh/km. Furthermore, the variability of motion parameters also affects the charging process during motion (Bartłomiejczyk, 2017). These factors have a significant impact on the economic effects of the IMC system (Bartłomiejczyk and Połom, 2020). Thus, the performance of the IMC system is complex, which predestines it for analysis using statistical methods.

For the IMC system operation, charging power is a crucial parameter. The newest batteries can achieve a charging power of 500 kW with a capacity exceeding 100 kWh which is expected to increase in the future. The charging power is limited by pantographs that should not be overloaded with a charging current of more than 120 kW in transit and 90 kW when stationary.

The following formula calculates the minimal length of traction network per route:

$$\frac{l'}{l} = \frac{e}{\frac{\eta . P_{ch}}{v} + e} \tag{1}$$

where l' represents the total line length [km]; l the distance travelled under the catenary [km]; η-the charging cycle efficiency; P_{ch} the charging power from the catenary [kW]; v the average speed of travel with catenary [km/h]; and e the vehicle's average energy consumption [kWh/km].

Trolleybuses in Gdynia are equipped with an energy data logger that records electrical and mechanical parameters of the ride including speed, traction drive current, vehicle current, and GPS location.

Records were made with a second resolution in CSV format and transferred from the vehicle to stationary database. Registrations of energy consumption on the trolleybus route in Morska street in Gdynia were used for the analysis. This is one of the main trolleybus corridors in Gdynia with a high intensity of car traffic and a significant impact of congestion. It allows us to reflect the work of the dynamic charging system in changing, severe traffic conditions.

This has created a huge database of energy consumption for trolleybuses that provides opportunities for detailed analyses. Data on energy usage while traveling can be used to simulate the charging and discharging cycle of the battery in a dynamic charging system in two stages: charging cycle (passing through a fixed length network section with an overhead catenary); and discharging cycle (passing through an autonomous section).

For the calculation of discharging, measurement data on the actual load of energy consumption by the vehicle are used. The calculations can define the length covered until the charging energy accumulated during the network section is fully utilized. After several repetitions for different registration data, the minimum degree of coverage for the traction network can be determined. In the charging cycle, the state of charge E_{bat} [kWh] of the traction battery is based on the state of charge in the previous iteration and charging power P_{ch}:

$$E_{bat}(t_n) = E_{bat}(t_{n-1}) + P_{ch} \cdot \Delta t \tag{2}$$

where Δt indicates the step of the iteration, which is the same as the interval of registration (1 s). The value of P_{ch} depends on the state of the vehicle due to reduced current capacitance of the collector. When the vehicle is standing, the value is lower. In every step of the calculations, the actual driven distance s is calculated as:

$$s(t_n) = s(t_{n-1}) + v(t_n) \cdot \Delta t \tag{3}$$

where v is the vehicle velocity. Where s is greater than the length of the catenary section l_{troll}, then autonomous mode (discharge) starts. In the discharging cycle, the state of charge E_{bat} of the traction battery is based on the state of charge in the previous iteration and the vehicle energy consumption P_{veh}:

$$E_{bat}(t_n) = E_{bat}(t_{n-1}) + P_{veh}(t_n) \cdot \Delta t \tag{4}$$

Cycle calculations are completed when the energy of the battery is at zero. The main outcomes of the calculations are the length of the autonomous running section and the ratio between the length of the catenary section and the total running length during the cycle. The algorithm of calculations is shown in Fig. 8.

An algorithm of calculations based on real measurement data allows for analysis of the real traveling and stopping time while in trolley mode and consider the real value of energy consumption from traction batteries during autonomous driving.

Fig. 9 shows an exemplary scatter plot of the calculation results with an average speed in the charging section and charging power of 120 kW while moving and 80 kW while standing. Each point marks the result of one driving cycle calculation. Consequently, we can select the best case values (with the minimal value - blue points) and the worst-case value (with the maximal value - red

