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Sustainable Use of the Catenary by Trolleybuses with Auxiliary Power Sources on the Example of Gdynia

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Abstract: The current developments in onboard power source technology, in particular, traction batteries, open up new potential in trolleybus transport and also make it possible to introduce electric buses. Thus far, trolleybus transport has required the presence of overhead lines (OHL). Introducing trolleybuses with onboard batteries makes it possible to grow the zero-emissions transport network in places with limited power supply capabilities and low population density, or in places where building OHL would not be possible. This improves the efficiency of trolleybus transport and makes environmentally friendly public transport more accessible to the local citizens. Despite their obvious advantages, traction batteries can also be problematic, as the drivers may overuse them (e.g., in the event of pantograph failure), and the public transport authorities and transport companies may plan connections in an ineffective way without preparing the necessary infrastructure (the absence of slipways or automatic connection capabilities), which in turn leads to inefficient use of the OHL. The article outlines the operation of the trolleybus transport network in Gdynia. The use of traction batteries in regular connections is analysed, and the potential for electrification of the bus line, some sections of which follow the traction infrastructure, is examined.

Keywords: trolleybus transport; catenary; alternative power sources; batteries; optical pantograph alignment system

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1. Introduction

Trolleybus transport is used in 280 cities around the world. In the past, trolleybuses saw both rapid growth and decline [1]. The factor that improved the position of the trolleybus in the transport networks was the fact that it is electrically powered, which proved crucial during fuel crises. On the other hand, when fuel was readily available and cheap, the trolleybus transport would lose ground to buses powered by internal combustion engines. One of the main arguments for winding up trolleybus transport was usually the need to maintain the costly traction infrastructure and power supply system, as well as limitations arising from the fact that trolleybuses cannot operate without the traction infrastructure. The need to keep a reserve fleet of buses with internal combustion engines for the eventuality of loss of electric power supply further affected the economic balance of trolleybuses as public transport means.

Rapid growth of alternative power supply sources, in particular, in the first decade of the 21st century, allowed the trolleybus to return to the municipal transport networks. Initially, onboard diesel power generators were widely installed in the vehicles. They were then replaced by batteries and supercapacitors [2]. The Achilles' heel of trolleybuses (i.e., their dependence on the traction infrastructure) was eliminated and at the same time became their greatest advantage. The existing overhead lines facilitate the development of connections serviced by trolleybuses with onboard batteries. The fact that it is no longer necessary to build new infrastructure on remote sections with low population density or small passenger flow, or on historical sites (e.g., in historical quarters) makes it easier to introduce zero-emissions public transport. Those solutions help ensure equal access to environmentally friendly transport means for all inhabitants of the city and its suburbs.

Currently, trolleybuses with various types of onboard batteries are widely used in numerous municipal transport networks. In Central and Eastern European countries which use European Union funds to finance the restoration and upgrade of their public transport networks, most of the newly purchased vehicles are equipped with onboard batteries [3–5]. The batteries are used both as alternative power sources in the event of a traction system failure and as primary power sources outside the traction infrastructure.

Growing electric public transport systems is one of the priorities of the EU transport policy. Climate changes caused by excessive emissions of pollution into the environment have accelerated the departure from vehicles with engines powered by fossil fuels [6]. Under the public transport policy of the European Union and other developed countries, internal combustion vehicles are gradually being replaced with electric vehicles [7]. Poland is also adjusting its development policy according to the international climate agreements and is planning a complete departure from conventional vehicles. Municipal public transport is now the main recipient of policy actions in Poland [8]. A number of aid programmes are in place, financed mainly from the budget of the European Union, to help municipal transport authorities purchase new electric- and hydrogen-powered buses or trolleybuses. One of the beneficiaries of those programmes and a good example of sustainable development of municipal transport based on low- and zero-emissions vehicles is the city of Gdynia [5,9,10].

1.1. Description of the Problem

Sustainable and efficient use of the overhead lines (OHL) is a key challenge for trolleybus network operators. Installing alternative power sources on board disincentivises trolleybus drivers and maintenance technicians to connect or reconnect pantographs to the OHL (e.g., in the event of pantograph misalignment). Driving under the OHL without connecting to it should be seen as an inefficient use of resources. Assuming that the trolleybus life cycle is around 20 years and with the currently available battery solutions, it can be inferred that the onboard batteries, if used reasonably, will have a similar life cycle. Excessive or unnecessary use of traction batteries may cause a more rapid expiration and thus increase the operating cost of the entire system.

Special technical solutions are employed to automate the connection of pantographs of trolleybuses with onboard batteries to the OHL. Those solutions make the connection process quick and efficient; it does not require an extended stay at the stop and thus does not affect the trolleybus schedule. For automatic connection of the trolleybus to the OHL, it must be fitted with special pantographs operated by the driver (usually using a compressed air system) and network devices, the so-called guide caps.

With efficient use of the OHL, trolleybuses with onboard batteries can cover longer routes and connections. The presence of OHL makes it possible to reduce the capacity of the onboard batteries and thus the weight of the vehicle, and also increase the number of passenger seats. Optimal adjustment of the battery capacity to the length of the section which the trolleybus must cover makes this solution economically sound and efficient. Overestimating the battery capacity is a major mistake that many trolleybus operators make.

Having identified the research gap related to the onboard energy carriers and the efficient and sustainable use thereof in trolleybus transport, an attempt was made to examine the possible solutions for optimal application of such solutions [11]. The growing interest on the part of trolleybus operators and authorities of various cities which do not utilise the in-motion charging technology for their trolleybuses makes this subject scientifically relevant [9,12].

This article outlines the results of the research conducted to answer the following research questions:

- What does the current development of trolleybus transport look like and are there any new competitive advantages arising from the technological progress?
- What are the good and bad practices in using alternative power sources in trolleybus transport?
- How does efficient and sustainable use of the existing (or new) traction infrastructure impact the expansion of the connections in trolleybus transport?
- Does the correct use of the OHL (i.e., reducing onboard battery use) impact the battery capacity?

