

Article

Transformation of Trolleybus Transport in Poland. Does In-Motion Charging (Technology) Matter?

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Abstract: Transport in cities is one of the most important sources of emissions. Electromobility is an essential element in the catalogue of activities of local authorities aimed at combating climate change. Over the years trolleybus transport has been characterised by both phases of development and regression and is still an essential component of zero-emission urban transport in about 300 cities worldwide. The development of electricity storage technology, especially in the form of a battery, has opened up new prospects for this mode of transport. A trolleybus equipped with a battery (in-motion charging technology) gains unique characteristics for operation independent of the catenary. This study presents the approach for assessing the development of in-motion charging for trolleybuses in all Polish cities operating this means of transport. A set of KPIs has therefore, been set and analysed. The analysis covers a comparison between 2014 and 2019, aimed at showing the development of technological innovations in this field. The results clearly show that in-motion charging technology leads to the development of trolleybus transport, although this development has mainly a qualitative dimension. A key factor determining the development of trolleybus transport using in-motion charging technology is progress in the development of traction batteries.

Keywords: public transport; trolleybus transport; electromobility; energy efficiency

1. Introduction

1.1. Environmental Challenges Facing the Transport Sector in Cities

Transport-related activities have always shaped urban space and affected the lives of residents. Prior to the industrial revolution, the scale of urban development was limited by the perspective of residents walking through the city [1]. This remained the case until the development of mechanised transport enabled the spatial expansion of cities. Such growth impacted the relations between the city and its surroundings, which resulted in the development of suburbanisation [2], contributing to, e.g., the increase in energy consumption [3] and greenhouse gas emissions [4].

Transport systems (not only in cities or suburban areas) have different damaging effects, such as noise and air pollution emissions (e.g., NO_x, CO, CO₂, PM₁₀, PM_{2.5}), the destruction of districts, declining city centres, urban sprawl, congestion and accidents [5]. A significant effect is the multi-dimensional and large-scale impact of transport on the natural environment [6]. According to the European Commission [7,8], transport sector generates around a quarter of the EU greenhouse gas emissions and is the second most significant greenhouse gas emitting sector after energy production. This was the reason behind the implementation of a complex set of solutions aimed at decreasing the demand for car use and promoting sustainable and active transport. Sustainable transport

activities also improve urban public transport that should be attractive and appealing while at the same time environmentally friendly [9]. There are numerous solutions which could be included in urban sustainability strategies, e.g., car-free zones, congestion charging [10], city centre access limits, electric vehicles (EVs), bus rapid transit (BRT), electric-powered two-wheelers (EPTWs), etc. Usually, the vast majority of such strategies contain also the promotion of walking and cycling [11].

Therefore, presently, climate change is one of the key megatrends shaping urban policies [12,13]. However, it is not the most important and not the only one. The World Economic Forum identifies six global megatrends especially relevant to cities, which are [14]: “(1) urbanisation, demographics and the emerging middle class; (2) rising inequalities; (3) sustainability; (4) technological change; (5) industrial clusters and global value chains; and (6) governance”. In turn, the literature review prepared by Maraš et al. [15] shows that there are two most essential megatrends in the development of passenger transport: (1) developing suburbanisation with the growth of megacities including such aspects as higher population density, infrastructure improvements, health risks, sustainable cities etc.; (2) growing environmental challenges, concerning most critically climate change: low carbon emissions, increase in global temperature, increased flood risks etc. Environmental sustainability and energy security remain challenges for local governments. To ensure excellence in customer service, public transport needs to adapt to a rapidly changing environment, which is determined by evolving customer expectations and technological changes [16–18].

To sum up, megatrends are significant challenges for urban transport. It would be advisable for cities to adjust their paths of development to current and future trends that should not be treated as threats but rather as opportunities. Liebl and Schwartz [19] indicate that in order to understand the trends they must be seen from two perspectives: the perspective of innovation which points out the need for something new in each trend and the perspective of diffusion that allows the level to which a specific trend influences the development of the particular area to be identified, such as urban public transport as presented here.

1.2. Public Transport as a Crucial Element of Environmental Response

Most of the negative phenomena resulting from the development of individual motorisation can be limited at the level of municipal policies. Thus, the impact on the sphere of transport in cities is an essential element in the implementation of the 1.5 °C goal set by the Paris Agreement in 2015 [20]. Activities included in those policies cover, e.g., supporting the use of other modes than a car [21], more effective land use, improved information for users and many others.

In many cities, in the modal split still, the car dominates significantly, and the high share of its use is particularly visible in long-distance travel [22]. However, even though recent years have brought increased interest in the so-called active modes (walking and cycling), in the urban functional area, public transport still remains as one of the key modes [23], especially in Poland [24]. It is characterised by high flexibility (various means of transport), diversified but high transport capacity (especially for rail means of transport and Bus Rapid Transit systems) and low environmental costs per passenger [25].

Due to the COVID-19 pandemic, even cities from well-developed countries fall into the “underfunding trap” in the area of urban transport [26]. The pandemic resulted in a dramatic reduction in demand for public transport [27] and a farebox decline of 40 billion EUR in 2020 [28]. Although mobility has been significantly reduced by lockdown and the increase in teleworking, some inhabitants have changed their transport behaviour, switching to cars and, to a lesser extent, to cycling. The first analyses indicate the severe challenges facing public transport. They already show symptoms of a structural change, and the road to return to the pre-pandemic situation will be a very long one [29,30]. Moreover, it will depend mostly on actions in the field of health and safety, rather than transport [29]. For systems based on electric means of public transport, the barrier to development may be the higher cost of purchasing them, which in turn determines the directions of support for public authorities at different levels.

Taking into account the above facts, and the actions taken before the COVID-19 pandemic aimed at improving the level of sustainability of urban transport through, e.g., electrification of public transport, the question arises whether the postulated scope and pace of electrification of public transport in cities will not slow down in the current epidemic situation. The challenges mentioned above result in the necessity to create a reasonable strategy for pandemic and post-pandemic periods. They need to be aimed at “strengthening” and developing the existing urban public transport systems. These, in turn, include trolleybus transport, which operates in about 300 cities around the world. In many of them, it is considered to be a fundamental, basic mode of transport, and in many of them, it is one of the transport modes that are critical for the undisturbed functioning of public transport [31,32].

The trolleybus is a very old means of transport developed in the 19th century. Thanks to its ‘energy flexibility’, allowing the use of electricity generated from various sources, and the low level of development of diesel buses, it has been perfectly suited to serve cities. The massive development of motorisation after the Second World War and the technological development of buses with internal combustion engines marked the beginning of a severe crisis for this mode of transport. The critical disadvantage of the trolleybus, namely its full dependence on the catenary, put it in a weaker competitive position compared to ever more excellent buses. A turn in European Union policy, the increasing environmental awareness of local authorities and the public, as well as technological progress in the area of electricity storage, have created a transformational gap for trolleybus transport. The spread of in-motion charging technology is a breakthrough in the development of the trolleybus, but the direction in which it develops needs to be monitored.

1.3. Organisation of the Paper

This study focuses on the transformation of public transport systems in the case of three trolleybus systems already operating in Poland, namely Gdynia-Sopot, Lublin and Tychy, the only Polish cities using trolleybuses in public transport. The paper aims at presenting the set of key performance indicators (KPIs) used in assessing trolleybus transport and monitoring its transformation into a modern and flexible solution with high potential for achieving environmental sustainability. Each of the cities involved in the analysis could be a good reference point for such considerations since they are in the process of developing their trolleybus system and introducing the in-motion charging model. On the basis of the study of these particular public transport (PT) systems, we have attempted to answer the research questions presented in Section 3.1.