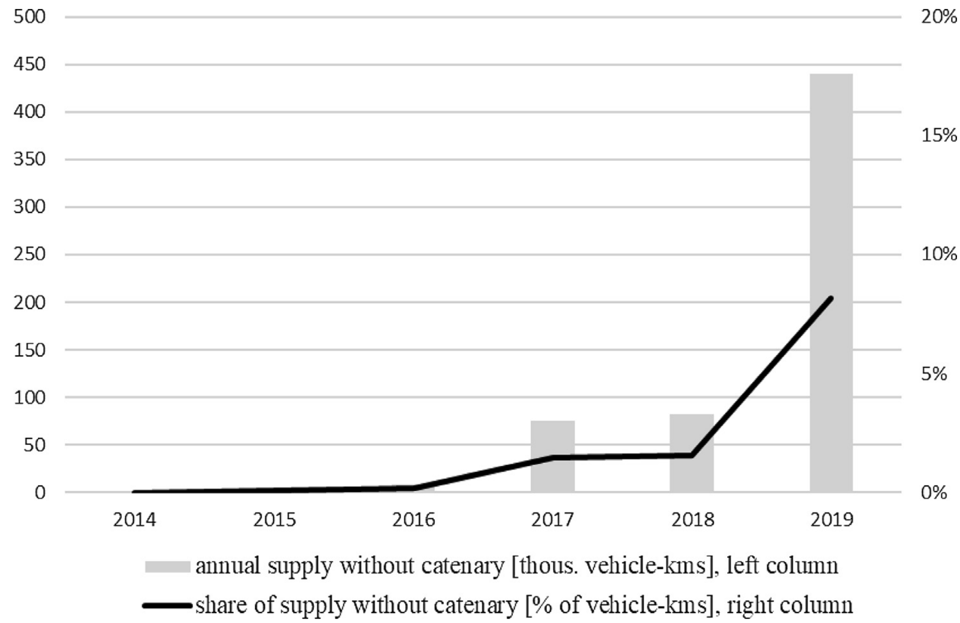

Fig. 6. Trolleybus vehicle kilometres without catenary in Gdynia and Sopot in 2014–2019. Source: own study based on (ZKM Gdynia, 2020).

Table 2
The share in operational work and the attitude of inhabitants towards further development of trolleybus transport in Gdynia between the years 2000 and 2018.

Emphasis		2000	2008	2015	2018
Share of trolleybuses in the operational work of public transport in Gdynia [%]		26	29	29	31
Opinions expressed by inhabitants on trolleybuses [%]	supporters of the introduction of new trolleybus lines	17	9	17	17
	supporters of the substitution of bus lines with trolleybus lines	11	9	9	11
	supporters of the current balance between buses and trolleybuses	42	52	56	53
	supporters of the substitution of trolleybus lines with bus lines	16	12	6	6
	respondents with no clear opinion	14	18	12	13

Source: own study based on the (ZKM Gdynia, 2019, 2016, 2009, 2001).

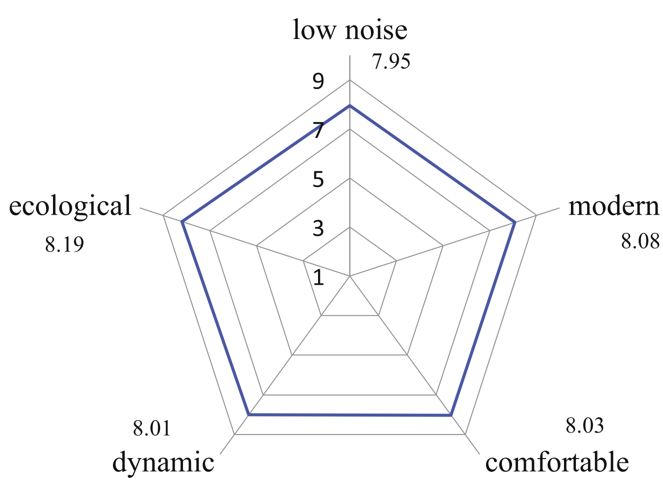

Fig. 7. Attitudes of Gdynia's inhabitants towards trolleybus features. Source: own work based on the (TROLLEY 2.0, 2020).

points). This defines the approximation line (red dotted line) that indicates the minimal rate of coverage for the transportation route by catenary by the function of speed. The covering rate depends on the speed of vehicle traffic. The higher the speed of movement, the smaller the time to cover a given distance, which reduces the charging time, according to equation (1). Thus, it is necessary to increase the degree of coverage of the transportation route.

The procedure is repeated for two parameters of charging:

- charging power of 120 kW while running and reducing charging power to 80 kW while standing due to the thermal limitation of the current collector. This can be relatively easily implemented in existing trolleybus systems:
- charging power of 250 kW while running and reducing charging power to 80 kW while standing. This requires a 'strong' supply system and in many cases will need an upgrade in infrastructure. This system was implemented in 2019 in Solingen, Germany, as part of the Battery-on-Bus (BoB) project.

Fig. 10 shows the approximation of the minimum rate values for the charging power 120 kW and 250 kW. Calculations are based on the energy consumption of 12-m vehicles. The average value of average speed is 14–18 km/h. Under this condition, if the battery is charged with 120 kW, at least 30%–35% of the route must be covered with a traction network. If the charging power is increased to 250 kW, covering 20% of the route with a traction network is sufficient.

5. Discussion

Transport plays a significant role in environmental degradation. The majority of adverse effects are concentrated at the city level (Gössling et al., 2019). CO_2 emissions from the transport sector in Poland increased from approximately 20 million tons in 1990 to more than 52.3 million tons in 2016 (Olecka et al., 2018). Some municipalities have implemented local Sustainable Urban Mobility Plans to encourage a shift to more sustainable transport (Okraszewska et al., 2018). An essential element to decrease emissions is the transformation of public transport into a zero-emission system. An existing zero-emission means of public transport is the trolleybus that is still operated in many cities worldwide.