1.2. Literature Review

The literature of the subject lacks studies that would make it possible to determine which variant of electric public transport development is the most efficient in terms of the overall total costs, including the cost of exchanging batteries during the vehicles' life. At this time, it is much easier to introduce electric buses into the municipal transport system than trolleybuses [13–20]. However, this apparent ease might prove costly in the long term. Electric buses require large (in terms of capacity and weight) onboard batteries [21]. New vehicles are fitted with numerous solutions improving the passengers' comfort which require power supply (e.g., air conditioning of the passenger compartment), which in turn makes it impossible to reduce the capacity of the batteries. An intermediate solution is the rapid charging stations located at terminuses, or the induction charging system at stops, which is considered a solution for the future. Insufficient knowledge on the battery life expectancy due to the fact that the batteries have not been operated long enough in regular public transport is used as an argument by electric bus enthusiasts and sceptics alike [21,22]. While the onboard batteries in electric buses deserve the benefit of the doubt, it should nevertheless be assumed that their life expectancy will be shorter than the vehicle itself. At some point, the battery will have to be replaced, which will increase the cost of the entire system. An alternative solution, particularly for cities with trolleybus transport, is using trolleybuses equipped with onboard batteries. The trolleybus batteries need not have a massive capacity, because on some sections of their routes, they are powered by overhead lines. This solution does not reduce the passenger space as much as in electric buses. Lower vehicle weight also reduces operating costs, and the wear of the wheels and suspension.

The combined trolleybus transport using vehicles with autonomous battery supply provides considerable flexibility in planning connections. This advantage of the trolleybuses is now used by multiple municipal transport systems around the world. One of the pioneers of traction batteries was the company Solaris Bus & Coach, which has been manufacturing low-floor trolleybuses since 2001 [5]. The first vehicles to utilise this solution were equipped with lead batteries which served as a backup power source for covering short distances in emergency situations. A large batch of next-generation battery-powered trolleybuses was ordered by Trolleybus Transport Company (Przedsiębiorstwo Komunikacji Trolejbusowej) in Gdynia. The nickel–cadmium batteries in those vehicles were supposed to allow covering a distance of 3 to 5 km in emergency situations [5,9]. As it turned out, the range of the trolleybuses was much higher and they were occasionally used on regular connections. Between the positive experiences with trolleybuses with onboard batteries and the rapid development of the battery technology, backup diesel generators were completely eliminated from the vehicles.

Today, the electric public transport systems are dominated by electric buses and trolleybuses equipped with lithium onboard batteries [23–26], which are smaller and significantly extend the range that can be covered without the overhead lines (due to higher capacity), but most importantly, those batteries have much longer life expectancy and are less affected by charging cycles. The technological progress of the traction batteries produced a solution known as in-motion charging, which charges the onboard batteries when the trolleybus is being powered by the OHL. This eliminates the need to make longer stops to recharge the onboard battery, saving time and operating costs, and reducing the size of the vehicle fleet required to service the transport system.

The number of scientific studies on organisational issues and the functioning of trolleybus transport is not too great. This is largely due to the popularity of trolleybuses, which have a limited range. The nearly 300 existing trolleybus systems worldwide are a relatively small number [27]. Scientific research concerns particular policies in the field of urban electric transport development, including trolleybuses [10,15,28–31], comparative studies of the development of various means of public transport, including trolleybuses [21, 32–34] and the impact of means of transport on the environment, in particular, greenhouse gas emissions, CO_2 and other harmful substances [28,35–39]. Few studies concern technical issues, including trolleybus drives [40–42], power supply infrastructure and catenary [43], vehicle development [19,20,44,45] and technical facilities [46]. The analysis of the literature shows that there are no case studies showing the efficiency of the use of the overhead contact line in connection with the advantages of onboard batteries.

2. Materials and Methods

A multistage research approach was applied, as shown in Table 1. The first stage included a literature review and identification of the research gap concerning the electrification of municipal transport networks using trolleybuses equipped with backup onboard batteries. In the second stage, the carriers' experiences with operating those vehicles were gathered and analysed. The next stage included determining the conditions of using trolleybuses with backup onboard batteries on the basis of the data from the Gdynia trolleybus transport authority. In the fourth stage, the threshold values were specified for efficient electrification of the bus line with the use of trolleybuses with onboard batteries. In the final stage, the conclusions and recommendations were formulated.

Table 1. Research stages, research goals, materials and methods.

Stage	Research Goals	Materials and Methods
1	Identification of the research gap	Materials: scientific publications and zoning documents Methods: desk research
2	Experiences with the development and operation of trolleybuses with onboard power supply	Materials: operating experiences of trolleybus operators from European countries Methods: qualitative analysis of the experiences with operating trolleybuses with autonomous power supply on regular connections
3	Specification of the conditions of using trolleybus with backup power supply on line connections	Materials: operating data of the Gdynia trolleybus transport company Methods: quantitative analysis of operating data
4	Feasibility study of electrifying the bus line using trolleybuses with backup power supply	Materials: data on the bus lines acquired from the municipal transport authority in Gdynia, data on traffic congestion and delays from Tristar Methods: calculation of electric power consumption, battery status and minimum capacity of traction batteries
5	Formulation of recommendations on efficient and sustainable use of the traction infrastructure in trolleybus transport	Materials: electrification simulation results for bus line no. 152 in Gdynia Methods: formulating conclusions from the conducted research

3. Overhead Lines Usage Policy for Servicing Vehicles with Alternative Power Supply

Attempts to make trolleybuses independent from the OHL have been made for decades. The main reason behind those efforts was extending the range to remote sections of bus lines where it would have been economically unjustified to build new traction infrastructure. In Central and Eastern Europe, an innovative solution was adopted in 1994 in the Czech town of Hradec Králové, hitching a trailer with a diesel power generator to a Škoda 14Tr high-floor trolleybus. This made it possible to extend the trolleybus line no. 1 from the terminus in Nový Hradec Králové district to the Kluky area which had low population density (Figure 1). Building on the good experiences with this solution between 1994 and 2001, a low-floor trolleybus was then purchased with an onboard diesel power generator.