This paper contributes to the field of knowledge of the impact of electromobility on public transport markets. A set of key performance indicators was developed. It is capable of supporting the decision-making process of local authorities, agencies and PT companies operating trolleybuses. KPIs are helpful first and foremost, because all the electromobility decisions have to be made concerning strict economic rules, especially those concerning environmental sustainability and energy efficiency.

Therefore, the remainder of the paper is as follows. The next section provides details about the impact of electromobility on the PT markets. Section 3 summarises the methods used while preparing and carrying out the research. Section 4 contains details on the analysed urban systems of Gdynia-Sopot, Lublin and Tychy and presents their predisposition to serve as an example and reference point for other analyses and studies. The Section 5 describes and discusses the research results. The Section 6 concludes the paper, highlights its shortcomings and draws future research directions.

2. Electromobility’s Impact on PT Markets

2.1. Battery as a Critical Element of the PT’s Electromobility System

The modern public transport system that uses electric energy includes a vehicle, power system and battery. Currently, technological progress is focused primarily on electricity storage represented by different generations of batteries. Presently, low and zero-emission transport is undergoing intense development by leading academic (universities), research, and scientific and industrial centres around

the world. The cause of this considerable growth is the search for solutions most appropriately suited to the requirements of the providers of new technologies and their users.

These solutions are still undergoing development. Among those already commercially available, the following can be mentioned:

- battery-powered vehicles,
- hybrid vehicles,
- fuel-cell vehicles,
- in-motion charging vehicles.

The common feature of all the above-mentioned technologies is the presence of a battery that constitutes the crucial part of the system. Figure 1 presents the flow charts for each system.

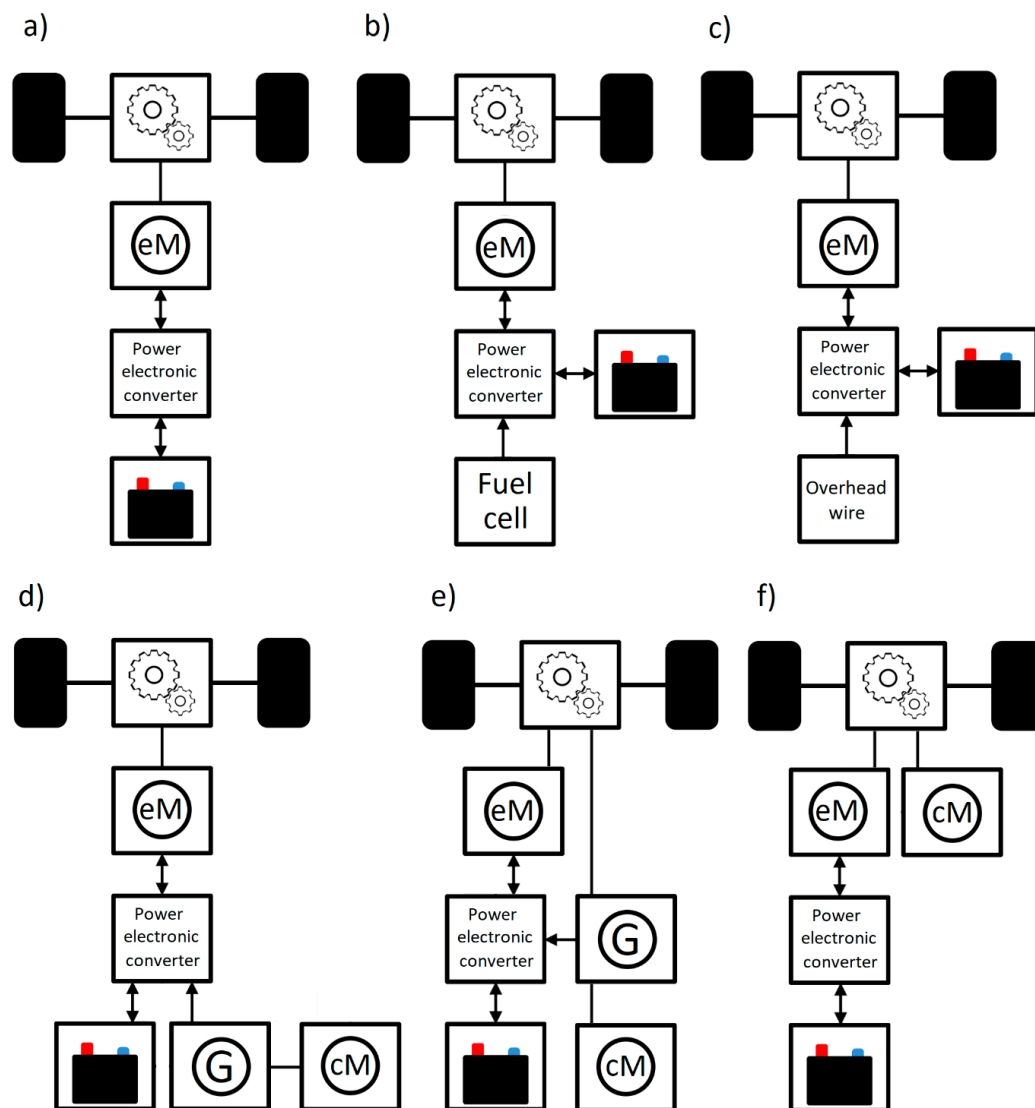


Figure 1. Electric vehicle flow charts; (a) battery-powered drive, (b) hydrogen-powered drive, (c) overhead wire powered trolleybus drive, (d) series hybrid drive, (e) series-parallel hybrid drive (f) parallel hybrid drive (arrows and torque transmission indicate electricity flows by lines). Source: [33–35].

For a propulsion system using fuel cells, the role of the battery is to store the energy generated during regenerative braking, to transfer additional power to the electric traction motor and provide a power source in the event of a failure so that overcurrent protection can operate.

As Figure 1 shows, the construction of every type of engine, which is an alternative to traditional diesel engines includes a battery. Its presence is evident in fully battery-operated systems as in such a case a battery constitutes the only source of power. Its functions, however, can vary when it comes to hybrid vehicles, and so:

- for a series-type hybrid, a battery is a source of power for the drive which is additionally supported by an internal combustion engine (ICE) transmitting energy to the generator, all to increase the distance the vehicle can travel;
- for a parallel-type hybrid a battery powers the electric motor (EM) which propels the same mechanical transmission together with the combustion engine;
- for a series-parallel-type hybrid, a battery powers the electric motor which propels the same mechanical transmission together with the combustion engine which additionally recharges the battery using a dedicated generator (G).

In a fuel-cell system, the battery is used to store energy generated during regenerative braking; it provides additional power for the electric motor and acts as the power source in emergencies ensuring the start-up of overcurrent protection mechanisms.

In in-motion charging vehicles, which include trolleybuses performing tasks outside the power supply network, the battery is the primary source of power on these sections. Increasing the functionality of vehicles is possible, thanks to this crucial element.

The use of a battery constitutes the critical element within the electromobility system. The choice of the appropriate battery requires careful consideration of the function it fulfils, the specific requirements of a given transport mode, as well as the longest possible and a hassle-free lifespan. For example, an electric vehicle powered solely by a battery should be equipped with a power source which has the following features [36,37]:

- high peak current,
- high capacity,
- a large number of work cycles,
- low weight,
- small dimensions,
- user safety.