The trolleybus transport system has experienced steady development over the last few decades in Gdynia and Sopot (Poland). First, its development was limited to the existing traction network and then followed by the introduction of modern vehicles and, investments that were partly funded by the EU. Implementation of an additional energy source in the form of an electrochemical battery marked another breakthrough, allowing trolleybuses flexibility on routes and adding a necessary feature in comparison to traditional diesel buses (Grygar et al., 2019). The IMC model of operation created a new 'milestone' for the development of the trolleybus transport in Gdynia and Sopot. Its development is the result of economic, environmental, operational, social, and

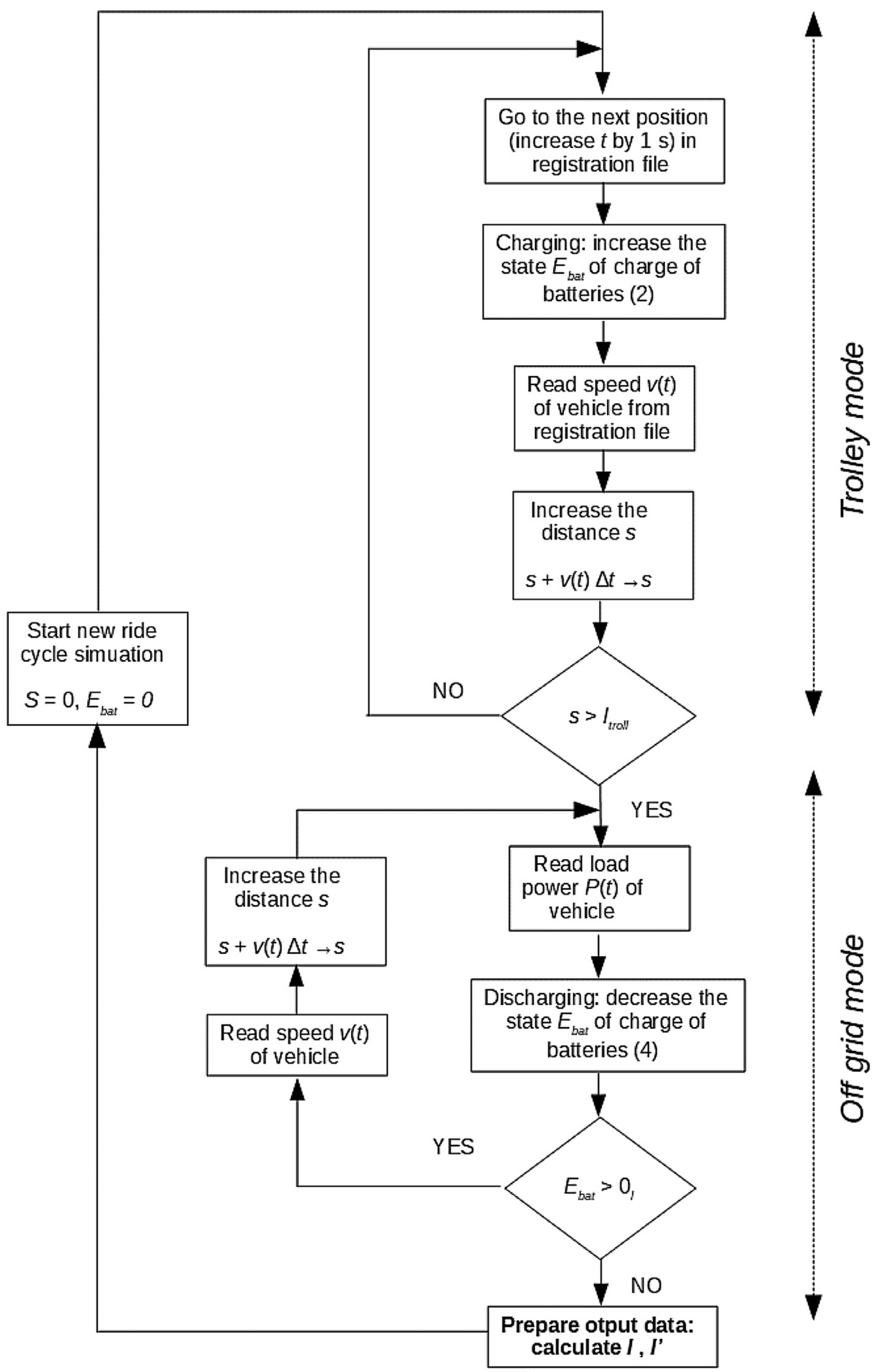

Fig. 8. Algorithm of energy load flow in Dynamic Charging. Source: own study.

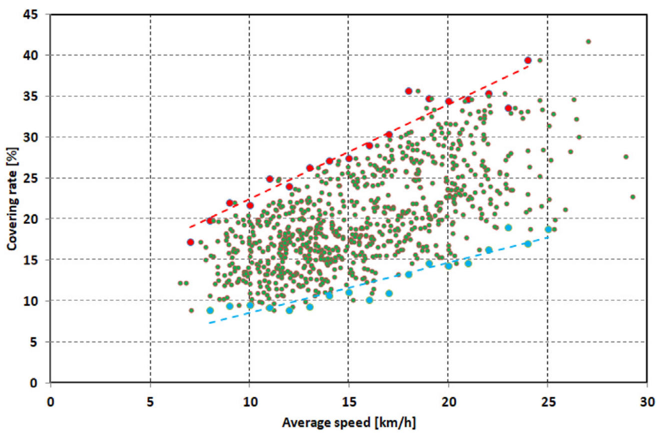

Fig. 9. Scatter plot of calculation results for average speed in charging section: charging power 120 kW. Source: own study based on (ELIPTIC Project, 2018).

technological influences. From an economic standpoint, low energy prices play a crucial role when considering the generally higher upfront costs of trolleybus rolling stock in comparison to traditional diesel bus. Besides, when used intensively on a given route, they can reach a threshold that makes them more cost-efficient (in the total lifecycle) than diesel buses.