Figure 1. Škoda 14Tr trolleybus with a diesel power generator on the trailer, servicing line no. 1 in Hradec Králové, Czech Republic, from 1994 to 2001 (photo taken by M. Janů).

The development of the diesel generators, followed by onboard batteries, has encouraged more trolleybus operators to follow in the footsteps of the Hradec Králové public transport authority. The issue of expanding trolleybus connections using the existing traction infrastructure is a complex one, involving various technical, organisational and functional aspects. The main topics include:

(a) designing optimal routes to eliminate driving on battery under the OHL—providing infrastructure which will make it possible to connect the pantographs on the first stop with the OHL after crossing the section without the catenary;
(b) upgrading the trolleybus stops infrastructure to enable connection to the OHL (sufficiently long bays, marked stopping area);
(c) designing the OHL connection point to eliminate possible collisions with other trolleybuses (installing the so-called guide caps on the exterior network lines if there is more than one connection point at the stop);
(d) training drivers and eliminating excessive use of the onboard batteries.

An optimal policy of using the existing traction infrastructure with the trolleybuses equipped with backup power supply may improve the efficiency of the infrastructure. With the OHL, trolleybuses with backup power supply, in particular, with the zero-emissions batteries conforming to the requirements of the European Union, may increase the share of environmentally friendly vehicles in the transport activity of the public transport system.

3.1. Gdynia as an Example

Since Poland's accession into the European Union, the trolleybus transport system in Gdynia has been a constant beneficiary of EU funds, which have made it possible to modernise the power supply system and almost the entire traction infrastructure, and build new line sections. The connection grid has also been significantly expanded. In 2004, Gdynia had nine trolleybus lines, while at the end of 2020, there were 16 lines serviced by trolleybuses (15 trolleybus lines and 1 bus line partially serviced by trolleybuses) [5,20]. Importantly, in that period, the first connections serviced by vehicles with onboard batteries were opened. These were initially temporary or emergency connections (e.g., during road works or temporary closures) and were subsequently introduced to regular connections. At this time, there are eight lines in Gdynia which, on some sections, do not have overhead catenary. Positive experiences with operating trolleybuses with onboard batteries are not always coupled with efficient use of the OHL. The public transport system in Gdynia is managed by the Municipal Transport Authority (Zarząd Komunikacji Miejskiej), while the trolleybus fleet, the power supply system and the traction infrastructure are owned by the Trolleybus Transport Company (Przedsiębiorstwo Komunikacji Trolejbusowej). Introducing trolleybuses with backup onboard power supply on regular connections should be coordinated with preparing the relevant infrastructure; however, this is not always the case. Given that driving on battery under the overhead lines is considered inefficient, the traction infrastructure should be modified accordingly, as should be the first stops at which the trolleybus calls after leaving the section without overhead catenary. The authorities in Gdynia are eager to open connections which use the advantages of onboard batteries, but there is clear lack of cooperation and coordination in terms of adjusting the infrastructure. Since it is accepted that it is easier and cheaper to cross the section with overhead catenary on battery power, no attempts are made to optimise the infrastructure. The most negative examples are the following lines:

- bus line no. 181, which, since early 2019, has been increasingly serviced by articulated trolleybuses. Initially, the trolleybus was used on this line as a test, but as the outcome was positive, the number of connections serviced by trolleybuses was increased. However, on the connections from Sopot to Gdynia, the trolleybuses drive along a 2.1 km long section under OHL, calling at five stops where the vehicle could connect the pantographs to the catenary;
- trolleybus lines no 29 and 33, which drive 2 km under the OHL, calling at three stops where they should connect to the catenary;
- trolleybus line no. 34, which drives 1.3 km under the OHL, calling at two stops where it should connect to the catenary (Figures 2 and 3). Similarly, on the return trip, the trolleybus, due to the absence of slipways, crosses an identical distance with two stops along the way under the OHL, driving on battery power.

There are multiple factors contributing to the inefficient use of the existing traction infrastructure by the trolleybuses. The main ones include the lack of sufficiently long bays which would make it easier for the trolleybus to stop and connect the pantographs to the OHL, while leaving sufficient space for other public transport vehicles. The next problem in line is the unfavourable geometry of the bus bays. In order to connect the pantographs to the OHL, the trolleybus must be stopped parallel to the overhead catenary, which is not always possible. The final problem is the absence of the appropriate slipways which would allow the trolleybuses to follow the route correctly.

Aside from examples of lack of appropriate policy for managing connections serviced by trolleybuses with backup power supply, Gdynia has also implemented outstanding solutions in that area. As of 1 September 2020, bus line no. 170 was replaced by trolleybus line no. 32 serviced by trolleybuses using in-motion charging technology. Due to the fact that a long section of the route does not have overhead lines, six trolleybuses with high-capacity onboard batteries were purchased specifically to service the line. As part of electrification of the trolleybus line, a special, ca. 200 m long branch of the OHL was built in both directions to enable convenient connection and disconnection of the vehicles to the OHL. Otherwise, the trolleybuses would have to drive 1 km longer on battery power, which, in some cases, could disrupt the connection [9] (Figure 4).

