Article

Technology Development and Spatial Diffusion of Auxiliary Power Sources in Trolleybuses in European Countries

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Abstract: Trolleybus transport is one of the classic means of public transport in cities. Its popularity varied in the past and was largely related to the fuel market situation. As fuel prices fell, electricity-powered transport lost popularity. The situation was similar during fuel crises. Trolleybuses gained in popularity then. Nowadays, the development of alternative power sources (APS) technology makes trolleybus transport partially independent of the overhead contact system, which is its great advantage. It is thus possible to develop trolleybus connections in areas where there is no justification for building overhead wiring infrastructure. The article analyses the development of on-board APS and their spatial diffusion in trolleybus systems in Europe. The main result of the research procedure indicates that the development of battery technologies, which could accelerate the closure of trolleybus transport due to the strong competition of electric buses not requiring an overhead contact line, allows for the dynamic development of this branch of transport. The situation in 71 trolleybus systems in Central and Western Europe which had any experience in the use of APS in 2011–2021 was examined. As a result of the analysis, the dynamics of APS diffusion were determined, in particular, a significant increase in the number of trolleybus systems using on-board batteries from 7 in 2011 to 44 in 2021.

Keywords: electromobility; public transport; trolleybus; electric bus; auxiliary power sources; battery

1. Introduction

Nowadays, trolleybus transport plays an important role in shaping low-emission public transport. This is largely due to modern technologies which have resulted in greater flexibility in shaping transport connections [1]. Traditional trolleybuses were attached to the overhead contact line and could overcome obstacles at a distance of 4–5 m from the traffic axis. The development of auxiliary power sources made trolleybuses somewhat independent of the power system, which was a substantial development impulse to many systems around the world [2]. Vehicles equipped with alternative power sources have become more economical due to the lack of a need to maintain a constant reserve of diesel buses in the event of a power system failure or closure of a part of the route for traffic [3]. The development of combustion generator technology in the 1990s enabled covering parts of routes without the need to supply power from the overhead contact system, as well as extending connections to peripheral sections or areas where it would be difficult to build the overhead wiring infrastructure, e.g., amongst historical buildings. Due to the emission of pollutants and noise, trolleybuses equipped with diesel units, while having the advantage of flexibility, simultaneously had all the disadvantages of buses, but with a higher purchase cost. The qualitative change occurred with the development of the technology of on-board batteries. The energy accumulated in them did not violate the most important advantage of trolleybuses—the lack of emissions at the place of operation. Trolleybus transport usually serves central business districts and areas with a high density of the urban tissue. Then the lack of pollution and low noise emissions are important advantages of trolleybuses, even with an unfavourable energy mix, as is the case, for
example, in Poland [4–7]. Technological development has contributed to the promotion of high-capacity batteries which are used to power sections of routes without overhead wiring. The economies of scale may reduce the costs of their purchase, service and disposal. The use of an on-board power source and efficient use of the overhead contact line leads to the conclusion that trolleybuses can be the best means of public transport [8]. They do not need capacious batteries limiting the number of passenger seats as in electric buses or such high investment outlays as tramway transport. In recent years, bi-articulated trolleybuses have also become popular, with their capacity equal to trams. Thus, the conditions for the use of auxiliary power sources in trolleybuses should be analysed in a special way [9,10].

The article postulates investigating the scale of using auxiliary on-board power sources in trolleybuses in Central and Western European cities. Identification of the scale and the type of the used auxiliary units will allow determining the dynamics of changes in relation to the information presented in the only scientific work dealing with this issue in a comprehensive manner, published in 2011 [11]. A comparison of the situation from March 2011 and March 2021 will allow determining the pace of adaptation of trolleybus transport to new technologies.

In order to achieve the research goal, the following questions were asked:

1. Has the scale of using auxiliary power sources in trolleybuses increased within the last 10 years?
2. Are diesel units still the most common source of auxiliary power?
3. Has the development of battery technology influenced the scale of their use in trolleybuses?

2. Literature Review

The increasing role of electrified public transport which implements the postulates of limiting greenhouse gas emissions into the atmosphere in the simplest way makes this issue interesting from the scientific point of view [12]. Scientific articles published in recent years in the best journals testify to the importance of the issue and, at the same time, indicate research gaps.

In the first stage of this research procedure, scientific articles from the last decade were analysed in order to identify all studies that deal in any way with on-board auxiliary power sources in trolleybuses. Their authors indicate that trolleybuses are an important means of transport in shaping sustainable and ecological public transport [13]. In many countries, policies are currently being implemented to reduce emissions from transport, including from public transport. The European Union points to a need to rapidly depart from fossil fuels in public transport [14–20]. Other non-European countries also have their own policies for the development of electromobility using trolleybuses [21,22]. Few cities implement a policy of excluding trolleybus transport, but these are cases where political decisions play a key role, not supported by in-depth analyses [23].