Often enough, it is impossible to find a battery which conforms to all the above criteria. In such a case a compromise, allowing for the fulfilment of all key-tasks expected of the battery, is necessary. When designing a battery, it is essential to select cells produced using technology appropriate for the purpose of usage expected of the new battery pack [38–40]. Differences influencing the use of battery can also occur between the same types of lithium-ion batteries (depending on the model or manufacturer). When selecting cells, the following parameters should be taken into consideration:

- working temperature range,
- permitted operating currents,
- requirements regarding dimensions and weight,
- safety requirements,
- maintenance requirements,
- forecasted cost of the battery pack.

The challenge of selecting the appropriate battery is a complex one. There are several factors that have to be taken into account. Their influence on the system operation has to be analysed together with the ease of use. Decisions made shall not only have technical repercussions, but will also be reflected in such functions of the vehicle as charging time, range, or user safety.

In the case of in-motion charging, apart from the necessity to take into account the above parameters, when selecting the battery, the following next criteria should also be taken into account:

travel time under the catenary, charging power from the catenary, and characteristics of the route operated with a battery.

2.2. Electromobility in Urban Public Transport

The implementation of electromobility in urban transport is a reasonable and natural step in the dissemination of this technology. It helps to reduce air pollution and traffic noise in cities that are both large clusters of people and generate a high demand for freight and passenger transport. The fundamental aspect contributing to the implementation of electromobility in public transport is choosing the model of its functioning. It is based on designated routes, breaks in courses in specific places and lasting time specified in the timetable. This specificity allows, on the one hand, to precisely define the requirements that vehicles should meet on a given route. On the other hand, it enables the management of timetables so that vehicles can be used in a way that ensures their longest possible operation. From an economic point of view, electric vehicles, which are more expensive to buy, should be used very intensively, near to their full capacity [41]. This can be done, for example, by keeping the batteries charged at an appropriate level, required for undisturbed use. It needs to be highlighted that the role of urban public transport as a leader of electromobility development and transformation is also to stimulate the development of charging infrastructure [42].

Today, over half a million electric vehicles are used in urban transport worldwide. The scope of their use is growing. It is estimated that by 2040 they may reach 67% share in the urban transport fleet. A parallel trend is the growing role of hydrogen vehicles, which may account for 6% of urban transport vehicles in 2040 [43]. Since 2017 electric-battery buses have been taking over other forms of public transport electric vehicles [44].

Currently, various charging strategies are used for electric vehicles in urban transport. They have a significant impact on the way vehicles are exploited [45] and for the requirements for battery parameters, namely:

- only charging at the depot (overnight charging),
- charging only at the end of routes (opportunity charging),
- mixed charging at the depot and at the end of routes (mixed, overnight and opportunity charging),
- vehicle charging while driving from the overhead line (in-motion charging).

The last presented method of charging is the next stage in the development of trolleybuses. Some trolleybuses were many years ago equipped with a battery that allowed them to drive without access to electric traction on short distances. This solution has enabled parking and manoeuvring and provided a safety margin in city traffic in the case of a network failure. However, with the development of batteries, these vehicles are evolving towards long journeys in the so-called autonomous mode (off-the-grid). This solution is effective due to the synergy of transport operations and the loading process [46–48]. In the case of buses, the charging time (apart from the necessary driver's break) is unproductive. The in-motion charging system is, therefore, very effective, but only in the case of urban transport systems using trolleybuses [49].

Time and charging conditions are crucial for the spread of electromobility in public transport [50]. For electric buses and trolleybuses dedicated to performing tasks beyond traction, it is necessary to know the distance to be covered by the vehicle between charging points. Once this is ascertained, the time needed to charge the vehicle should be taken into account. This time can be calculated with Equation (1).

$$t_{\text{manoeuvring}} + \frac{S * (E_t + E_{ko}) * 3600}{E_n * C} = t_{\text{charging}} [s] \quad (1)$$

- $t_{\text{manoeuvring}}$ —time needed for the manoeuvre to drive up and down to the charging installation
- S —length of the bus route [km]
- E_t —empirically determined energy value needed to drive 1 km by an electric vehicle [kWh]
- $(100\% E_t)$ for the selected ambient temperature or month [kWh/km].

- ▶ E_n —nominal battery energy [kWh]
- ▶ t_{charging} —charging time [s].

*Current C (1C) is a one-hour current, i.e. the one that charges the battery from 0 to 100% capacity for one hour or discharges from 100 to 0% capacity in one hour.

The application of Equation (1) requires information about the vehicle parameters such as traction energy consumption and for non-traction purposes [51] and two battery parameters: its nominal energy and one-hour charging current multiplication factor.

This innovation supports the implementation of the assumptions of sustainable transport, Sustainable Urban Mobility Plans (SUMPs) and urban environmental policies. Usually, these documents involve providing low-emission transport in cities. Particularly crucial in supporting sustainable transport is the reduction of noise and greenhouse gas emissions. New charging systems, including in-motion charging, and new generation batteries make it possible to meet these demands.

3. Methods

3.1. Case Study

A case study is a popular research method [52] in social sciences [53], also used in examining urban transport systems, including public transport [54]. Moreover, every city or metropolitan area has its own specifics resulting from geographical, historical or socio-economic reasons [55,56]. Benchmarks in the field of implementing innovations are a valuable contribution to the knowledge of electromobility in urban public transport. Therefore, diverse characteristics of possible cases should be analysed to justify the use of case study method [57]. However, there are different approaches to the role of the case study in theory building, the research procedures and their elements [58].

The outcome of using this method should be theoretical constructs, propositions or midrange theory from case-based, empirical evidence [57]. These prove to be an ideal method when researchers have to use different, dispersed data sources and various kinds of data [59]. Case studies are rich, empirical descriptions of particular instances of a phenomenon that are typically based on a variety of data sources. Despite some critical voices about the undemanding character of case study as a method and methodology, it has to be clearly stated that it is rigorous, complex, robust and represents strong practical evidence [52,60,61]. Taking into consideration all of the identified elements of the method, the research framework prepared on the basis of [52,53,57,62] is presented in Table 1.

A case study is a method for examining electromobility in public transport systems also used on the World Economic Forum [63] as a leading method for research about using electric buses and implementing smart charging systems. Research similar to ours, based on case studies, was recently made for Poland as a whole country [64,65] and Poland's capital city, Warsaw [66]. Approaches similar to this one (combining case study and KPIs) were used in similar fields of research [67–70].

According to the most cited approach of R.K. Yin [53,62] it was decided to design this study in answer to the following research questions:

- **RQ1: Does in-motion charging technology contribute to the development of trolleybus transport?**
- **RQ2: Which factor(s) have the most significant influence on the development of in-motion charging technology in trolleybus transport?**

To answer these questions, a set of KPIs was created that address various areas of trolleybus transport. With their support, it is possible to monitor the transformation of the trolleybus transport system. Thanks to innovations in the field of electricity storage and its technical and operational properties, trolleybus could serve as a “platform development”. The aforementioned transformation with in-motion charging technology makes the trolleybus system more dependent on the traction battery.

Table 1. Research framework.