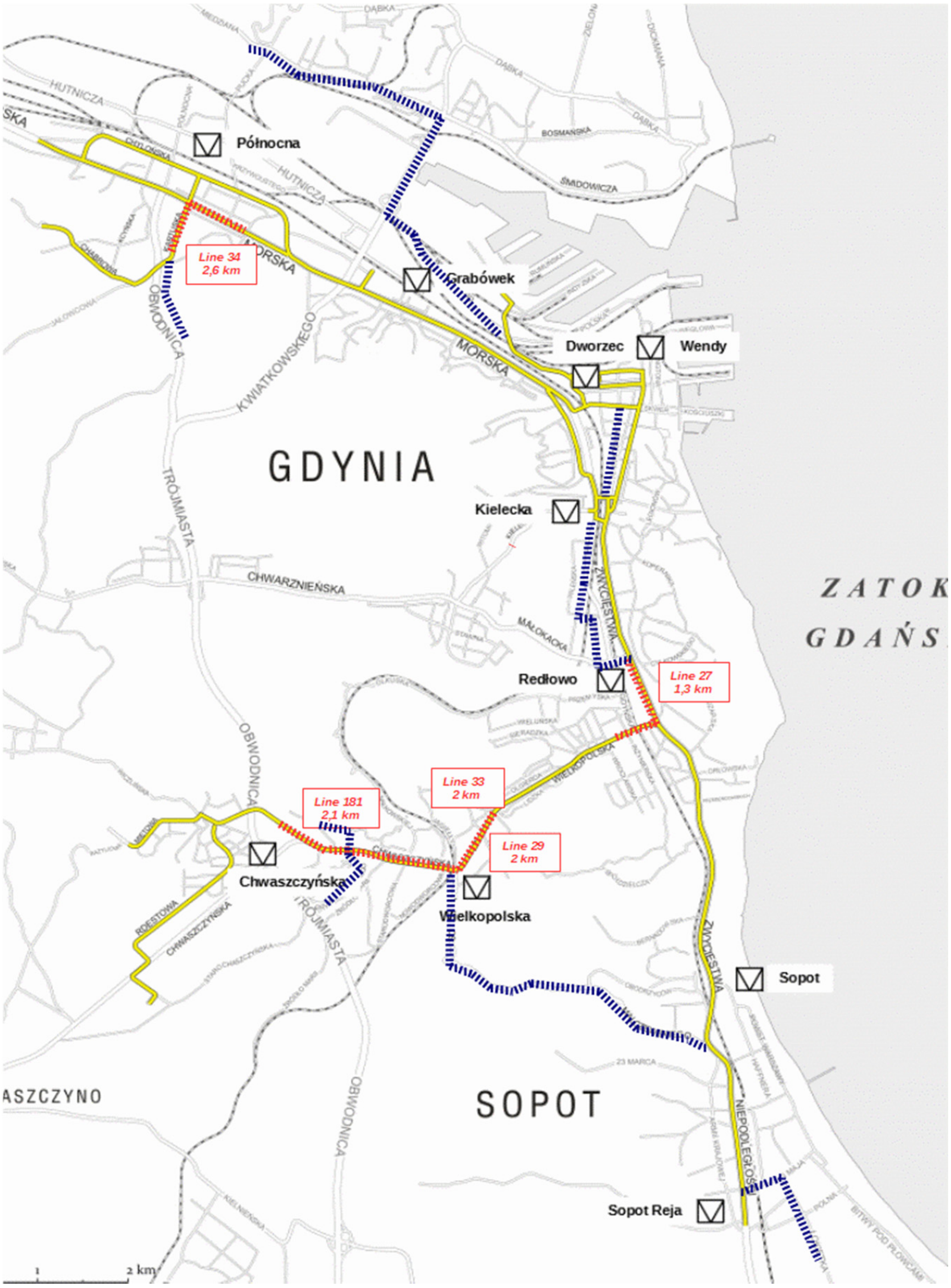

Figure 2. Trolleybus traction infrastructure in Gdynia and sections serviced on battery power. The routes driven on battery power on the sections without the OHL are marked in blue, and on the sections with the OHL are marked in red (in the case of line 34, driving on battery power on the section with overhead catenaries occurs in both directions, each 1.3 km long).

Figure 3. A trolleybus driving on battery power under the OHL due to the absence of an adequate site to connect the pantographs to the catenary (photo taken by K. Grzonka).

Figure 4. Automatic connection of an IMC trolleybus to the OHL (photo taken by K. Grzonka).

Table 2 shows a summary of the trolleybus lines in Gdynia serviced by vehicles with backup battery power. The total distance covered on battery power and the distance covered on battery power on sections with OHL are highlighted. It should be pointed out that due to the inefficient use of the existing infrastructure on some lines, the trolleybuses drive on battery power mostly under the OHL; this concerns 21% of all trolleybus connections.

Table 2. Trolleybus lines in Gdynia where backup power is used.

Line	Distance Covered on Battery Power [km]	Distance Unnecessarily Covered On Battery Power [km]	Share of Unnecessary Battery Operation
27	7.5	1.3	17%
29	7.4	2	27%
33	3.7	2	54%
34	9.8	2.6 [1]	26%
181 [2]	12.1	2.1	17%
		Total	21%

[1] 1.3 km in one direction; [2] bus line partially serviced by trolleybuses.

3.2. European Examples of Using Trolleybuses with Onboard Batteries on Regular Connections

New technological developments in traction batteries have contributed to widespread application of this solution in most trolleybus systems in Europe. Modernisation of the trolleybus transport systems in Central and Eastern European countries, financed mainly by the European Union funds, involves acquiring new fleets of vehicles, which are usually equipped with onboard batteries which have sufficient capacity to enable servicing regular connections. EU funding has made it possible to significantly expand the trolleybus networks in Polish cities (Gdynia, Lublin, Tychy), and also in the Czech Republic (Ostrava), Hungary (Budapest) and Romania (Cluj-Napoca). Despite a different economic environment, the countries of the former Soviet Union also choose vehicles with traction batteries to upgrade their trolleybus fleets. The situation in Western Europe is largely similar. Most trolleybus systems expand their fleets with vehicles capable of driving without connection to the OHL. One particular example is the city of Solingen, Germany, which is expanding its IMC trolleybus network. Figure 5 shows an IMC station for trolleybuses in Solingen. Outside Solingen, other German cities which operate trolleybus systems (Eberswalde and Esslingen) also expand their lines using battery-powered vehicles. This policy has also been adopted by cities in France (Lyon, Saint-Etienne), Switzerland (Lausanne, Zurich) and Italy (Parma, Milan). The changing optics on trolleybuses is clearly visible. In the past two decades, there was much discussion about the purpose of maintaining various trolleybus systems in Europe, and some systems were liquidated (e.g., in La-Chaux-de-Fonds), but today, the new technology has brought a renaissance of trolleybus transport which is gaining popularity.