The conducted analysis of scientific sources has shown that most of the published articles concern specific issues or analyse conditions specific to a particular transport system (Table 1). Among the papers, there is no synthetic study summarising the use of on-board auxiliary power sources in trolleybuses.
| Subject                        | Source                                      | Aim of the Study                                                                 |
|-------------------------------|---------------------------------------------|----------------------------------------------------------------------------------|
| Designing connections         | Ajanovic [24]                               | Designing the use of electric vehicles in urban transport should depend on a favourable energy mix (energy from renewable sources). |
|                               | Bartłomiejczyk and Polom [25]               | Designing trolleybus connections in Prague with the use of alternative power sources. |
|                               | Gohlich [26]                                | Modelling the use of electric buses/trolleybuses taking into account the total cost of the vehicle life. |
|                               | Mathieu [18]                                | Complex design of connections in public transport, competitiveness of electric buses. |
|                               | Naranjo et al. [27]                         | On-board energy storage systems in public transport vehicles—an example of a Bus Rapid Transit (BRT) system in Bogota. |
|                               | Perujo et al. [19]                          | The prospect of electrification of individual and collective transport.           |
|                               | Polom and Bartłomiejczyk [11]               | Analysis of the use of alternative power sources in trolleybuses in European countries. |
|                               | Polom [28]                                  | Analysis of the use of alternative power sources in trolleybuses in European countries. |
|                               | Polom [29]                                  | Spatial development of trolleybus connections in Gdynia when powered by on-board batteries. |
| Diesel unit                   | Polom and Bartłomiejczyk [11]               | Analysis of the use of alternative power sources in trolleybuses in European countries. |
| Environmental impact          | Klucininkas et al. [30]                     | A comparative study of emissions of pollutants by a city bus and a trolleybus in Kaunas. |
|                               | Lie et al. [31]                             | The carbon footprint of electric buses in Trondheim.                              |
|                               | Pietrzak and Pietrzak [32]                  | Research on the environmental impact of the implementation of electric vehicles in public transport in Szczecin. |
| In-Motion-Charging            | Bartłomiejczyk and Polom [33]               | Characteristics of the Slide-In project in Landskrona.                           |
|                               | Bartłomiejczyk and Polom [8]                | Analysis of charging battery-operated trolleybuses from an overhead contact system. |
|                               | Berigk et al. [34]                          | Analysis of the possibilities of electrification of urban transport lines using the In-Motion-Charging technology in Germany. |
|                               | Wolek et al. [2]                            | Assessment of the use of In-Motion-Charging technology in Poland.                |
| On-board batteries            | Alfieri et al. [35]                         | Investigation of the possibility of replacing the diesel unit with on-board batteries. A comparison of different battery technologies in Naples. |
|                               | Borowik and Cywinski [36]                   | Modernisation of the trolleybus transport system in Tychy, purchase of trolleybuses with on-board batteries. |
|                               | Gao et al. [37]                             | Assessment of the dependence of the capacity of on-board batteries on the frequency of their charging. |
|                               | Rogge at al. [38]                           | Assessment of the possibility of electrification of bus lines with battery-operated vehicles (buses, trolleybuses) depending on the battery capacity and the charging power. |
| Operating costs               | Berckmans et al. [39]                      | On-board battery cost analysis in 2030.                                           |
|                               | Pietrzak and Pietrzak [40]                  | Economic aspects of using electric buses in public transport in Szczecin.         |
The literature review shows that trolleybus transport remains an important scientific issue, but there are no scientific studies that would allow the comparison of various technological solutions. A lack of studies summarizing and synthesizing information was identified. This article aims to fill this APS gap. Most of the articles analyze the specific situation in the selected trolleybus transport system. There is a lack of comparative studies, such as the life cycle costs of a vehicle, for trolleybuses equipped with diesel generators and on-board batteries, which may be a further development of this study. As a result of the conducted review, information was obtained that there are practically no studies on diesel aggregates and supercapacitors in the scientific circuit [11], while on-board batteries are gaining popularity, especially in the In-Motion Charging (IMC) technology [2,8,33–38].

3. The Idea of Auxiliary Power Sources in Trolleybuses

Trolleybuses combine the features of a bus and a tram. Moving on the streets, they have a certain freedom in avoiding obstacles, but, like trams, they cannot move away from the overhead contact system. Since the creation of the first trolleybuses, solutions have been sought to increase their flexibility and to enable short journeys without a need for being

| Subject | Source | Aim of the Study |
|---------|--------|------------------|
| Potkány et al. [41] | Comparison of the operating costs of electric buses and buses with diesel engines using the Life Cycle Cost method. |
| Sheth and Sarkar [42] | Comparative Life Cycle Cost analysis of the operating costs of electric buses and diesel buses in India. |
| Yusof et al. [43] | Analysis of the operating costs of electric buses in Brunei. |
| Petkov [44] | Analysis of the functioning of trolleybus transport in Bulgaria. |
| Polom and Wiśniewski [20] | Policies for the development of electromobility in public transport in Poland. |
| Tica at al. [45] | Characteristics of the policy of implementing trolleybuses in public transport. |
| Tsolas [46] | DAE assessment of the operation of trolleybus lines in Athens and Piraeus. |
| Tucki et al. [47] | Characteristics of the development policy of electromobility in public transport in Poland and in the European Union. |
| Wolek et al. [13] | Determining the profitability threshold for the operation of trolleybuses in relation to buses with diesel engines, the case of Gdynia. |
| Elin [48] | Characteristics of the infrastructure for charging buses (trolleybuses) with on-board batteries. |
| Gallet et al. [49] | Proposed model for calculating demand for electricity for public transport vehicles equipped with on-board batteries. |
| Hamacek [50] | A proposal of energy savings in trolleybuses through the effective use of regenerative braking. |
| Kühne [1] | Characteristics of the experience of innovative solutions in trolleybus transport in Germany. |
| Pejšova [51] | Comparison of the operating costs and pollutant emissions of various means of public transport. |
| Wang et al. [21] | Assessment of energy consumption by electric buses in real road conditions. |
| Supercapacitors | Polom and Bartłomiejczyk [11] | Analysis of the use of alternative power sources in trolleybuses in European countries. |

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**Table 1. Cont.**
attached to the overhead contact line. Battery solutions have been tested already since the early 1930s, but the simple technology of the times did not allow for their everyday use. In the following years, attempts were made to use internal diesel engines while reducing the advantages of the lack of emissions from trolleybuses.