From an operational point of view, the development of trolleybus transport in Gdynia and Sopot depends on the ability of trolleybuses to travel independently using batteries. IMC operation provides an optimal solution between expensive investments in infrastructure and the size of the battery in a trolleybus. High-capacity batteries that provide long daily ranges for e-buses can account for up to 50% of the vehicle price (Bartłomiejczyk and Kołacz, 2020). From a managerial point of view, IMC trolleybuses are recommended for cities already operating trolleybuses because of the effective compromises among energy consumption, service quality (Varga et al., 2019) and battery capacity. Therefore, to answer to the first research question, trolleybuses using IMC technology will become increasingly similar to electric buses, retaining the operational advantage of charging, but incurring higher costs for the construction and/or maintenance of the overhead network.

An essential issue of the transport system is its social support. It is even more important in Poland, as the funding for public

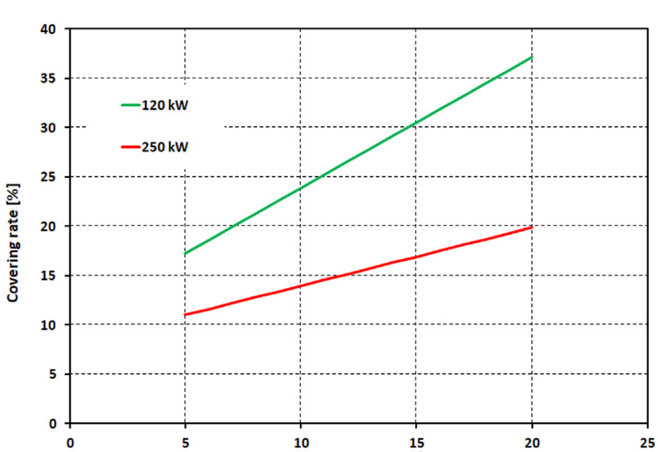

Fig. 10. Minimal covering rate for several charging methods (time value in brackets indicates the time after which charging power is reduced). Source: own study based on (ELIPTIC Project, 2018).

transport is provided mainly from the budgets of local and regional self-government with support from the EU for selected investments in rolling stock and infrastructure. In our study we used different results of marketing research to analyse the social support for trolleybus transport. Between 2000 and 2018 the number of residents opposing a trolleybuses decreased substantially (from 16% in 2000 to only 6% in 2018).

The main infrastructure cost is the length of the overhead trolleybus contact line since it must be sufficient to charge the vehicle. Its required length (or rather the network coverage rate) depends on the transportation traffic and charging power. Case study analysis from Gdynia and Sopot confirms that the maximum length of catenary needed to make IMC trolleybuses fully operational and reliable is decreasing as battery capacity increases. The Gdynia and Sopot case study indicates that trolleybus transport can be increased without extending overhead contact lines. Our findings show that at least 30% of the catenary length is needed to maintain the flexible and seamless supply for IMC trolleybuses. The exact value depends on traffic conditions of a particular route and should be determined on a case-by-case basis. The off-catenary operations can be further extended when the charging power is increased from 120 kW to 250 kW.

In comparison to an electric battery-bus, the IMC trolleybus can operate with a smaller capacity battery. This is supported by findings that show that the maximum battery capacity of 120 kWh provides the lowest lifecycle emissions for EVs in public transport (Xylia et al., 2019). IMC technology optimizes costs of the battery size and capacity because that technology does not require the larger battery capacity to prevent the shortage of energy as it is in case of the classic battery-electric buses (Wu et al., 2019).

Environmental factors play a significant role in the development of trolleybus transport. The undeniable advantage of trolleybuses is zero-emission local operations. As an increasing share of renewables was pointed out as one of the most effective strategies to decrease GHG emissions in public transport (Ou et al., 2010; Sánchez et al., 2013), it is necessary to use renewable energy sources and diversify the energy demand throughout the day. Our results confirm that the system presents a high susceptibility to increase the share of renewable energy, even without radical changes in existing technology and the way trolleybuses are operated. A theoretical model including 100% renewable energy makes the trolleybus the most efficient solution even at relatively low mileages. Therefore IMC trolleybuses can efficiently operate with a significant reduction of the overhead contact line, positively answering the second research question. The evidence is the substantial increase in off-catenary trolleybus operations in Gdynia and Sopot in 2019, reaching 8.17% of the total supply.

6. Conclusions

The development process of trolleybus transport has been characterized by phases of expansion and contraction that have often led to the closure of trolleybus lines. Its decline that began in the middle of the 20th century in many cities aided the expansion of the automotive industry. The fuel crisis of the 1970s finally reversed this trend.

Until the 1980s, the narrowly understood costs of public transport that effectively came down to the operations and maintenance of a given mode of transport served as the basis for the preservation of a trolleybus line. Currently, a much broader analysis is needed, including the evaluation of external costs and ecological effects using LCC methodology.

Innovative advancements such as drive and power storage means trolleybuses are similar to electric buses. Recent IMC developments (wireless line operation) have been tested in various

EU projects including ZeEUS (Cagliari, Italy), ELIPTIC (Wołek et al., 2018) and TROLLEY 2.0 (Eberswalde – Germany, Gdynia – Poland, Szeged – Hungary) (TROLLEY 2.0, 2020).