Figure 5. IMC station for trolleybuses in Solingen, Germany (photo taken by M. Bartłomiejczyk).

4. Models of OHL Usage—Gdynia as an Example

As part of the conducted research, it was attempted to determine the possibility of electrification of bus lines using the existing trolleybus OHL. Using the trolleybus OHL to charge electric buses is shown for bus line no. 152 in Gdynia (Figure 6). The length of the line in one direction is 13 km, with two sections of the route—Section 1A (1.5 km) and Section 1B (2 km)—running under an existing OHL. Importantly, building an additional, 2 km long section of the OHL (Section 2) could connect the two existing sections into a single, 5.5 km long one. The following variants of electrification of line no. 152 were analysed:

- TBUS-1 variant: servicing the line with a dynamic charging system using the existing OHL (Section 1A and 1B), and a stationary charging station at the Oksywie Dickmana terminus;
- TBUS-2 variant: expanding the TBUS-1 variant with a new OHL section (Section 2);
- EBUS variant: servicing the line with electric buses charged with a rapid charger installed at the Oksywie Dickama terminus.

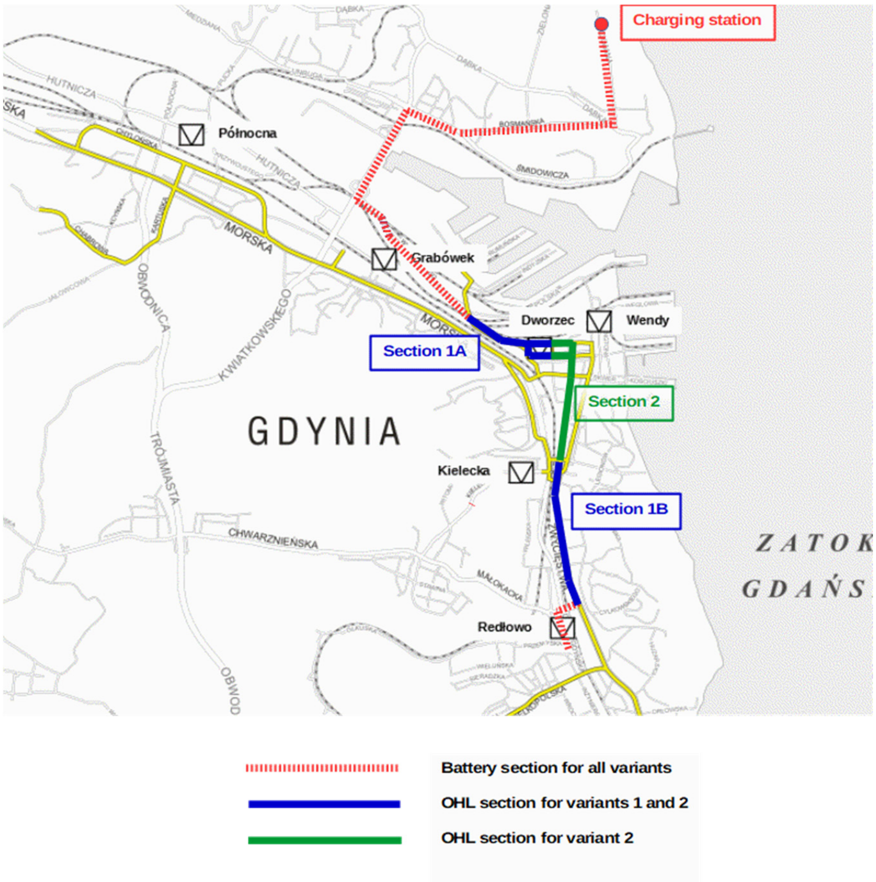

Figure 6. Bus line no. 152 electrification variants.

The power supply analysis was based on the real-life data on municipal transport from the Tristar system in Gdynia (The Tri-City: Gdansk, Sopot, Gdynia; Intelligent Agglomeration Transport System: Tristar, is designed to automatically manage traffic in the Tri-City area. The Tristar system carries out multiple measurements of vehicle traffic in the Tri-City road network. One of the measured values is the time of arrival and departure of buses and trolleybuses to and from stops. This allows the actual charging time to be accurately determined). This allowed us to include real-life travel times on dynamic charging sections (trolleybus network) and the parking time on the terminus. This approach makes it possible to study the charging systems, taking into consideration the traffic congestion, which significantly affects the available charging time.

The crucial aspect for the performance of electric vehicles is the charging power. In the case of the IMC (in-motion charging) systems, the main limitation of the charging power is the maximum current load capacity of the receivers. In the currently used solutions, the maximum current load capacity is 500–600A, which allows charging with 300–500 kW. However, due to thermal restrictions, the maximum acceptable current drawn from the mains drops to ca. 150A, reducing the maximum power usage rate and thus the average usable charging power. Figure 7 shows the correlation between the maximum charging power and the usage rate thereof. The diagram was prepared on the basis of the recorded current drawn by an articulated trolleybus in winter conditions. Increasing the maximum charging power would require a more complicated charging structure, increasing the charging price and the weight of the charging converter. Thus, the maximum usage rate of the existing charging capacity should be used. The highest usage rate, approach 1, is observed for the converter nominal power of 80–90 kW; however, in many cases, this power is inadequate. Furthermore, with the latest electric power technology developments, converters with higher power capacity can be built. At 150 kW, the possible usage rate of the charger power reaches 80%, which can be considered optimal power. Given the drop of the usage rate, increasing the charging power even further seems unjustified.