The popularisation of auxiliary on-board power systems in trolleybuses took place in the 1980s and 1990s [11]. These were mainly internal diesel units that served as generators supplying the vehicle’s basic propulsion system. At the beginning of the 21st century, the first trolleybus of this type was also built in Central and Eastern Europe, and in 2001 it started operating on line no. 1 in the city of Hradec Králové in the Czech Republic [52]. Today, such a solution is available from all trolleybus manufacturers in the European Union and Switzerland (Hess, Solaris, Škoda, Van Hool) [11]. The advantage of a trolleybus equipped with a diesel unit lies in its unlimited range—it can run as long as the amount of fuel allows. Yet, trolleybuses equipped with a diesel unit generate significant noise and are not emission-free. In addition, cities using this type of vehicle indicate high fuel consumption.

The diesel unit is the first and, at the same time, the most popular form of increasing the flexibility of trolleybuses and their independence of power supply from the overhead contact system. The second group of auxiliary power sources includes various on-board battery solutions that have been gaining in popularity in recent years. Their advantage is the lack of emissions of pollutants and noise, thus maintaining the most important features of a fully electric vehicle. With the growing interest in batteries, the technology became popular and developed very intensively in 2011–2021. At the beginning of the analysed period, lead, nickel-metal hydride and nickel-cadmium batteries were used, whose mass was significant whereas their life and energy capacity were limited. In mid-2010s, the availability of lithium batteries significantly increased, and they replaced the older solutions. Lithium batteries allow for deep and frequent discharges and regular use without the service life being noticeably affected.

The last group of solutions for an auxiliary power source in trolleybuses includes supercapacitors, which, however, have not become as popular as diesel units or on-board batteries. In the last decade, the supercapacitor solution has been tested in only 5 cities. They can be quickly charged, but their energy capacity is not as high as of lithium batteries.

The idea of using APS in trolleybuses contributes to the spatial development of connections. The most promising is the use of on-board batteries, in particular in the In-Motion-Charging technology, which allows shaping connection routes quite freely, using the advantages of trolleybuses, power supply from the traction network, and the possibility of passing sections without traction infrastructure (overhead line, catenary). A traditional trolleybus requires full route electrification, a vehicle with on-board batteries for the majority of traction, and the in-motion-charging technology allows the power supply to be limited to approximately 20–40% (cf. Figure 1).

![Figure 1. Characteristics of the electrification of trolleybus routes.](image-url)
4. Meta-Study

The research presented in this article was prepared on the basis of a review of literature sources, in particular scientific articles, unpublished materials of trolleybus carriers and organisers, as well as information obtained from professional websites. First, peer-reviewed scientific sources were analysed to identify research gaps. As a result, a conclusion was drawn that trolleybus transport is becoming more and more popular, also among researchers, but there is no comprehensive study on the use of innovative solutions as regards on-board power sources. Conducting such a study will create a basis for further research in the field of comparing the efficiency of the development of trolleybus transport and electric buses. In the second stage, the obtained information was aggregated for 71 trolleybus systems in operation in 2011–2021 in Central and Western Europe which had experience with vehicles equipped with any auxiliary power source. States that came into existence after the collapse of the Union of Soviet Socialist Republics (Belarus, Russia and Ukraine) were excluded from the analysis. Due to the lack of reliable sources, it would not be possible to conduct the same analysis for all systems. The third stage concerned the analysis and presentation of model solutions for the development of trolleybus transport using alternative power sources in route traffic, as well as technology diffusion based on the example of Polish trolleybus systems.

5. Results

5.1. Diffusion of Auxiliary Power Sources for Trolleybuses in 2011–2021

The article analyses the scale of APS use in 2011–2021. The attempt to systematise information in the field of APS operation in Central and Western Europe allowed defining the dynamics of changes taking place in the field of the development of technology and its dissemination. Table 2 presents information on the types of on-board auxiliary power sources in trolleybuses used in 71 public transport systems that have had any experience with diesel units, supercapacitors and on-board batteries.

Table 2. Comparison of the scale of use of the auxiliary power sources in trolleybuses in European cities in 2011–2021.

| Country       | City           | On-Board Diesel Units | On-Board Supercapacitors | On-Board Batteries | Comments                                      |
|---------------|----------------|-----------------------|--------------------------|--------------------|------------------------------------------------|
| Austria       | Linz           | •                     | •                        | •                  |                                               |
|               | Salzburg       | •                     | •                        | •                  |                                               |
| Bulgaria      | Burgas         | •                     |                          |                    |                                               |
|               | Pleven         | •                     |                          |                    |                                               |
|               | Stara Zagora   | •                     | •                        | •                  |                                               |
|               | Sofia          | •                     |                          |                    |                                               |
|               | Varna          | •                     |                          |                    |                                               |
| Czech Republic| Brno           | •                     |                          |                    |                                               |
|               | České Budějovice| •                    |                          |                    |                                               |
|               | Hradec Kralové | •                     |                          |                    |                                               |
|               | Mariánské Lazně| •                     |                          |                    |                                               |
|               | Opava          | •                     |                          |                    |                                               |
|               | Ostrava        | •                     |                          |                    |                                               |
|               | Plzeň           | •                     |                          |                    |                                               |
|               | Prague         | •                     |                          |                    |                                               |
|               | Ústí nad Labem | •                     |                          |                    |                                               |
|               | Zlín           | •                     |                          |                    |                                               |