Phase	Step		Tool	Outcome	Part of the Paper
Defining and designing	1. Identifying the problem		Literature review protocol	Research problem	1.1.–1.3.
	2. Building theory		Literature review protocol	Research questions	2.1.–2.2., 3.1.
	3a. Describing the method	3b. Designing data collection and analysis	Literature review protocol	Case study procedure with protocol	3.1.–3.2.
Preparing, collecting	4. Conducting a case study		Case study protocol	Filled case study protocol	4.1.–4.2.
Analysing and concluding	6. Preparing results		Research report template	Filled research report	5.1.–5.2.
	7. Compared to rival theories		Literature review protocol, research report template	Finished manuscript	5.3.
	8. Modifying or enhancing theory (if required)		Literature review protocol, research report template		5.3., 6
	9. Concluding the cross-case report		Research report template, paper template		6

Moreover, in cities that already use them, it may still constitute the basis for the transformation of the current, traditional public transport into electromobility.

This study should be defined as exploratory, descriptive [71] and deductively oriented [58]. To meet the requirements of those, the creation of a KPI set supplements the case study itself as a tool for monitoring trends in the development of electromobility in public transport in cities. We chose all three trolleybus systems operating in Poland. They represent a maturity in the development of the “traditional” trolleybus systems but also implement the in-motion charging scheme that is the transforming factor of the trolleybus transport supply. Data collection was made possible thanks to TROLLEY 2.0 project (Horizon 2020, European Commission) and cooperation with the trolleybus operators—PKT Gdynia sp. z o.o., MPK Lublin sp. z o.o. and TLT Tychy sp. z o.o.

Taking into account the full description of the research approach, in this paper, the research results are presented in two parts. Firstly, Section 4 describes the characteristics of public transport in selected cities to highlight its specifics and justify the choice of a detailed analysis and developing a set of KPIs. Then in Section 5, we present the KPIs (Sections 5.1 and 5.2) and discuss the results (Section 5.3).

3.2. KPIs

It should be clearly highlighted that focusing on KPIs has its weaknesses. First of all, it does not determine the interdependencies between variables, so from the point of view of the cognitive value, it does not allow for the discovery of correlations between them or the cause-effect relationships.

However, it is believed that in the case of dispersed data sources and the diverse nature of data, the use of KPIs to control the current state and trends is justified as it allows the use of a maximum number of variables significant (relevant) for the decision-making process. Often, various types of variables (quantitative, but mostly qualitative) cannot be used in mathematical and statistical models. Another advantage of this approach is the ease of interpretation for decision-makers.

The choice of KPIs as the best approach in our study was justified because it was used in similar research, including research on performance systems for local authorities [72], high tech infrastructure construction [73], road freight transport [74], decarbonising supply chains [75], product-service system lifecycles [76], environmentally sustainable, energy-efficient ports [67], agent-based simulation in urban logistics [77], public transport [78] and smart city (e.g., tracking, citizens) [79]. Usually, KPIs are divided into groups and have their own scales.

According to Liyanage and Vilalba-Romero [80], the KPIs should be characterised by rules as follows:

- be general indicators of performance-focused on critical aspects of outputs or outcomes,
- constitute a set of a limited, manageable number of KPIs being maintainable for regular use,
- be possible to implement in the systematic use of KPIs (access to relevant data),
- data collection connected with the calculating of KPIs must be made as simple as possible,
- be possible to use on every project for easy comparison of performance;
- be accepted, understood and owned across the organisation,
- evolve, be possible to change and refine.

In this paper, we want to propose a framework to ease the development of a monitoring system and present the most suitable indicators. Firstly, the initial set of KPIs was built, and after filtering and cleaning (among others, grouping the very detailed KPIs into more aggregated ones), the final set was proposed. Therefore, our framework suggests KPIs (KPI library, KPI catalogue) for the monitoring of achieving objectives. The description of KPIs should help to identify and extract specific data needed to calculate KPIs. This description was based on the approach of Røge and Lennon [72] and Liyanage and Vilalba-Romero [80]. However, despite the great effort put into preparing a complete, up-to-date and adequate set of KPIs, it has to be noted that it should be continuously controlled and updated in the future.

4. Public Transport System in Cities of Gdynia, Lublin and Tychy

4.1. Description of the Study Sites

In Poland, there are three public transport systems with trolleybuses: in Gdynia-Sopot (north of the country), Lublin (south-east) and Tychy (south) (see Figure 2). Table 2 presents the basic data for each described city since they have different morphological and demographical features.



Figure 2. Location of trolleybus systems in Poland. Source: own preparation.

Gdynia is a medium-sized city located on the Baltic Sea in northern Poland. It is an element of the core of the Gdańsk-Gdynia-Sopot Metropolitan Area), which includes 57 communes with different socio-economic morphology [81]. The city gained city rights in 1926, and its development was related to the building of a seaport in the location of a fishing village. The spatial layout of the city development was thus shaped at the time of the rising popularity of passenger car transport. The current spatial structure of Gdynia has an island-strip character with the seaport located centrally [82]. As a consequence, it is prone to transport congestion, especially in the conditions of an increase in the number of passenger cars, which is a nationwide trend. Sopot, neighbouring Gdynia, is a small city with a unique location in the centre of the Metropolitan Area. Its development strategy focuses on spa and tourist functions [83].

Tychy is a mid-size city located in the Upper Silesian Metropolis. In the spatial structure of the city, a clear division into three zones can be distinguished. The first is the urbanised central part, surrounded by the second- suburban districts with industrial zones. The third zone is the outer ring of open areas with a predominant share of forests [84]. The dynamic development of the city took place in the 1950s. In 1951, Tychy was granted city rights. Then a decision was made to expand the town. It was to serve as a “commuter town” for a massive industrial complex in the Upper Silesian Industrial District. The location was an optimal one—a result of a compromise between avoiding the

environmental nuisance of heavy industry and convenient access to workplaces in the centre of the Industrial District. Later, Tychy became the centre of the Polish automotive industry. The operation of trolleybuses started in Tychy in 1982. Its launch was de facto a consequence of the introduction of martial law in 1981 by the communist regime, which resulted in restrictions in access to liquid fuels and the search for alternative means of urban transport [85].

Lublin is the largest city in the eastern part of Poland, and in terms of population—the 9th city in the country. It was granted city rights in 1317. The city's distinguishing feature is its varied topography with a clear, but unique, historically shaped spatial structure. It includes a central, urban zone, with an area of downtown development, areas of residential districts developed at various time periods, and industrial manufacturing areas. [86]. The dynamic development of the city took place after the Second World War. Currently, Lublin is one of the important transportation hubs, as well as one of the largest academic centres in Poland.

4.2. Current Status of the Electromobility in Study Sites

The development of trolleybus transport in Poland and worldwide was characterised by development and regression phases. These were shaped by the current level of bus transport development, oil prices and the policy of local and national authorities [31].

The oldest trolleybus system currently operating in Poland is in Gdynia. The development of trolleybuses in this city started in 1943, when Germany began to feel a shortage of liquid fuels. In 1947 a trolleybus connection with neighbouring Sopot was launched. Trolleybus transport in Lublin has been operating since 1953 and is currently the largest system of its kind in Poland.

The operation of trolleybuses started in Tychy in 1982. Its launch was de facto a consequence of the introduction of martial law in 1981 by the communist regime, which resulted in restrictions in access to liquid fuels and the search for alternative means of urban transport [85].

Apart from three trolleybus systems in Poland, the electromobility landscape in urban transport is complemented by 15 tram systems, the youngest of which has been operating in Olsztyn since 2015. In recent years, there has also been an increase in the role of electric buses in urban public transport in Poland.

The development of electromobility in the cities analysed for obvious reasons depended on the degree of development of trolleybus transport. Although activities aimed at increasing the use of electric buses are being undertaken, trolleybus transport still forms the backbone of electromobility systems in these cities. (see Table 3).