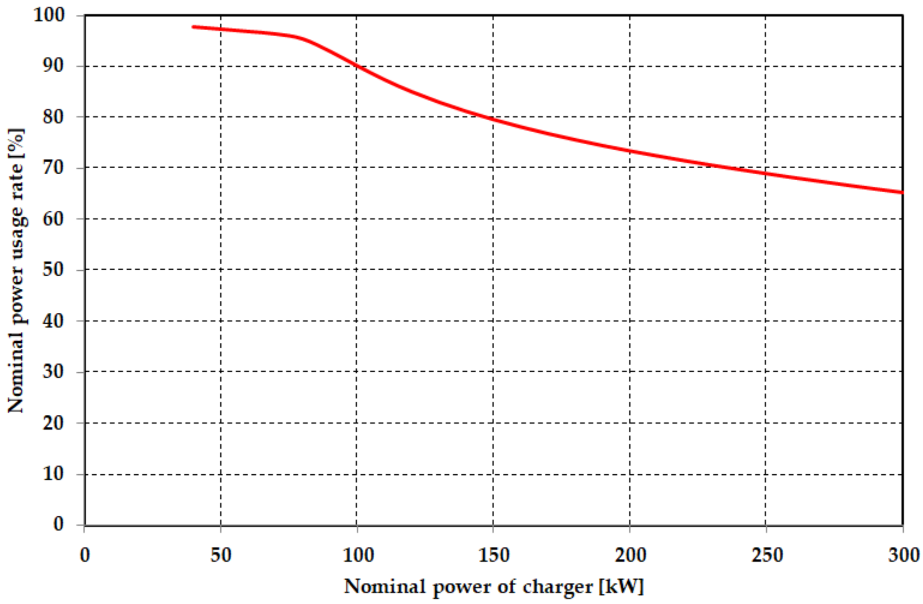

Figure 7. Nominal usage rate of the charger power.

The line is serviced by articulated vehicles. The maximum power consumption of the articulated trolleybus in harsh winter conditions was estimated at 2.6 kWh/km.

Figure 8 shows the energy consumption results in the form of the maximum traction battery discharge level. Two values are provided for each variant:

- minimal: theoretical value, assuming that the vehicle schedule is optimised in terms of charging and no traffic congestion,
- maximal: calculated on the basis of the current real-life parking times on the termini-nuses and the time of departure from individual stops.

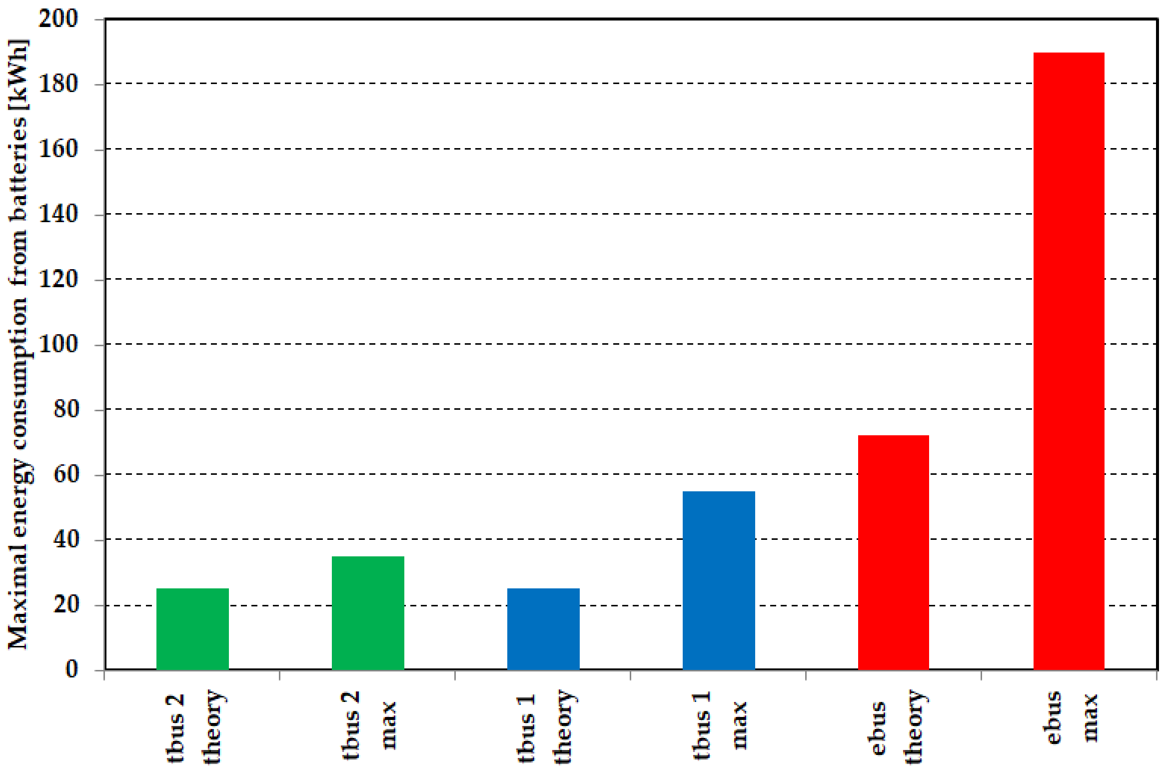

Figure 8. Maximum traction batteries discharge level (energy consumption) in individual servicing variants of line no. 152.

Firstly, the difference between the maximum and minimal battery discharge level value should be noted. The lowest discharge level was observed for the TBUS-2 variant (i.e., with the vehicle powered mostly from the OHL along the route). The highest discharge level was observed for the variant with minimal usage of the existing infrastructure (i.e., EBUS).