Estonia Tallin •
## Table 2. Cont.

| Country         | City                  | On-Board Diesel Units | On-Board Supercapacitors | On-Board Batteries | Comments                                                                 |
|-----------------|-----------------------|-----------------------|--------------------------|--------------------|--------------------------------------------------------------------------|
| France          | Limoges               | •                     | •                        | •                  |                                                                          |
|                 | Lyon                  | •                     | •                        | •                  |                                                                          |
|                 | Nancy                 | •                     | •                        | •                  |                                                                          |
|                 | Saint Etienne         | •                     | •                        | •                  | TVR vehicles powered by a trolleybus overhead line, guided on a rail in the road |
| Germany         | Eberswalde            | •                     | •                        | •                  |                                                                          |
|                 | Esslingen am Neckar   | •                     | •                        | •                  |                                                                          |
|                 | Solingen              | •                     | •                        | •                  |                                                                          |
| Greece          | Athens                | •                     | •                        | •                  |                                                                          |
| The Netherlands | Arnhem                | •                     | •                        | •                  | Second-hand trolleybuses purchased from Eberswalde (DE) with diesel units |
| Hungary         | Budapest              | •                     | •                        | •                  |                                                                          |
|                 | Debrecen              | •                     | •                        | •                  |                                                                          |
|                 | Szeged                | •                     | •                        | •                  |                                                                          |
| Italy           | Ancona                | •                     | •                        | •                  |                                                                          |
|                 | Bologna               | •                     | •                        | •                  |                                                                          |
|                 | Cagliari              | •                     | •                        | •                  |                                                                          |
|                 | Genoa                 | •                     | •                        | •                  |                                                                          |
|                 | La Spezia             | •                     | •                        | •                  |                                                                          |
|                 | Lecce                 | •                     | •                        | •                  |                                                                          |
|                 | Milan                 | •                     | •                        | •                  |                                                                          |
|                 | Modena                | •                     | •                        | •                  |                                                                          |
|                 | Naples                | •                     | •                        | •                  |                                                                          |
|                 | Parma                 | •                     | •                        | •                  |                                                                          |
|                 | Rome                  | •                     | •                        | •                  |                                                                          |
|                 | Saremo                | •                     | •                        | •                  |                                                                          |
| Lithuania       | Kaunas                | •                     | •                        | •                  | Test use of a supercapacitor on a Jelcz trolleybus; used trolleybuses purchased in Arnhem (NL) with diesel units |
| Latvia          | Riga                  | •                     | •                        | •                  | The world’s first trolleybuses with a hydrogen generator powering on-board batteries * |
| Norway          | Bergen                | •                     | •                        | •                  |                                                                          |
| Poland          | Gdynia                | •                     | •                        | •                  |                                                                          |
|                 | Lublin                | •                     | •                        | •                  |                                                                          |
|                 | Tychy                 | •                     | •                        | •                  |                                                                          |
| Portugal        | Coimbra               | •                     | •                        | •                  |                                                                          |
Table 2. Cont.

| Country | City                | On-Board Diesel Units | On-Board Supercapacitors | On-Board Batteries | Comments                     |
|---------|---------------------|-----------------------|--------------------------|-------------------|------------------------------|
|         |                     | 2011 | 2021 | 2011 | 2021 | 2011 | 2021 |                          |
| Romania | Brașov              |      |      |      |      |      |      | •                         |
|         | Cluj-Napoca         |      |      |      |      |      |      | •                         |
|         | Galați              |      |      |      |      |      |      | •                         |
|         | Timișoara           |      |      |      |      |      |      | •                         |
| Slovakia| Banská Bystrica     |      |      |      |      |      |      | •                         |
|         | Bratislava          |      |      |      |      |      |      | •                         |
|         | Žilina               |      |      |      |      |      |      | •                         |
| Spain   | Castellón de la Plana|      |      |      |      |      |      | •                         |
| Sweden  | Landskrona          |      |      |      |      |      |      | •                         |
|         | Bern                |      |      |      |      |      |      | •                         |
|         | Biel                |      |      |      |      |      |      | •                         |
|         | Fribourg            |      |      |      |      |      |      | •                         |
|         | Genève              |      |      |      |      |      |      | •                         |
|         | La Chaux-de-Fonds   |      |      |      |      |      |      | Decommissioning of the system in 2014 |
| Switzerland| Lausanne         |      |      |      |      |      |      | •                         |
|         | Luzern              |      |      |      |      |      |      | •                         |
|         | Montreux-Vevey      |      |      |      |      |      |      | •                         |
|         | Neuchatel           |      |      |      |      |      |      | •                         |
|         | Schaffhausen        |      |      |      |      |      |      | •                         |
|         | Saint Gallen        |      |      |      |      |      |      | •                         |
|         | Winthertur          |      |      |      |      |      |      | •                         |
|         | Zürich              |      |      |      |      |      |      | •                         |
| Total   |                     | 71  | 49   | 49   | 5    | 2    | 7    | 44                        |

* use of the selected solution in the trolleybus system.