Taking all transport-related costs into account is essential since EVs offer a better total cost of ownership than diesel buses (Mathieu, 2018). Without taking external costs into account, the comparison does not include a variety of impacts and makes trolleybus transport uncompetitive in comparison to diesel bus transport, mainly because of high upfront infrastructure and rolling stock costs. External costs may vary according to the local energy mix. The share of no-emission energy production is one of the critical determinants of battery-powered EVs' break-even mileage. To increase the benefits of mass electrification of public transport in Polish cities, including Gdynia and Sopot, the structure of electricity generation should be changed, according to the principle of sustainable development. Development of renewable sources of energy at a local and national level is a feasible activity that increases the ecological advantages of trolleybuses and battery buses.

Further development of trolleybus transport in Gdynia and Sopot will be determined by innovations in vehicle drive and battery and the economic potential of the cities to develop and maintain the system. In Gdynia and Sopot, trolleybuses operated on seven lines in 2019 partly without catenary, including one line in which they co-existed with buses. This trolleybus solution is beneficial economically, environmentally, ecologically, and socially as well as from operational and technological points of view. Modern trolleybuses with lithium-ion batteries can travel up to 50 km without catenary and can provide services in areas without overhead network which, until now, had been excluded from trolleybus service.

Further development of IMC in trolleybus transport will gradually blur the differences between trolleybuses and battery e-buses. Moreover, adding more electricity from renewable energy sources to the high mileage of vehicles would increase the environmental and economic benefits of electromobility provided by IMC trolleybuses. IMC has the potential to revitalize trolleybus transport in a growing number of European cities.

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CRediT authorship contribution statement

Marcin Wołek: Conceptualization, Funding acquisition, Investigation, Project administration, Visualization, Writing - original draft. **Michał Wolański:** Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing - original draft. **Mikołaj Bartłomiejczyk:** Data curation, Formal analysis, Investigation, Methodology, Resources, Visualization, Writing - original draft. **Olgierd Wyszomirski:** Conceptualization, Investigation, Supervision, Writing - original draft. **Krzysztof Grzelec:** Formal analysis, Resources, Validation, Writing - review & editing. **Katarzyna Hebel:** Methodology, Resources, Validation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Ajanovic, A., Haas, R., 2016. Dissemination of electric vehicles in urban areas: major factors for success. Energy 115. https://doi.org/10.1016/j.energy.2016.05.040.

Alfieri, L., Bracale, A., Caramia, P., Iannuzzi, D., Pagano, M., 2019. Optimal battery sizing procedure for hybrid trolley-bus: a real case study. Elec. Power Syst. Res. 175 https://doi.org/10.1016/j.epsr.2019.105930.

Ally, J., Pryor, T., 2016. Life cycle costing of diesel, natural gas, hybrid and hydrogen fuel cell bus systems: an Australian case study. Energy Pol. 94, 285–294. https://doi.org/10.1016/j.enpol.2016.03.039.

Andwari, M.A., Pesiridis, A., Rajoo, S., Martinez-Botas, R., Esfahanian, V., 2017. A review of Battery Electric Vehicle technology and readiness levels. Renew. Sustain. Energy Rev. 78, 414–430. https://doi.org/10.1016/j.rser.2017.03.138.

Bartłomiejczyk, M., 2019. Driving performance indicators of electric bus driving technique: naturalistic driving data multicriterial analysis. IEEE Trans. Intell. Transport. Syst. 20, 1442–1451. https://doi.org/10.1109/TITS.2018.2850741.

Bartłomiejczyk, M., 2017. Practical application of in motion charging: trolleybuses service on bus lines. In: Proc. 2017 18th Int. Sci. Conf. Electr. Power Eng. EPE 2017 0–5.. https://doi.org/10.1109/EPE.2017.7967239.

Bartłomiejczyk, M., Kołacz, R., 2020. The reduction of auxiliaries power demand: the challenge for electromobility in public transportation. J. Clean. Prod. 252 https://doi.org/10.1016/j.jclepro.2019.119776.

Bartłomiejczyk, M., Połom, M., 2020. Dynamic charging of electric buses as a way to reduce investment risks of urban transport system electrification. In: Gopalakrishnan, K., et al. (Eds.), TRANSBALTICA XI: Transportation Science and Technology: Proceedings of the International Conference TRANSBALTICA. Springer Nature Switzerland AG. https://doi.org/10.1007/978-3-030-38666-5_32.

Bartłomiejczyk, M., Połom, M., 2016. Multiaspect measurement analysis of breaking energy recovery. Energy Convers. Manag. 127, 35–42. https://doi.org/10.1016/j.enconman.2016.08.089.

Bartosiewicz, B., Pielesiak, I., 2019. Spatial patterns of travel behaviour in Poland. Travel Behav. Soc. 15, 113–122. https://doi.org/10.1016/j.tbs.2019.01.004.

Bergk, F., Biemann, K., Lambrecht, U., Prof, D., Pütz, R., 2016. Potential of in-motion charging buses for the electrification of urban bus lines. J. Earth Sci. Geotech. Eng. 6, 347–362.