Electromobility in urban transport in Poland has gained a strong development impulse thanks to EU funds directed through the Operational Program Infrastructure and Environment, and some of the Regional Operational Programs for regions, for the years 2014–2020. It is also supported within national funding scheme.

A characteristic feature of trolleybus transport in the analysed cities is the implementation of the in-motion charging model, which uses the potential of the existing trolleybus network and a battery in the vehicle. Currently, trolleybuses operate outside the catenary over relatively short distances (2–5 km), but experience and analyses have shown that this distance may be extended [41,51].

Table 2. Basic characteristics of the analysed cities.

	Population (2019)	Population Density in 2019 [Inhabitants per km ²]	Budget Revenues per Capita in 2019 [PLN]	GDP per Capita, Current Prices [Poland = 100], 2016	Motorisation Index [Cars/1000 Inhabitants]	Forestry [%]
Gdynia-Sopot	246,348 (Gdynia), 35,719 (Sopot)	1823 (Gdynia), 2067 (Sopot)	7323 (Gdynia), 10,607 (Sopot)	145.2 *	622 (Gdynia), 762 (Sopot)	44% (Gdynia), 52% (Sopot)
Lublin	339,784	2304	6942	92.1 **	578	11.1%
Tychy	127,590	1560	7124	126.6 ***	641	26.8%
Poland	38,383,000	123	7466 ****	100	635	29.6%

Source: own study based on a dataset of Polish Statistical Office. * subregion including cities of Gdańsk, Gdynia and Sopot ** subregion, including Lublin and several surrounding counties. *** subregion, including Tychy and several neighbouring counties. **** only for category of cities with county status (66 cities in Poland).

Table 3. Basic features of the trolleybus transport systems in Poland in 2019.

City	Operator	Means of Transport	Ownership	Total Supply [Vehicle-km]	Length of Catenary [km]	Number of Vehicles	Average Speed [km/h]
Lublin	MPK Lublin sp. z o.o.	T, B, e-B	municipal	5,028,500	145.8	121	13.6
Gdynia-Sopot	PKT Gdynia sp. z o.o.	T	municipal	5,383,116	87.2	96	14.3
Tychy	TLT Tychy sp. z o.o.	T	municipal	1,292,000	44	23	no data

Remarks: T—trolleybus, B—diesel bus, e-B—electric bus. Source: own study based on the data of the operators, cities and IGKM (Economic Chamber of Public Transport, Poland).

5. Results and Discussion

5.1. KPIs Selection Process

As mentioned in Section 3.2, KPIs are a fairly widely used tool, in particular for monitoring and comparing comprehensive urban transport systems. In research and implementation projects under the Horizon 2020 programme, they were used among others, in projects such as EBSF (European Bus System of the Future) [87] and ELIPTIC (Electrification of Public Transport in Cities).

Such an innovative system as trolleybuses operating in the in-motion charging model requires the creation of an adequate monitoring system. The traditional trolleybus system, fully network-dependent, required taking into account two elements, i.e., a vehicle and charging system. In the case of the in-motion charging model, one more component must be considered, namely the rechargeable battery, with all the consequences described in Section 2 of this paper.

Therefore, the process of selecting the appropriate KPIs forming a comprehensive scheme for monitoring trolleybus transport in the in-motion charging model requires taking into account all three components, i.e., the vehicle, battery and charging system.

Each monitoring system is a compromise between the accuracy and availability of data. In the process of creating the KPI scheme for the monitoring of the transformation of the trolleybus transport system, data obtained directly from trolleybus operators and secondary data available in the public domain were used. In our study, the comprehensiveness of the analysis was maintained by selecting KPIs from the following areas: battery, energy, operation and economics (see Table 4).

5.2. Results of KPI Mainframe for Trolleybus Systems in Poland

After reviewing the data on the trolleybus systems for the analysed cities, the data shortages were identified and a dataset with variables for all the cities was agreed. This set was refined to address the previously mentioned research questions regarding the chosen research approach.

To be able to compare the different trolleybus systems, a KPI mainframe for 2014 and 2019 was developed (see Table 4). The choice of the year 2014 is related to the fact that the first in-motion charging trolleybuses in Lublin were launched in regular operation in that year.

5.3. Discussion

The average mileage of vehicles in 2019 showed considerable variation, ranging from 41.5 to 56 thousand vehicle-kilometres (vehicle-km). The highest average mileage increase in the analysed period was recorded in Lublin (26%). Trolleybus vehicles equipped with batteries are expensive. Therefore, they need to be operated intensively to ensure that the unit cost of acquiring rolling stock is as low as possible. All the described systems show considerable reserves in this respect, although mileages depend on the construction of the timetable and the proportion between all-day and peak tasks.

The density of trolleybus supply showed the highest value in Gdynia-Sopot, almost twice as high as in Tychy. The highest growth rate of this indicator was characteristic of Lublin, due to a significant increase in the volume of trolleybus supply in 2014–2019.

The cost of a trolleybus vehicle-kilometre is higher in comparison to a diesel bus, as the costs associated with the operation and modernisation of the network must be taken into account. In the case of Gdynia-Sopot and Lublin trolleybus systems, the cost level remained relatively similar, while a significant increase (over 37%) was recorded in Tychy. However, it should be noted that at present, this cost is comparable to other trolleybus systems in Poland.

Electricity consumption is one of the most essential and critical parameters allowing the assessment of particular electromobility solutions. In the case of three trolleybus systems, the differentiation in the level of energy consumption is partially explained by the operations of the rolling stock of different sizes—the largest share of articulated vehicles of about 18 m in length was a characteristic of Lublin. In Tychy, only standard vehicles (12 m length) were operated. Higher values of electricity consumption are also influenced by the fact that most trolleybuses have electrically powered heating

and air conditioning, which is not always the norm for electric buses. Noteworthy is the reduction of the unit electricity consumption in Gdynia by 8% compared to 2014, thanks to investments in the network infrastructure and the appropriate configuration of the vehicles purchased recently [88].

The unit cost of electricity is also an ‘external’ parameter, although an increase in the proportion of renewable energy produced by trolleybus operators themselves should be anticipated. Electricity costs in trolleybus companies serving Gdynia-Sopot and Tychy were similar, while in Lublin—significantly higher, although its share was rather minor factor influencing total cost—its share varied between 6% in Tychy and 11% in Lublin in 2019 (Figure 3).

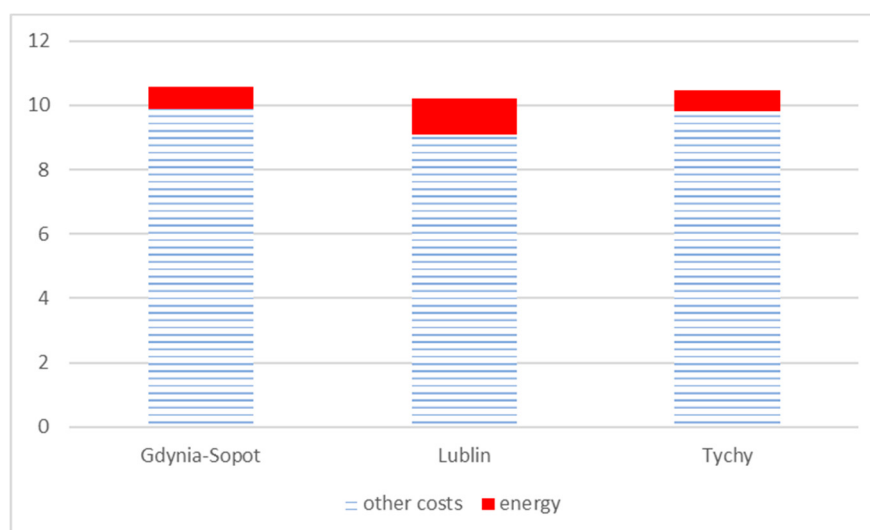


Figure 3. Cost of energy and other costs of the trolleybus vehicle-kilometre in Polish trolleybus systems in 2019 [PLN]. Source: own study based on data collected from the operators.