In March 2021, 65 trolleybus systems used trolleybuses with various types of auxiliary drives. The number of cities using them has increased by 11 since 2011, because there were 54 trolleybus systems in that year. The structure of the applied technologies has significantly changed. At the beginning of the decade, mainly diesel units were used (49). Only seven cities had trolleybuses with on-board batteries. In the following years, the number of systems using diesel units did not change, although some cities that had not previously operated any APS introduced them into operation, and some carriers abandoned this solution in favour of batteries. On the other hand, the number of carriers using trolleybuses with on-board batteries has changed significantly from seven to 44. The number of trolleybus systems equipped with supercapacitors also decreased from five to two, which indicates a failure of this solution. The considerable popularity of on-board batteries indicates the popularisation of technology and good experience in their use.

5.2. Review of Selected Policies Regarding the Use of Auxiliary Power Sources in Trolleybuses

Selected transport policies assuming the use of trolleybuses equipped with on-board auxiliary power sources have been characterised below. The choice of cities results from the variety of applied solutions and from factors influencing the use of trolleybuses. Both small towns using single connections and large towns which, thanks to additional methods of powering trolleybuses, spatially developed connections have been presented. It has been shown that, thanks to modern propulsion solutions, trolleybus transport can be an effective alternative to buses that, for example, have been replaced in Rome and are planned to be replaced in Prague.
5.2.1. Bergen (Norway)

There are currently only two trolleybus systems in Scandinavian countries. The first one operates in Bergen (Norway), and it was launched in 1950 [53]. The other one is a small system in Landskrona (Sweden), which was inaugurated in 2003 [33]. Both trolleybus networks are small and concern single connections and a small fleet of vehicles. In the 1970s, the 1990s and at the turn of 2000s and the 2010s, attempts were made to shut down trolleybus connections. Until 2020, there was one trolleybus line in Bergen, on which 6 trolleybuses were exploited, additionally equipped with diesel units. A particularly difficult situation arose in 2005, when a decision was made to build a tramway system. In the following years, however, it turned out that it was a relatively expensive investment and it was worth keeping trolleybuses in operation. Replacing them with trams would require significant infrastructural investments beyond economic viability. In addition, it was decided to complement both systems, and in 2019 a decision was taken to modernise and extend the trolleybus route. In the same year, 10 articulated trolleybuses equipped with 55 kWh batteries were ordered, which were delivered by the end of 2020 [54,55]. On-board batteries allow for a journey of about 11 km without a need for powering from the overhead contact system. The charging technology while driving on the overhead line power will reduce the down time. The on-board power supply will allow avoiding the construction of overhead wiring in the city centre, as the line will be extended to the western district of Lyngbø via city centre. If the project proves successful, a greater number of lines served by trolleybuses will use the new overhead wiring infrastructure.

5.2.2. Gdynia (Poland)

Gdynia is an example of effective implementation of innovative technologies in trolleybus transport. Being a participant in many international projects, it is set as an example of effective development of zero-emission transport [13]. As in other post-communist countries of Central and Eastern Europe, also in Poland, as a result of the socio-economic transformation in 1989, there was a serious decline in public transport. Taking responsibility for this sphere of economy by local self-governments with insufficient resources has led to the collapse of three trolleybus systems in Poland and a serious weakening, bordering on the shutdown of the remaining three [3,20]. As a result of Poland’s accession to the European Union, funds have appeared for the modernisation and development of environmentally friendly transport, including trolleybuses.

Since 2004, in the next 16 years, the city of Gdynia transformed trolleybus transport from neglected to exemplary in Europe. The use of auxiliary power sources has also contributed to this. The Trolleybus Transport Company in Gdynia decided to use traction batteries, which were unpopular at the end of the 2000s. Their low popularity at that time resulted from their novelty and lack of experience. Thanks to the implementation of on-board batteries, trolleybus-operated connections appeared in areas of the city where there was no overhead wiring infrastructure. Sections serviced by trolleybuses powered by energy stored in on-board batteries appeared on eight lines (Figure 2) [29]. Thanks to the use of the existing overhead wiring, trolleybuses are recharged while in motion without the need for long stops (as in the case of electric buses) [2,8].
5.2.3. Prague (the Czech Republic)

The Czech Republic is one of the countries where trolleybuses are a popular means of public transport. The reasons for such a policy lie in several aspects: a large number of existing systems in relation to the national scale, a high level of development of the electrotechnical industry, the activity of manufacturers of trolleybus rolling stock with a key position on the European market (Škoda), the use of innovative technologies in the field of electric drives and the overhead wiring infrastructure. Prague was one of the few cities where trolleybus transport functioned but was closed. In 1936–1972, the network of trolleybus connections was expanded only to be shut down as a result of the global trend to abandon electric vehicles in favour of diesel ones. It was a political decision resulting from the low prices of diesel fuel. Back then, trolleybuses were losing to buses. However, the situation on the fuel market changed quickly, and many cities returned to electric public transport. The Czech capital also planned to launch again trolleybus transport, but the unfavourable circumstances resulting from the political and economic transformation at the turn of the 1980s and the 1990s made it difficult. A new project to launch a trolleybus network in Prague appeared in the 2010s. Auxiliary power sources installed in new trolleybuses proved conducive. In October 2017, a test trolleybus route was launched; it was aimed to allow examining the legitimacy of further trolleybus expansion in Prague [25]. The topographic conditions of the city favour solutions based on electric vehicles, but due to significant congestion and a large difference in elevation, it is necessary to supply them from overhead wiring. Otherwise, it would be necessary to install large capacity on-board batteries in the vehicles. Trolleybus tests were successful, which led to the adoption of a phased plan for putting trolleybuses into operation [56,57]. Then, steps were also taken to electrify the suburban routes [58]. Prague’s trolleybus system will use on-board batteries. Each of the planned routes will only be partially equipped with overhead wiring. On the remaining parts, mainly steep climbs, trolleybuses will be powered by batteries.