Borowik, L., Cywiński, A., 2016. Modernization of a trolleybus line system in Tychy as an example of eco-efficient initiative towards a sustainable transport system. J. Clean. Prod. 117, 188–198. https://doi.org/10.1016/j.jclepro.2015.11.072.

Chang, C.C., Liao, Y.T., Chang, Y.W., 2019. Life cycle assessment of alternative energy types – including hydrogen – for public city buses in Taiwan. Int. J. Hydrogen Energy 44, 18472–18482. https://doi.org/10.1016/j.ijhydene.2019.05.073.

Chen, C., Yu, Y., Osei-Kyei, R., Chan, A.P.C., Xu, J., 2019. Developing a project sustainability index for sustainable development in transnational public–private partnership projects. Sustain. Dev. 27, 1034–1048. https://doi.org/10.1002/sd.1954.

Chen, F., Taylor, N., Kringos, N., 2015. Electrification of roads: opportunities and challenges. Appl. Energy 150, 109–119. https://doi.org/10.1016/j.apenergy.2015.03.067.

CIVITAS DYN@MO Project, 2016. EU. URL. http://civitas.eu/content/dynmo. accessed 5.18.18.

Connolly, D., Mathiesen, B.V., Ridjan, I., 2014. A comparison between renewable transport fuels that can supplement or replace biofuels in a 100% renewable energy system. Energy 73, 110–125. https://doi.org/10.1016/j.energy.2014.05.104.

Corazza, M.V., Guida, U., Musso, A., Tozzi, M., 2016a. A European vision for more environmentally friendly buses. Transport. Res. Transport Environ. 45, 48–63. https://doi.org/10.1016/j.trd.2015.04.001.

Corazza, M.V., Guida, U., Musso, A., Tozzi, M., 2016b. A new generation of buses to support more sustainable urban transport policies: a path towards 'greener' awareness among bus stakeholders in Europe. Res. Transport. Econ. 55, 20–29. https://doi.org/10.1016/j.retrec.2016.04.007.