The environmental effects of electric traction in transport are strictly dependent on the method of primary energy generation. For this analysis, the share of renewable energy sources has been assumed for individual electricity suppliers who have signed contracts with trolleybus operators. Although the value of this indicator does not depend on the specific operator or the city that owns it, it makes it possible to calculate the environmental effects, for example in the replacement of diesel buses by trolleybuses.

From the in-motion charging technology perspective, one of the key indicators is the ratio of the mileage of the catenary to the total mileage of all vehicles. In the analysed cases, the so-called “scheduled mileage”, calculated from the timetables, was taken into account. Data for Lublin was estimated, based on the daily mileages for selected working days in 2014 and in 2019. However, in this city, trolleybus vehicles using in-motion charging technology started operating for the first time in Poland (in 2013 but more lines were included in 2014). Nevertheless, based on the analysis of historical timetable, the value of this indicator, in this case, was estimated at 0.12% for 2014.

The highest share of trolleybus transport supply beyond the catenary in 2019 was observed in Gdynia and Sopot, where almost every tenth vehicle-kilometre was made in this way. Although in-motion charging technology has only recently been used in Tychy, its share in the trolleybus transport supply has already exceeded 2.5%. Growth of off-the-grid operations was also noted in Lublin and amounted to 2.85% of the total trolleybus supply in 2019 (Figure 4). In this case, the off-the-grid operation has a dual nature—it could be realised with a diesel auxiliary unit and with battery. In-motion charging scheme in Lublin amounted to 2.25% of the total vehicle-kilometres in 2019, marking significant growth since 2014. In this city, the possibilities of flexible route shaping thanks to batteries and auxiliary diesel units are used on a large scale in operations with the mass reconstruction of the road network.

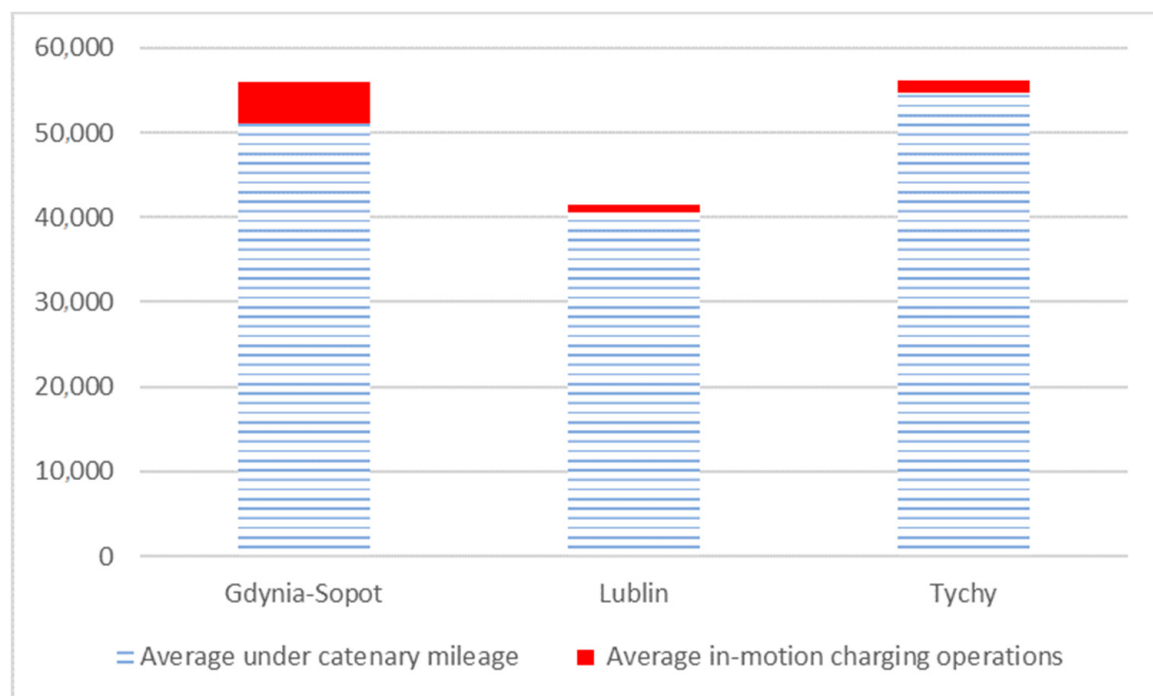


Figure 4. Average trolleybus mileage in Polish cities in 2019 [km]. Source: own study based on data collected from the operators.

A complementary indicator to the previous one is the share of trolleybus lines where in-motion charging technology is used in practice. Of course, this does not translate directly into the number of operators outside the network. Individual lines differ in frequency and length of the sections where off-catenary services are carried out. As already mentioned, in-motion charging technology was used for the first time in regular service in Lublin in 2014. Since then, there was a gradual increase in the share of trolleybus lines in the city, where this type of operation is used. Also, in the service of Gdynia and Sopot, there has been a gradual increase in the importance of in-motion charging expressed in the share of lines where this technology is used. In Tychy, this method of operation has been developed only recently, but it already covers two trolleybus lines.

Due to the flexible possibility of shaping the trolleybus route, in-motion charging technology marks another stage in the development of this urban transport mode. Full dependence on the catenary network is no longer a constraint on the growth of trolleybus transport. It creates opportunities for the replacement of diesel buses by trolleybuses equipped with batteries. In the analysed period in Lublin, buses were thus replaced on four lines, and in Gdynia (partially) on one.

The above analysis leads to a positive answer to the first research question, whether in-motion charging technology leads to the development of trolleybus transport. This development has a qualitative dimension primarily and is expressed in the possibility of at least maintaining the current level of operational work, as well as in the creation of new options for the spatial expansion of trolleybuses into areas without catenary.

The possibility of developing trolleybus transport in connection with in-motion charging technology is determined by the share of trolleybuses equipped with accumulator batteries and their capacity, determining the range.

In all trolleybus systems analysed, the share of vehicles equipped with accumulator batteries exceeded 50% in 2019 (Figure 5). It was the highest in Tychy (78%), but it should be noted that already in 2014 it was 71%. However, all vehicles at that time had NiCd batteries; since that time the trolleybus operator from Tychy purchased several vehicles with modern traction batteries. The example of the trolleybus operator PKT Gdynia shows that it is possible to replace NiCd batteries with a new

generation NMC battery [41]. More than 2/3 of trolleybuses equipped with traction batteries were operated by a trolleybus operator in Gdynia, more than half—in Lublin.

The indicator showing the potential range of operation outside the network is the average capacity of the traction battery. Here, another advantage of the in-motion charging technology is visible, namely the possibility of having batteries with smaller capacity. As a result, the cost of the purchase could be decreased as well as the weight of the vehicle. The largest increase in average battery capacity was observed in the trolleybuses of the operator serving Gdynia-Sopot (by 216% to 50.5 kWh). Relatively high battery capacity was also characteristic of MPK Lublin trolleybuses—in 2019 it amounted to 43.3 kWh, although it should be noted that already in 2014, the average value was at 34 kWh, significantly exceeding the values of other trolleybus operators in Poland.