5.2.4. Rome (Italy)

Trolleybus transport in Italy was very popular, although the periods of development were intertwined with regression. As in other European countries, also in Italy trolleybus transport was shut down from the late 1960s to the 1980s. In the past, there were even
several dozen trolleybus systems, and nowadays, since the beginning of the 21st century, 16 networks have been in operation. In 2002, the operation of the trolleybus transport in the city of Cremona was discontinued, and the infrastructure was physically removed in 2015. It was the only case of the closure of the trolleybus network in Italy in the 21st century. Simultaneously, in 2009, trolleybus connections in the city of Chieti, suspended in 1992, were reactivated. Construction of four new systems was also initiated—in Lecce (launched in 2012), Pescara (under construction since 2012), Rimini (intercity BRT system, launched in 2020) and Rome (launched in 2005). The trolleybus system in the Italian capital deserves special attention, as trolleybus transport existed in this city in the years 1937–1972. In 2005, a new trolleybus route was opened. On route 90, trolleybuses equipped with on-board batteries replaced diesel buses in order to strengthen public transport with environmentally friendly measures. Due to the historic centre of the city, only part of the route is equipped with overhead wiring [1]. The rest of the route, e.g., around Termini station, is powered by on-board batteries (Figure 3).

Another route was also opened in 2019, partly built as a BRT corridor. 45 trolleybuses equipped with diesel units were purchased to serve it [59]. Both trolleybus routes in Rome prove that it is possible to serve historic cities with valuable historical buildings where it is not possible to build overhead wiring or it would disturb the aesthetics of the space.

5.2.5. Solingen (Germany)

The trolleybus network in Solingen was launched in 1952. The decision of the city authorities was to replace trams whose infrastructure was significantly damaged during World War II and only provisionally rebuilt after the warfare [60]. In the following years, trolleybus transport developed spatially, until the mid-1990s, when the transport company was partially privatised, and the new investor suggested replacing the worn-out trolleybuses with modern low-floor buses. The municipal authorities did not agree to this solution. Social resistance was also noticeable. After the decision to maintain trolleybus

Figure 3. Solaris Trollino 18 Ganz trolleybus awaiting departure from the terminus at Termini railway station, powered by on-board batteries (photo by Marcin Polom).
transport, it was modernised, including, among others, the replacement of the vehicle fleet. New articulated trolleybuses were equipped with diesel units, which enabled the extension of selected routes.

A new chapter of trolleybuses in Solingen started in 2018 with tests of the so-called battery trolleybuses (in German Batterie-Oberleitungs-Busse—BOB). They were supplied by a Polish manufacturer Solaris in cooperation with a German electrotechnical company—Kiepe Electric. The purpose of vehicles with on-board batteries charged while in motion is to enable further expansion of trolleybus connections, including the electrification of lines previously served by diesel buses [61,62]. So far, four articulated trolleybuses have been delivered and another 16 articulated and 16 standard trolleybuses have been ordered [63].

5.3. Spatial Diffusion of the Technology of Auxiliary Power Sources in Trolleybus Transport

Among trolleybus transport operators, the phenomenon of diffusion of innovations related to the use of on-board batteries is noticeable. Due to the relatively small number of trolleybus systems, most of them maintain close relations, especially within one country. There are also platforms for cooperation between trolleybus carriers within various organisations and projects. The International Association of Public Transport (UITP), which has strongly supported the development of trolleybus transport in recent years, is an example of such cooperation. Another form of cooperation involves international projects, such as Eliptic, Trolley or Trolley 2.0, promoting the development of trolleybus transport and the use of innovative solutions in terms of vehicles, power systems, catenaries and promotion [64–69].

5.3.1. Germany

In Germany, there are currently three trolleybus systems in the cities of Eberswalde, Esslingen am Neckar and Solingen. The first of them was a partner in European projects, incl. in the Trolley project, within the framework of which it promoted the use of supercapacitors in trolleybuses [65]. However, the innovation that attracted the attention of other networks was not the supercapacitor, but trolleybuses produced by Solaris. So far, such companies as Berkhof, HESS, MAN and Van Hool have traditionally supplied trolleybuses to the German market. The emergence of a new manufacturer with a flexible offer regarding its products has attracted the interest of other carriers. As a result, the entire rolling stock was replaced and expanded in Esslingen in 2015–2019 [70]. In consequence, it was possible to expand the connections, because on-board batteries were installed in trolleybuses. A similar situation occurred in Solingen, where it was first decided to purchase 4 BOB type articulated trolleybuses in 2017–2018, and after successful tests, the order was increased by an option of 16 vehicles [71]. In 2020, a decision was also taken to purchase 16 standard-length trolleybuses [72]. All vehicles that will ultimately be delivered in the coming years will receive on-board batteries, contributing to the electrification of many bus routes.