ELIPTIC Policy Recommendations, 2017. ELIPTIC Project Consortium. Bremen &

Köln. https://doi.org/10.4135/9781483399300.n14.
ELIPTIC Project, 2018. ELIPTIC Project. URL. http://www.eliptic-project.eu/. accessed 1.23.18.
European Commission, 2016. A European Strategy for Low-Emission Mobility. COM(2016) 501 final.
European Commission, 2013. Together towards Competitive and Resource-Efficient Urban Mobility. COM(2013) 913 Final.
European Commission, 2009. Action Plan on Urban Mobility. COM(2009) 490 Final 1–13.
European Commission, 2007. Towards a New Culture for Urban Mobility. COM(2007) 551 Final.
European Environment Agency, 2012. Urban Adaptation to Climate Change in Europe. https://doi.org/10.2800/41895.
Fitzová, H., Matulová, M., 2020. Comparison of urban public transport systems in the Czech Republic and Slovakia: factors underpinning efficiency. Res. Transport. Econ. https://doi.org/10.1016/j.retrec.2020.100824.
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. Appl. Energy 230, 344–356. https://doi.org/10.1016/j.apenergy.2018.08.086.
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. https://doi.org/10.1016/j.energy.2017.01.101.
Gdynia City Council, 1998. Act on Transport Policy of City of Gdynia. Gdynia City Council, Gdynia.
Gilham, P., 2000. Case Study Research Methods. Continuum, London.
Gössling, S., Choi, A., Dekker, K., Metzler, D., 2019. The Social Cost of Automobility , Cycling and Walking in the European Union, vol. 158, pp. 65–74.
Grygar, D., Koháni, M., Štefún, R., Drgoňa, P., 2019. Analysis of limiting factors of battery assisted trolleybuses. Transp. Res. Procedia 40, 229–235. https://doi.org/10.1016/j.trpro.2019.07.035.
Hamacek, Š., Bartłomiejczyk, M., Hrbáč, R., Mišák, S., Stýskala, V., 2014. Energy recovery effectiveness in trolleybus transport. Elec. Power Syst. Res. 112, 1–11. https://doi.org/10.1016/j.epsr.2014.03.001.
Harris, A., Soban, D., Smyth, B.M., Best, R., 2020. A probabilistic fleet analysis for energy consumption, life cycle cost and greenhouse gas emissions modelling of bus technologies. Appl. Energy 261. https://doi.org/10.1016/j.apenergy.2019.114422.
Hassan, A.M., Lee, H., 2015. Toward the sustainable development of urban areas: an overview of global trends in trials and policies. Land Use Pol. 48, 199–212. https://doi.org/10.1016/j.landusepol.2015.04.029.
Helne, T., Hirvilammi, T., 2015. Wellbeing and sustainability: a relational approach. Sustain. Dev. https://doi.org/10.1002/sd.1581.
Hołyszko, P., Filipek, P., 2016. Estimation of the running costs of autonomous energy sources in trolleybuses. J. Ecol. Eng. 17, 101–106. https://doi.org/10.12911/22998993/65456.
International Energy Agency, 2019. Global EV Outlook 2019. Scaling-Up the Transition to Electric Mobility. International Energy Agency.
Islam, A., Lownes, N., 2019. When to go electric? A parallel bus fleet replacement study. Transport. Res. Transport Environ. 72, 299–311. https://doi.org/10.1016/j.trd.2019.05.007.
Kliucininkas, L., Matulevicius, J., Martuzevicius, D., 2012. The life cycle assessment of alternative fuel chains for urban buses and trolleybuses. J. Environ. Manag. 99, 98–103. https://doi.org/10.1016/j.jenvman.2012.01.012.
Köhler, J., Whitmarsh, L., Nykvist, B., Schilperoord, M., Bergman, N., Haxeltine, A., 2009. A transitions model for sustainable mobility. Ecol. Econ. 68, 2985–2995. https://doi.org/10.1016/j.ecolecon.2009.06.027.
Kołoś, A., Taczanowski, J., 2016. The feasibility of introducing light rail systems in medium-sized towns in Central Europe. J. Transport Geogr. 54, 400–413. https://doi.org/10.1016/j.jtrangeo.2016.02.006.
Lajunen, A., 2018. Lifecycle costs and charging requirements of electric buses with different charging methods. J. Clean. Prod. 172, 56–67. https://doi.org/10.1016/j.jclepro.2017.10.066.
Lajunen, A., 2014. Energy consumption and cost-benefit analysis of hybrid and electric city buses. Transport. Res. C Emerg. Technol. 38, 1–15. https://doi.org/10.1016/j.trc.2013.10.008.
Mathieu, L., 2018. Electric Buses Arive on Time - Marketplace, Economic, Technology, Environmental and Policy Perspectives for Fully Electric Buses in the EU.
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. Elec. Power Syst. Res. 142, 163–175. https://doi.org/10.1016/j.epsr.2016.09.032.
Mohamed, M., Ferguson, M., Kanaroglou, P., 2018. What hinders adoption of the electric bus in Canadian transit? Perspectives of transit providers. Transport. Res. Transport Environ. 64, 134–149. https://doi.org/10.1016/j.trd.2017.09.019.
Nordelöf, A., Romare, M., Tivander, J., 2019. Life cycle assessment of city buses powered by electricity, hydrogenated vegetable oil or diesel. Transport. Res. Transport Environ. 75, 211–222. https://doi.org/10.1016/j.trd.2019.08.019.
Okraszewska, R., Romanowska, A., Wołek, M., Oskarbski, J., Birr, K., Jamroz, K., 2018. Integration of a multilevel transport system model into sustainable Urban mobility planning. Sustainability 10. https://doi.org/10.3390/su10020479.
Olecka, A., Bebkiewicz, K., Chłopek, Z., Jędrysiak, P., Kanafa, M., Kargulewicz, I., Rutkowski, J., Sędziwa, M., Waśniewska, S., Marcin, Ż., 2018. Poland's National Inventory Report 2018. Greenhouse Gas Inventory for 1988-2016., UN Framework Convention on Climate Change and its Kyoto Protocol. Warsaw.
Ou, X., Zhang, X., Chang, S., 2010. Alternative fuel buses currently in use in China: life-cycle fossil energy use, GHG emissions and policy recommendations. Energy Pol. 38, 406–418. https://doi.org/10.1016/j.enpol.2009.09.031.
Patella, D., Perchel, A., Jaques, I., Lee-Brown, J., Baker, M., Joy, O., Amato, C., Steinmetz, R., Van der Ploeg, R., Breen, E., Koks, Z., Aritua, B., Yang, Y., Deng, H., Beukes, E.A., Qu, L., Guerrero, A.H., Turner, P., Fang, H., Damasceno, A., 2018. Electric Mobility & Development: an Engagement Paper from the World Bank and the International Association of Public Transport. UITP, World Bank.