The difference arises from the different impacts of traffic congestion on electric vehicle charging. In the case of a standard electric bus (EBUS variant), the vehicle is charged only when parked at the terminus. In the event of delayed arrival, the parking time and thus the charging time is reduced accordingly. Figure 9 shows the histogram of delay of arrival of the vehicle at the Oksywie Dickmana terminus (prepared on the basis of data from the Tristar system). For 12.5% of connections, the delay exceeded 5 min, and for 5% of connections, 10 min. Assuming the parking time of 20 min, this significantly reduces the charging time. As a result, the battery cannot be fully recharged; consequently, the battery capacity must be increased to compensate. In the case of dynamic charging, the impact of congestion on charging time is different (Figure 10). The travel time on the OHL section (i.e., the charging time) does not drop below the minimum value arising from the traffic speed. Furthermore, disruptions caused by traffic congestion extend the travel time, thus improving the charging conditions. Therefore, dynamic charging from the trolleybus OHL reduces the impact of traffic disruptions on the battery charging process. Moreover, the longer the OHL section, the lower the impact on charging.

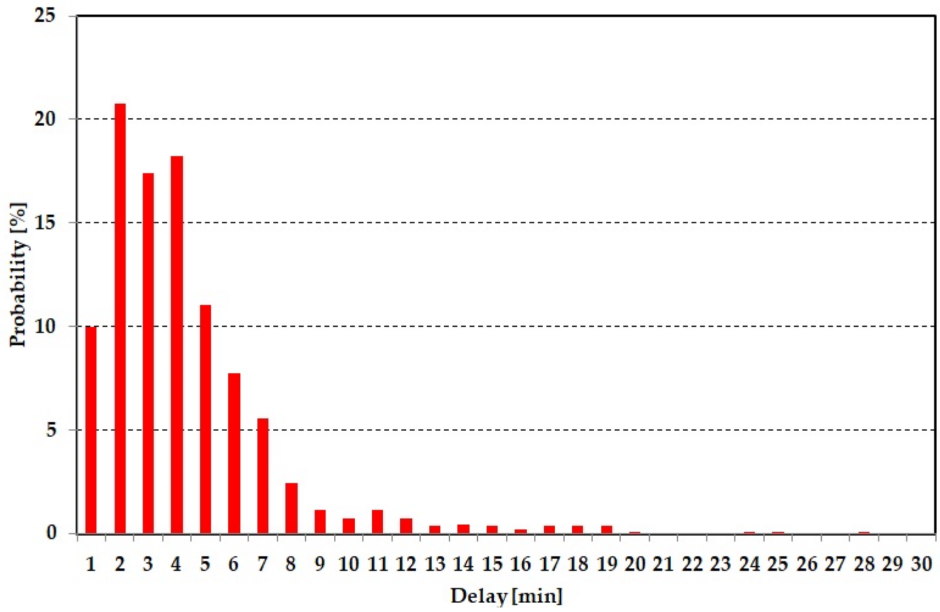

Figure 9. Delay of arrival of line no. 152 to the terminus.

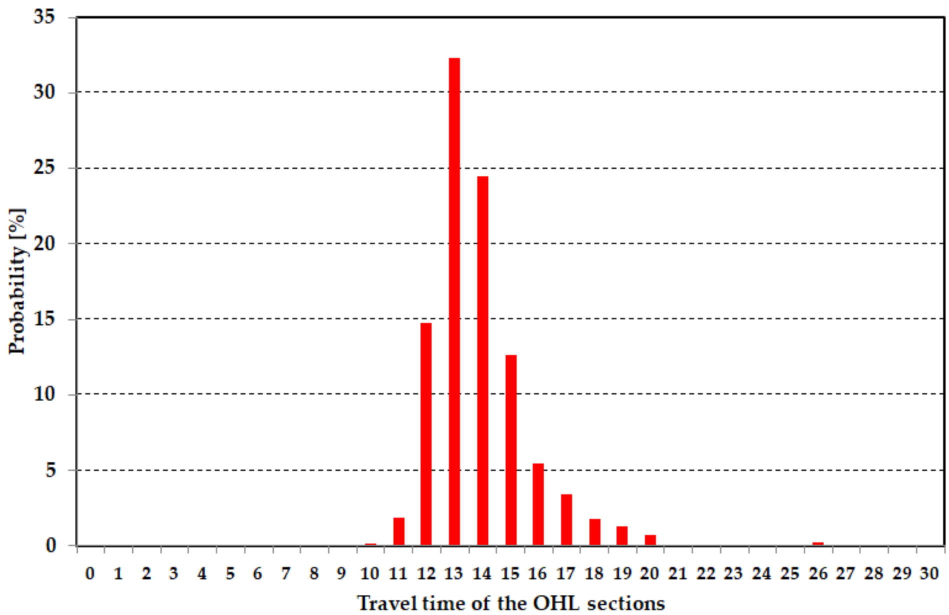

Figure 10. Histogram of the total travel time on OHL sections (TBUS-1 variant).

Dynamic charging from the trolleybus OHL also changes the battery operating cycle, making it possible to reduce the battery capacity. In the stationary charging variant (EBUS), the vehicle is charged once per travel cycle. In the case of line no. 152, dynamic charging makes it possible to divide the cycle into several subcycles with lower discharge levels, thus making it possible to reduce the battery capacity (Figure 11).