5.3.2. Poland

The situation in Poland was similar to the diffusion of the battery technology in German trolleybus systems. The appearance of on-board batteries in trolleybuses in Gdynia has led to their widespread use in the other two systems, namely in Lublin and Tychy. At the end of the 2000s, the Trolleybus Transport Company in Gdynia was looking for solutions that would increase the flexibility of trolleybuses in case of emergency. At that time, there were no plans for their route use. A rare solution in those years was chosen—on-board batteries. Due to the availability of various solutions, it was decided to use the nickel-cadmium technology, which guaranteed long battery life when rarely used (typical of emergencies). In 2009, two Solaris trolleybuses were put into service in Gdynia [11]. After successful tests, all vehicles purchased then in Gdynia already had on-board batteries. Since 2015, due to the technological development of batteries, the lithium-ion technology has been implemented, which enables regular route use [29]. The stage related to the spatial
development of connections has begun thanks to new on-board batteries. In the following years, identical trolleybuses were put into operation in Lublin and Tychy [36]. The situation repeated itself in 2019–2020. Gdynia was the first city to decide to use trolleybuses in the In-Motion-Charging technology [2,13,20]. It is then possible to travel on a longer section without an overhead line. After good experiences in Gdynia, Tychy used the same solution, ordering the same trolleybuses in March 2021, which will allow the electrification of another bus line.

5.4. SWOT Analysis of Trolleybuses with APS

The research presented in the article shows that trolleybuses, thanks to the use of APS, can be a good alternative for the development of non-emission public transport. However, the boundary between a trolleybus and an electric bus is losing ground, which in the future may lead to a departure from classic trolleybuses. Table 3 presents a SWOT analysis of the use of trolleybuses with APS, in particular with on-board batteries, because, as previously shown, such vehicles are currently mainly produced.

Table 3. SWOT analysis of the use of trolleybuses from APS.

| Strengths | Weaknesses |
|-----------|------------|
| 1. Extensive experience in the operation of trolleybus transport, including vehicles with APS | 1. The dynamic development of battery technologies will result in a complete departure from trolleybuses in favor of electric buses |
| 2. The existing traction infrastructure reduces the development costs of trolleybus connections operated by vehicles with APS | 2. Lack of adequate studies of the economic viability of the development of public transport based on trolleybuses and electric buses, in order to demonstrate a better solution |
| 3. Lower capacity of on-board batteries affects operating costs, vehicle weight and the number of passenger seats | 3. Making political decisions on the development of urban public transport, related, for example, to the ease of obtaining funds for the purchase of electric buses |
| 4. Greater flexibility of trolleybuses with APS than electric buses | 4. Fast consumption of on-board batteries affecting the cost of life of the vehicle |

| Opportunities | Threats |
|---------------|---------|
| 1. Further development of battery technologies may contribute to the reduction of their mass, which will have a positive impact on the operating costs of trolleybus transport | 1. Excessive promotion of electric buses may contribute to the departure from trolleybuses, although it is not justified by scientific research |
| 2. Conducting in-depth case studies may affect competition between trolleybuses and electric buses in favor of trolleybuses, whose global emissions are lower due to smaller batteries | 2. Public criticism of the existence of the overhead contact line infrastructure as disturbing the space may lead to its liquidation, which is an important competitive advantage over electric buses |
| 3. Alignment of opportunities in access to funds for the purchase of electric buses and trolleybuses may contribute to the development of the existing trolleybus transport systems | 3. The increasing number of producers of electric buses may reduce the costs of purchasing vehicles, which will have a negative impact on the comparison with the purchase of trolleybuses, where the producers’ market is limited |
| 4. Plans to build new trolleybus systems in the largest European cities (Berlin, Prague and others) may contribute to the interest in them also in smaller cities | |

The conducted SWOT analysis showed that trolleybus transport has mainly the risks resulting from unequal treatment in competition with electric buses. There is a specific “fashion” for electric buses on the European market, which influences the development of the producers’ market and, consequently, may lead to a significant reduction in purchase costs. However, there is a lack of in-depth studies that would allow for an unquestionable determination which type of vehicle in its life cycle is characterized by a better cost and environmental balance.
6. Discussion

This article is the first attempt in the literature to systematise information on the experience related to the use of auxiliary power sources in trolleybuses. Due to the prospect of electrification of public transport and a shift away from fossil fuels, trolleybuses are gaining in popularity. New connection networks are designed along with the expansion of the existing ones [36]. The use of on-board power sources has increased the flexibility of trolleybus transport, enabling the spatial expansion of connections into areas with a lower population density or with difficult conditions to build the overhead wiring infrastructure [13].

The acceleration of the development of battery technologies in recent years has been determined by the necessity to cope with unfavourable climate changes. This is related to the departure of both private and mass transport from vehicles powered by fossil fuels. Building a high-capacity, low-weight on-board battery is a key issue in the design of new vehicles. Trolleybuses combine the operational advantages of the bus and environmental protection due to the lack of emissions of pollution at the place of use; therefore, they are the optimal solution for public transport. Electric buses, which could become the biggest competition for trolleybuses, however, have many more disadvantages. The necessity to install a battery with considerable capacity and unladen weight limits the vehicle capacity. In addition, the necessity to recharge at terminuses, at stops or in the depot creates a need for more vehicles and increases operating costs. Trolleybuses charged in motion do not require additional down time [13,33].