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. J. Clean. Prod. 140, 53–61. https://doi.org/10.1016/j.jclepro.2016.02.054.
Rupp, M., Handschuh, N., Rieke, C., Kuperjans, I., 2019. Contribution of country-specific electricity mix and charging time to environmental impact of battery electric vehicles: a case study of electric buses in Germany. Appl. Energy 237, 618–634. https://doi.org/10.1016/j.apenergy.2019.01.059.
Ryzhkov, A., 2018. Local public transport in Russia : regulation , ownership and competition. Res. Transport. Econ. 69, 1–11. https://doi.org/10.1016/j.retrec.2018.04.010.
Sánchez, J.A.G., Martínez, J.M.L., Martín, J.L., Holgado, M.N.F., Morales, H.A., 2013. Impact of Spanish electricity mix, over the period 2008–2030, on the life cycle energy consumption and GHG emissions of electric, hybrid diesel-electric, fuel cell hybrid and diesel bus of the Madrid transportation system. Energy Convers. Manag. 74, 332–343. https://doi.org/10.1016/j.enconman.2013.05.023.
Simons, A., Bauer, C., 2015. A life-cycle perspective on automotive fuel cells. Appl. Energy 157, 884–896. https://doi.org/10.1016/j.apenergy.2015.02.049.
Stempien, J.P., Chan, S.H., 2017. Comparative study of fuel cell, battery and hybrid buses for renewable energy constrained areas. J. Power Sources 340, 347–355. https://doi.org/10.1016/j.jpowsour.2016.11.089.
Swanborn, P., 2010. Case Study Research: what, Why and How? SAGE Publications.
Tong, F., Hendrickson, C., Biehler, A., Jaramillo, P., Seki, S., 2017. Life cycle ownership and social costs of alternative fuel options for transit buses. Transp. Res. PART D 57, 287–302.
Trolley 2.0, 2020. TROLLEY 2.0 Project. URL. https://www.trolleymotion.eu/trolley2-0/. accessed 2.10.19.
Trolley Project, 2013. INTERREG IVB Cent. Eur. Program. URL. http://www.trolley-project.eu/index.php?id=18. accessed 1.18.18.
UITP, 2019a. Public Transport Trends 2019. Brussels.
UITP, 2019b. UITP. www.uitp.org accessed 2.14.19.
UN, 1987. Our Common Future: Report of the World Commission on Environment and Development, 4. United Nations Comm, p. 300. https://doi.org/10.1080/07488008808408783.
United Nations. Economic and Social Council, 2020. Progress towards the Sustainable Development Goals. Report of the Secretary-General. https://doi.org/10.1017/S0020818300001818.
Varga, B., Tettamanti, T., Kulcsár, B., 2019. Energy-aware predictive control for electrified bus networks. Appl. Energy 252. https://doi.org/10.1016/j.apenergy.2019.113477.
Wang, R., Wu, Y., Ke, W., Zhang, S., Zhou, B., Hao, J., 2015. Can propulsion and fuel diversity for the bus fleet achieve the win-win strategy of energy conservation and environmental protection? Appl. Energy 147, 92–103. https://doi.org/10.1016/j.apenergy.2015.01.107.
Wołek, M., Hebel, K., 2020. Strategic planning of the development of trolleybus transportation within the cities of Poland. In: Sierpinski, G. (Ed.), Smart and Green Solutions for Transport Systems. 16th Scientific and Technical Conference "Transport Systems. Theory and Practice 2019" Selected Papers. Springer Nature Switzerland AG, Cham. https://doi.org/10.1007/978-3-030-35543-2.
Wołek, M., Wolanski, M., Jagiełło, A., Suchanek, M., Szmelter, A., 2018. 3.4. Conventional Full Evaluation. The Test Results. Elaborated within the ELIPTIC Project (H2020 Programme Contract Nr 636012). Internal report.
World Economic Forum, 2019. A Vision for a Sustainable Battery Value Chain in 2030 Unlocking the Full Potential to Power Sustainable Development and Climate Change Mitigation.
Wu, Z., Guo, F., Polak, J., Strbac, G., 2019. Evaluating grid-interactive electric bus operation and demand response with load management tariff. Appl. Energy 255. https://doi.org/10.1016/j.apenergy.2019.113798.
Xu, Y., Gbologah, F.E., Lee, D.Y., Liu, H., Rodgers, M.O., Guensler, R.L., 2015a. Assessment of alternative fuel and powertrain transit bus options using real-world operations data: life-cycle fuel and emissions modeling. Appl. Energy 154, 143–159. https://doi.org/10.1016/j.apenergy.2015.04.112.
Xu, Y., Gbologah, F.E., Lee, D.Y., Liu, H., Rodgers, M.O., Guensler, R.L., 2015b. Assessment of alternative fuel and powertrain transit bus options using real-world operations data: life-cycle fuel and emissions modeling. Appl. Energy 154, 143–159. https://doi.org/10.1016/j.apenergy.2015.04.112.
Xylia, M., Leduc, S., Laurent, A.-B., Patrizio, P., Silveira, S., 2019. Impact of bus electrification on carbon emissions: the case of Stockholm. J. Clean. Prod. 209, 74–87.
Xylia, M., Silveira, S., 2018. The role of charging technologies in upscaling the use of electric buses in public transport: experiences from demonstration projects. Transport. Res. Part A Policy Pract 118, 399–415. https://doi.org/10.1016/j.tra.2018.09.011.
Yin, R.K., 2012. Applications of Case Study Research, third ed. SAGE Publications, Thousand Oaks, CA.
Zheng, H.W., Shen, G.Q., Wang, H., 2014. A review of recent studies on sustainable urban renewal. Habitat Int. 41, 272–279. https://doi.org/10.1016/j.habitatint.2013.08.006.

ZKM Gdynia, 2020. ZKM Internal Report on Supply of Trolleybus Transport. Gdynia.
ZKM Gdynia, 2019. Preferencje i zachowania komunikacyjne mieszkańców Gdyni. Raport z badań marketingowych 2018. [Preferences and Transport Behavior of Citizens of Gdynia. Marketing Research Report 2018. Gdynia.
ZKM Gdynia, 2016. Preferencje i zachowania komunikacyjne mieszkańców Gdyni. Raport z badań marketingowych 2015. [Preferences and Transport Behavior of Citizens of Gdynia. Marketing Research Report 2015. Gdynia.
ZKM Gdynia, 2009. Preferencje i zachowania komunikacyjne mieszkańców Gdyni. Raport z badań marketingowych 2008. [Preferences and Transport Behavior of Citizens of Gdynia. Marketing Research Report 2008. Gdynia.
ZKM Gdynia, 2001. Preferencje i zachowania komunikacyjne mieszkańców Gdyni w 2000 r. Raport z badań marketingowych [Transport Preferences and Behaviour of Citizens of Gdynia in 2000. Marketing Research Report]. Gdynia.