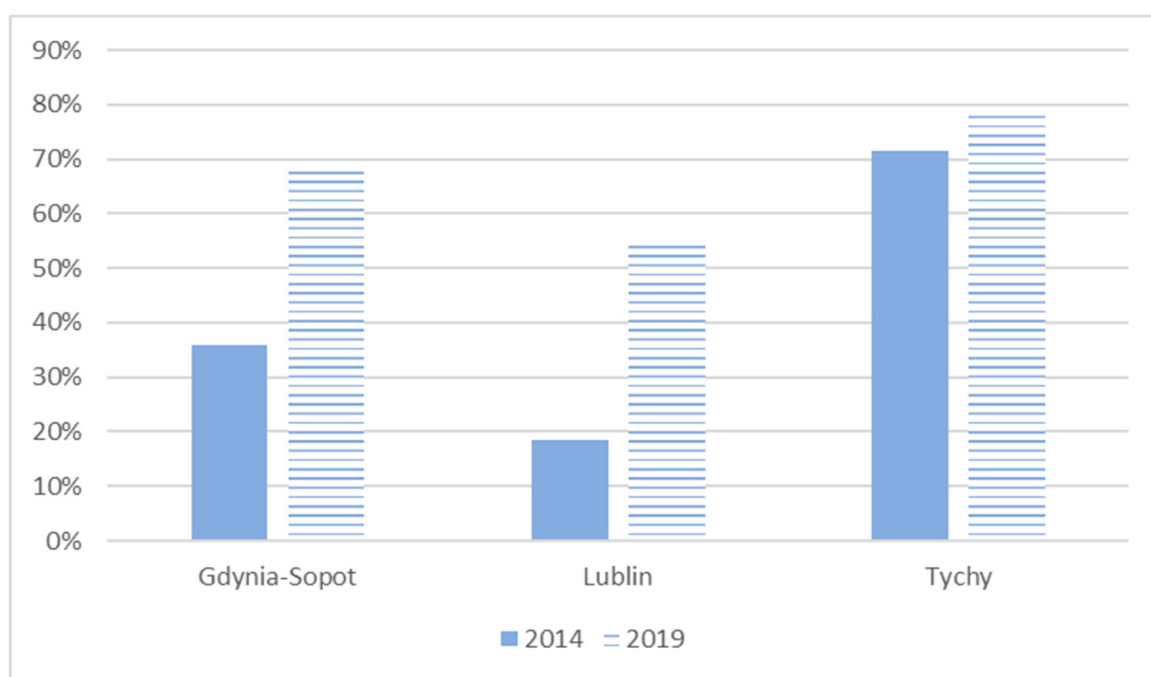


Figure 5. Share of battery trolleybuses in 2014 and in 2019 [%]. Source: own study based on data collected from the operators.

Due to the critical importance of batteries for the development of in-motion charging operations, an additional qualitative analysis showing the process of battery transformation in trolleybus systems in Poland was made.

The analysis of changes in KPI values indicates that the most significant changes resulting from the implementation of in-motion charging technology take place in the area of traction batteries. Figure 6 confirms it, as it shows the quantitative and qualitative changes in the number of batteries used in trolleybus vehicles in Poland in 2014 and 2019.

The change in the technology of trolleybus traction batteries began with the development and spread of lithium-ion technologies. They have significant advantages and allow for more flexible planning of their charging strategy. Apart from a significantly lower negative impact on the environment, lithium-ion batteries are characterised by a lack of memory effect, lack of the impact of the so-called dendrites which lead to internal short circuits of the battery cell. Among the main advantages of lithium technology is the fact that they have more than twice the energy density, which allows the installation of a battery with twice the capacity of the same weight. The memory effect of NiCd technology limits the possibility of using in-motion charging. Analysing Figure 6, the quantitative advantage of lithium technologies that can be used with a properly selected in-motion charging system

is visible. Attention should also be paid to the significant increase in battery capacity as this determines the range of operations that can be performed beyond the catenary.

Thanks to the use of the KPI framework, it was possible to reduce the differences in the size of trolleybus systems to a standard analytical level. This made it possible to find an answer to the second research question, namely stating which factor(s) have the most significant influence on the development of in-motion charging technology in trolleybus transport. A key factor determining the development of trolleybus transport using in-motion charging technology is progress in the development of traction batteries. The noticeable increase in average battery capacity is accompanied by a change in the generic structure in which NMC and, to a lesser extent, LTO batteries predominate.

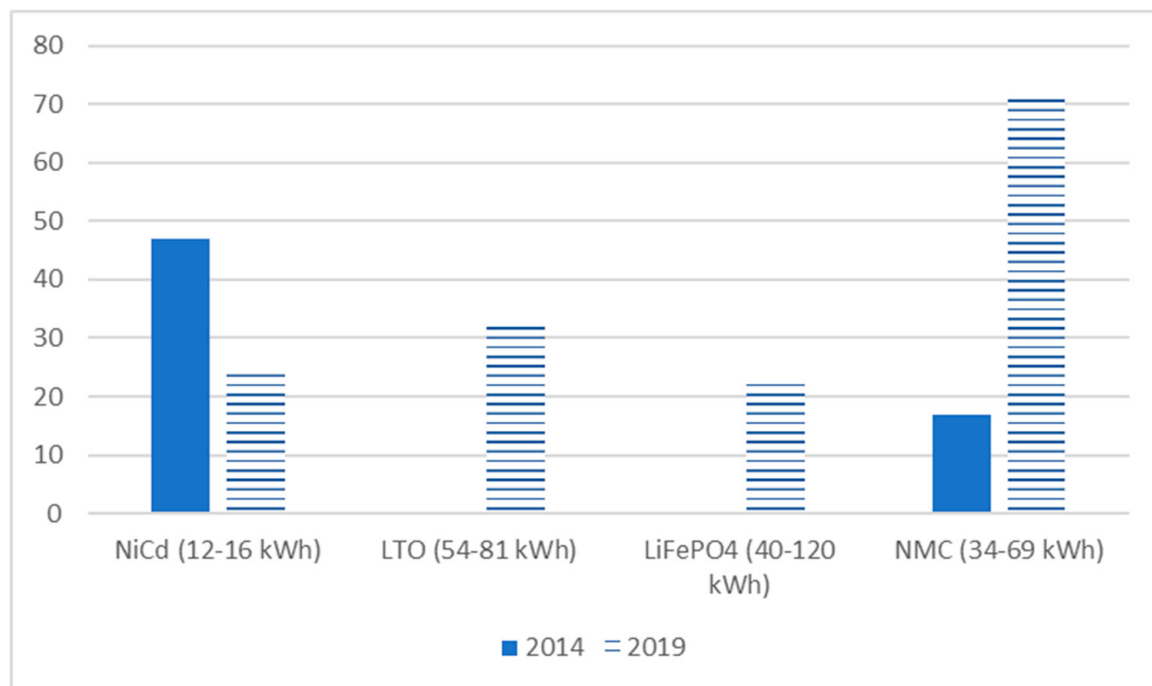


Figure 6. Changes in the number and structure of trolleybus batteries in Poland in 2014 and 2019.
Source: own study based on data collected from the operators.

Technological progress in the field of batteries is the reason in-motion charging technology is becoming increasingly widespread in trolleybus transport. It makes the trolleybus less and less different from a classic electric bus with batteries. The popularisation of vehicles with batteries allows for the qualitative and quantitative development of trolleybus transport in cities where it is already in use.