In the past, trolleybus transport was a very popular solution in cities, especially those with a large difference in elevation. One of the greatest disadvantages has always been dependence on overhead wiring and inflexibility in shaping connections. If there was a need to close a part of the road to traffic, it was necessary to send replacement buses, which generated unnecessary costs. Therefore, for several decades, solutions have been sought to increase the flexibility of trolleybuses. Since the 1930s, solutions based on batteries have been tested, but due to their weight at that time, it was impossible to apply them on a larger scale (Figure 4).

![Timeline of the development of alternative power sources in trolleybuses in Europe.](image)

In the 1950s, diesel units were tested which would be used as generators to power the trolleybus drive system. This solution also offered better prospects for trolleybuses, but the weight of the internal diesel engine did not allow its use. Only in the 1970s, when trolleybuses were again gaining in popularity due to the global fuel crisis, solutions for alternative power sources were developed. In the 1990s, in Western Europe, diesel units
were regularly installed in trolleybuses, but apart from the advantage of independence of overhead wiring, trolleybuses also had the disadvantages of diesel buses. They have become vehicles emitting pollution into the atmosphere as well as considerable noise. The breakthrough came at the end of the 2000s, when installation of batteries with a much lower weight, longer life and high capacity began. Initially, it was the nickel-cadmium technology, and in the following years it was based on the lithium element. Trolleybuses equipped with on-board batteries retained the greatest advantage of fully electric vehicles characterised by zero pollution and low noise emissions, while at the same time they gained independence similar to electric buses. Due to the use of lithium batteries, which allow for regular route use and many discharge cycles, it has become possible to develop connections into areas devoid of the overhead wiring system. The small weight and size of the battery (usually four times smaller than in electric buses) do not limit the passenger capacity, and recharging from overhead wiring does not require long stops or replacement with other vehicles [50].

7. Conclusions

The popularity of trolleybus transport in Europe has been related to fuel prices [45,73]. In the event of crises, trolleybuses grew in importance. However, their most important disadvantage was their dependence on overhead contact lines and inflexibility in shaping connections. It was an especially important feature in the case of road works or closure of a part of the route, e.g., due to sports events or street protests. At that time, a rolling stock reserve in the form of diesel buses was kept, which worsened the economic balance of trolleybus transport [3]. Many operators and manufacturers were looking for solutions that would make the operation of trolleybuses easier and reduce their disadvantages related to power supply from overhead wiring. Since the beginning of the 20th century, battery solutions have been tested, and then those related to internal diesel engines, but none of them met the expectations. The technological underdevelopment did not allow for a wider use of such solutions.

Climate changes that have been taking place over the last two decades have forced many countries, as well as the European Union, to introduce restrictive measures aimed at eliminating diesel vehicles [12,15,18,19]. It is assumed that public transport will be transformed into zero emission one. A strong political impulse has contributed to the dynamic development of battery technologies, which allowed for partial independence from overhead wiring. The combination of the advantages of on-board batteries and the overhead contact line allowed trolleybus transport to gain a competitive advantage over other means of public road transport.

Currently, the existing trolleybus networks are being developed, and new ones are being designed (e.g., in Berlin, Iasi, Pescara, Prague) [25,56–58]. Trolleybuses have once again become an important means of public transport in European countries. Out of 71 trolleybus systems analysed in 2021, 65 had vehicles with any on-board auxiliary power source, and 44 of them have trolleybuses equipped with on-board batteries (compared to only 7 in 2011). A departure from diesel units in favour of emission-free batteries has been identified [11,28]. The popularisation of battery solutions may contribute to obtaining a better price and further development consisting in reducing the battery size and increasing its capacity and lifetime. Many of the analysed cities have introduced in-motion charging solutions, namely charging the battery while driving with power supply from the overhead line [13,33]. The main examples include trolleybus systems in Bergen, Gdynia and Solingen [29,54,55,61–63].

An assessment of the optimal use of the existing overhead contact lines and the minimisation of on-board battery capacity remains an important research issue in the future. This is a feature of trolleybuses that significantly improves their assessment in comparison to electric buses which often have overestimated capacity, because they are recharged, for example, only at the depot during night stops [1,34,35,37,40]. Fairness in spatial access to zero-emission means of transport is also important [32]. Thanks to
on-board batteries, trolleybuses can handle a greater number of connections without the need to build overhead wiring infrastructure, also in areas with low demand for public transport services.

Summarizing the research presented in this article, the verified hypotheses resulting from the research questions posed at the beginning. The following responses were obtained:

1. The scale of the use of APS in trolleybus systems in European cities slightly increased over the period of 10 years, but it should be emphasized that their use in linear traffic generally increased. In 2011, APS systems were mainly used as an alternative source of power in the event of failure of the trolleybus traction infrastructure. Nowadays, APS is successfully used for the spatial development of trolleybus connections,

2. In 10 years the APS structure in trolleybuses has completely changed. Currently, emission-free combustion aggregates are being abandoned in favor of emission-free on-board batteries. While in 2011 only 7 cities had experience in operating trolleybuses with batteries, in 2021 there were already 44. Trolleybuses with combustion units remain in operation, but new vehicles are only equipped with on-board batteries, or supercapacitors,

3. The development of battery technologies contributed to their popularization in trolleybuses. Thanks to the use of on-board batteries, the trolley-bus transport has gained a great attribute and can develop spatially without the need to invest in power infrastructure. This is of particular importance for the development of connections in sparsely populated areas.

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