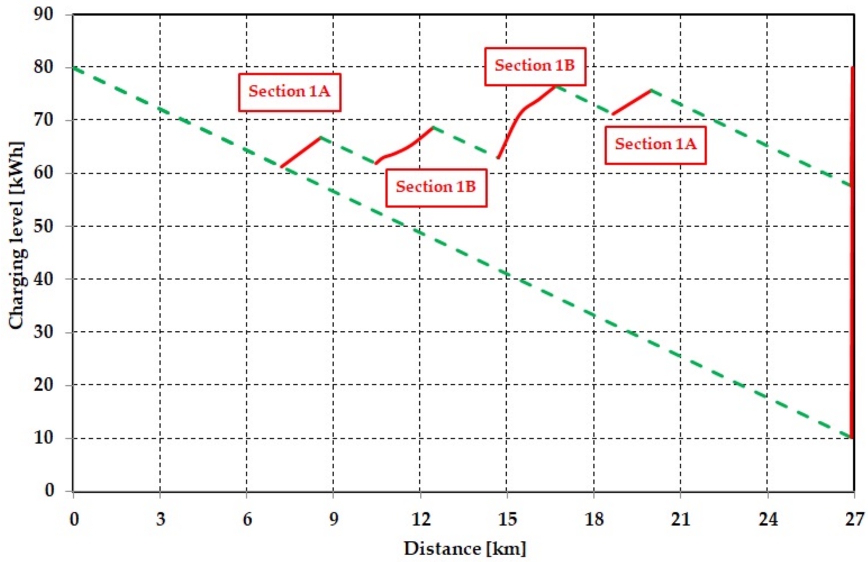

Figure 11. Comparison of the battery status as a function of the route for servicing line no. 152 by an electric bus and a trolleybus (variant 1).

5. Discussion

Conducting a study on the trolleybus transport system in Gdynia in the field of effective use of the overhead contact line and the advantages of onboard batteries, it was shown that the large regime of using additional power only under necessary conditions and connecting trolleybuses to the overhead line without idle runs under it creates the possibility of limiting the battery capacity and starting new connections. This is crucial for policies to develop zero-emission transport in cities. Transport operating costs are of key importance for operators. The possibility of reducing the capacity (and weight) of onboard batteries improves the economic balance. At the same time, it does not reduce the vehicle capacity, so it does not affect the need to increase the frequency of trolleybuses. We managed to verify the thesis that the correct use of the traction network limits the battery capacity and does not require oversizing of their size.

The analyses discussed in the article open the possibility of further research in the field of shaping connections using onboard batteries, especially in IMC technology. Trolleybuses are considered a classic public transport means in the cities, along with tramways, subways and light rail. The popularity of trolleybuses has fluctuated in the past. Their main disadvantage has always been the dependence on the traction infrastructure, which generated high costs and made it difficult to expand connections. Currently, the development of alternative power sources, in particular, the onboard batteries, has contributed to a renaissance of trolleybus transport. Onboard power supply has changed the perception of trolleybuses by eliminating travel disruptions in the event of a partial closure of the route (e.g., due to road works or other obstacles). Furthermore, batteries have allowed expanding the trolleybus connections into areas with less accessibility to public transport systems (low frequency of arrivals and departures), with low population density or where building the traction infrastructure would not be possible. The majority of trolleybus companies in Europe have upgraded their fleets in recent years, purchasing vehicles with onboard batteries.

New technological developments have also created significant competition for conventional trolleybuses in the form of electric buses. However, the apparently easy implementation of such vehicles for passenger connections (since electric buses do not require a power supply infrastructure) may prove problematic for developing public transport systems. Since electric buses can only be charged at specific points, they require batteries with higher capacity, which are heavier. This in turn reduces the number of passenger seats on the bus and increases the operating costs. In order to maintain the number of available seats, the operators must have a larger fleet of vehicles on the streets (higher frequency of arrivals and departures). The article presents the research procedure that allowed verifying the hypotheses that resulted from the research questions posed in the first part. Firstly, it has been shown that the development of onboard battery technology affects not only the popularisation of electric buses, but also a solution for trolleybus transport. Thanks to innovative solutions, trolleybuses have gained competitive advantages; on the one hand, they have gained flexibility and independence in relation to the catenary, and on the other hand, using it, they can have batteries with a smaller capacity installed. They were also looking for answers as to whether there are threats to the use of onboard power sources. It was confirmed that an appropriate regime for applying such solutions is necessary and staff training is needed to sustainably use power sources installed in vehicles, in particular, batteries. Idle runs with battery power under the overhead line do not improve the economic balance of trolleybus transport. The next issue concerned the dependence of the use of the overhead contact line and the effectiveness of the development of trolleybus connections. The great advantage of developing trolleybus transport with the use of onboard batteries is the possibility of limiting their capacity and weight. With an extensive trolleybus traction infrastructure, it is possible to replace bus lines with zero-emission vehicles. As a result, the correct use of the OHL leads to a reduction in vehicle costs and the operation of trolleybuses. The appropriate size of the battery adjusted to the actual operating conditions of the trolleybus line (the length and nature of the section without the OHL) improves the economic balance of trolleybus transport.

6. Conclusions

Having identified the research gap (i.e., the lack of comparative studies on servicing public transport connections by electric buses and trolleybuses), an in-depth analysis was conducted on the basis of operating data from the municipal transport system in Gdynia. The research verified the opinions voiced in scientific publications and trade press on the efficiency of electric buses and their alleged superiority over trolleybuses. Our analysis shows that in a city with a trolleybus traction infrastructure, provided that the infrastructure is used efficiently, it is possible to electrify a bus line using trolleybuses equipped with relatively small (in terms of size and power) onboard batteries, as opposed to the large, high-capacity batteries of electric buses which would service the same line.

The bus line running under the overhead lines, at least on some sections, can be serviced by IMC trolleybuses (i.e., charged in motion). This requires conducting relevant case studies and adjusting the capacity of onboard batteries to the traffic conditions of the given connection line. However, this solution is much more profitable for the public transport authority than introducing electric buses which are powered by large, high-capacity batteries with limited life expectancy, and can thus generate significant operating costs in the future (e.g., onboard battery replacement) and affect the performance of the public transport system.

The use of OHL infrastructure for dynamic charging allows reducing the capacity of traction batteries. This is especially important in terms of long-term running costs, as lower battery capacity brings lower replacement cost. In the analysed case, it is possible to reduce the battery capacity from 180–200 kWh to 50–80 kWh. It also brings environmental benefits, as both the production of batteries and their disposal are harmful to the environment.

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