According to the flexibility it gives to trolley bus operators, in-motion charging technology marks another stage in the development of this urban transport mode. Full dependence on the overhead line network ceases to be a constraint on its development and creates opportunities for the development of new business models (e.g., replacement of diesel buses). The environmental benefits associated with this, however, depend to a large extent on how the electricity used to power trolleybuses is generated.

As the discussion is based on the quantitative approach with the KPIs, it is essential to underline several important drivers and barriers for the development of in-motion charging trolleybuses. Table 5 lists the main drivers and obstacles that are dependent mostly on the external factors to operators and public transport authorities. They should also be taken into account when the expansion of the trolleybus system with in-motion charging technology is planned.

Table 4. KPIs for chosen cities—values for 2014 and 2019.

No	KPI	KPI Category	KPI Description	Unit	Gdynia-Sopot			Lublin			Tychy		
					2014	2019	Change	2014	2019	Change	2014	2019	Change
1	Average mileage	operation	Trolleybus vehicle-km/number of trolleybuses	km	56,453	56,074	−0.7%	33,063	41,558	26%	61,571	56,174	−9%
2	Density of trolleybus supply	operation	Trolleybus vehicle-km/1000 inhabitants	vehicle-km/inhabitants	17.4	19.08	9.7%	8.9	14.8	66.3%	10.05	10.13	0.8%
3	Average energy consumption of trolleybus transport	energy	Energy consumption of trolleybuses in total/vehicle-kms	kWh/km	2.15	1.98	−7.9%	1.87	2.24	19.8%	1.74	1.87	7.5%
4	Catenary independence	operation	Vehicle-kms without catenary (battery mode)/total number of vehicle-kms	%	0	8.71%	n.a.	0.12%	2.25%	1775%	0	2.57%	n.a.
5	Number of bus lines partly or fully replaced by in-motion charging trolleybus	operation	Number of diesel bus lines replaced with trolleybuses	piece	0	1	n.a.	0	4	n.a.	0	0	n.a.
6	Cost of trolleybus vehicle-km	economics	Total costs of trolleybus transport/total number of vehicle-kms of trolleybus transport	PLN/vehicle-km	8.78	10.58	20.5%	10.33	10.2	−1.3%	7.60	10.45	37.5%
7	Share of battery trolleybuses	battery	Number of trolleybuses with batteries/total number of trolleybuses	%	36%	69%	89%	18.5%	54.5%	195%	71.4%	78.3%	9.7%
8	Average battery capacity	battery	Total capacity of batteries in trolleybuses/number of batteries	kWh	16	50.54	216%	34	43.3	27%	12	19.3	61%

Table 4. Cont.

No	KPI	KPI Category	KPI Description	Unit	Gdynia-Sopot			Lublin			Tychy		
					2014	2019	Change	2014	2019	Change	2014	2019	Change
9	Share of renewable energy in trolleybus transport	energy	Energy from renewable sources/total energy consumed by trolleybuses	%	no data	27.85%	n.a.	no data	15.82%	n.a.	no data	15.82%	n.a.
10	Unitary cost of energy	economics	Total costs of energy for trolleybuses/number of vehicle-kilometres	PLN/vehicle-km	no data	0.70	n.a.	no data	1.10	n.a.	no data	0.63	n.a.
11	Share of trolleybus lines with in-motion charging operations	operation	Number of trolleybus lines with in-motion charging operations/total number of trolleybus lines	%	0	40%	n.a.	18%	92%		0	29%	n.a.

Currency exchange as of 18.11.2020: 1 EUR = 4.47 PLN, 1 USD = 3.76 PLN, source: National Bank of Poland, www.nbp.pl. Source: self-study based on data collected from operators (MPK Lublin sp. z o.o., PKT Gdynia sp. z o.o., and TLT Tychy sp. z o.o.), public transport authorities (ZKM Gdynia and ZTM Lublin) and IGKM (Economic Chamber of Public Transport).

Table 5. Drivers and barriers for the in-motion charging trolleybuses.

Drivers	Barriers
Technological advancement in batteries. EU policy supporting transformation of transport system toward zero-emission level. National and local policy supporting electromobility development in public transport. Lack of infrastructure investments in the catenary. Priority in traffic for public transport vehicles (i.e., bus lanes). Complex urban mobility policy aimed on reducing the role of individual car. Focus on greening the energy.	High upfront costs of purchasing modern vehicles. Impact of COVID-19 on the farebox in public transport. Impact of the COVID-19 on the transport behaviour of citizens. Systemic traffic congestion. Increase in electricity costs.

6. Conclusions

This analysis of trolleybus systems in Poland indicates the spread of in-motion charging technology. The starting point for its development was a technological breakthrough in traction batteries. This breakthrough was both quantitative (significant increase in the share of vehicles equipped with batteries and growth of operations beyond catenary) and qualitative (popularisation of NMC and LTO batteries instead of NiCd). As in-motion charging technology leads to the development of trolleybus transport, it creates new possibilities for the spatial expansion of trolleybuses into urban areas without catenary. Although the costs of purchasing in-motion charging trolleybuses are still high, they can be partly compensated for by the lack of necessary investment in the development of network infrastructure. Another factor supporting the perspectives for the development of in-motion charging trolleybuses is a gradual decrease in the cost of batteries.

The use of KPIs, which have a synthetic form, allows for comparison of trolleybus systems of different sizes. However, the KPI framework created for this article within the TROLLEY 2.0 project has some limitations. One of the most serious is the lack of qualitative assessment, which should accompany the quantitative analysis. For this purpose, the article also uses data showing the transformation of battery technologies in the discussed trolleybus systems in Poland. This supplementary information presents the background of public transport changes in Poland. Also drivers and barriers were identified to support qualitative analysis. The other limitation is due to the lack of data or limited access to data for in-motion charging technology use or trolleybuses systems in Poland. However, the accessed data (from the public domain and the cities) allowed for the results to be calculated and compared in time and space.

This study provides some initial insights into the transformation of public transport systems with the use of new technologies in trolleybuses and corresponds to the previous research results in e.g., ELIPTIC project [89], also for Gdynia [90]. It is a good benchmark and reference paper for similar ones, as the electromobility in urban public transport is developing very fast, becoming a promising pro-ecological way to make cities more sustainable. Any subsequent research, though, should be focused on the development of such systems in different parts of the world, and the development of in-motion charging technology itself.

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Abbreviations

BRT	Bus Rapid Transit
CO	Carbon monoxide
CO ₂	Carbon dioxide
EU	European Commission
EV	electric vehicle
GHG	greenhouse gas
KPI	Key Performance Indicator
kWh	kilowatt-hour
LTO	lithium-titanate
MPK Lublin sp. z o.o.	a municipal trolleybus and bus transport operator operating in Lublin (PL)
NiCd	nickel-cadmium
NMC	nickel manganese cobalt
NO _x	nitrogen oxides
PKT—Przedsiębiorstwo Komunikacji Trolejbusowej sp. z o. o.	a municipal trolleybus transport operator operating in Gdynia and Sopot (PL)
PM _{2.5}	atmospheric particulate matter with a diameter of less than 2.5 micrometres
PM ₁₀	coarse atmospheric matter with a diameter of less than 10 micrometres
PT	public transport
TLT Tychy sp. z o.o.	a municipal trolleybus transport operator operating in Tychy (PL)
SUMP	Sustainable Urban Mobility Plan

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