



Transport Geography Papers of PGS

2023, 26(1), 22-39

DOI 10.4467/2543859XPKG.23.002.17399

Otrzymano (Received): 27.12.2022

Otrzymano poprawioną wersję (Received in revised form): 21.02.2023

Zaakceptowano (Accepted): 21.02.2023

Opublikowano (Published): 31.03.2023

EVOLUTION OF SECOND-GENERATION ELECTROMOBILITY IN PUBLIC TRANSPORT IN POLISH CITIES¹

Rozwój elektromobilności II generacji w transporcie publicznym polskich miast

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¹ Badania i artykuł wykonano przy wsparciu finansowym Wydziału Geografii i Geologii w ramach Programu Strategicznego Inicjatywa Doskonałości w Uniwersytecie Jagiellońskim.

Citation: Kołoś A., Fiederń Ł., Taczanowski J., Parol A.R., Gwosdz K., Guzik R., Łodziński J., 2023, Evolution of second-generation electromobility in public transport in Polish cities, *Prace Komisji Geografii Komunikacji PTG*, 26(1), 22–39.

Abstract: Transport activities are a significant factor in environmental pollution, especially in cities. Therefore, measures aimed at electrification of public transport are particularly important. The aim of the paper is to present the origins, status and development dynamics of electromobility in Polish cities, especially the second generation of electromobility, i.e. vehicles that do not require continuous connection to the energy source. In practice the second-generation electric vehicles can be identified with battery-powered vehicles, hydrogen and hybrid vehicles. The study was prepared on the basis of an analysis of literature, industry documents or development strategies. In addition, a database of information on zero- and low-emission vehicles in public transport (i.e. electric and hybrid buses) was compiled to analyse the phenomenon. The study shows that the implementation of electromobility in Poland has already emerged from the initial phase. The possibilities for developing battery technology vary in cities of different sizes. In 2021 in Poland, the share of low-emission buses in the public transport fleet was several times higher than that of electric vehicles among passenger vehicles. It is most likely that the Polish road to electromobility leads primarily through public transport. The following factors influencing the development of electromobility were identified: these were primarily EU and Polish legislation and regulations, the presence of manufacturers of rolling stock and electrotechnical equipment, and – at the local scale – organisational, economic and social issues.

Keywords: electromobility, zero and low-emission buses, urban public transport, cities, Poland

Introduction

Probably the greatest challenge of the 21st century is to mitigate the damage to the environment caused by human activity. The impact of humanity on the Earths' environment and ecosystems is widespread including global warming, loss of biodiversity and soil degradation. A significant human-induced process is environmental pollution, of which transport activities are an important factor, in particular in urban areas. In transport the type of propulsion system is the key factor – internal combustion engines are responsible to a great extent for air-pollution.

Hence, the development of electromobility policies is particularly important. Actually, it would be more correct to use the word “electrotransport”, and even more correct to talk about low-emission transport, but the term “electromobility” is now commonly used in the literature (Altenburg et al., 2016; May, 2018; Zhao, 2018; Pietrzak, Pietrzak, 2019; Bartłomiejczyk, Kołacz, 2020; Połom, Wiśniewski, 2021; Yigitcanlar, 2022). We are thinking here of all types of powertrain that ensure that there are no emissions associated with providing the energy necessary to move the vehicle,

at least at the point of movement. It should be noted that transport is also responsible for other emissions, non-exhaust sources such as abrasion of brake or clutch wear, graphite from current collectors or, last but not least, secondary dust emissions from roads, and pollution from power generation.

It should be emphasised that one of the first applications of electromobility on the contemporary Polish territory was in Wrocław, where the first electrically operated tram was inaugurated in 1893 (Kołoś, 2006). Electromobility based on vehicles powered from the overhead line or the third rail (where a **continuous** connection to the electrical supply system is required for operation) was spread mainly before World War I and in the inter-war period and, although it has seen a renaissance since the end of the 20th century, it should rightly be referred to as **the first-generation electromobility**. In contrast, at the beginning of the 21st century, there has been a massive development of transport based on electrically powered vehicles, which in order to move require only a **temporary** access to the energy source. These include battery-powered vehicles (both plug-in and catenary systems), hydrogen vehicles and hybrid powertrain vehicles which in

the present paper are considered as an intermediate form until the new technologies have stabilised. We refer to these means of transport as **the second-generation electromobility** (Guzik et al., 2021). Of course, numerous intermediate solutions are also possible – such as hybrid trains or trolleybuses with additional diesel propulsion.

The aim of the article is the in-depth insight into the origins, the present state and development dynamics of second-generation electromobility in Polish towns & cities, particularly in a spatial context. It should be noted that the omission of first-generation vehicles (especially trolleybuses and, of course, rail traction) from the analysis is not due to its lesser usefulness, but it was dictated solely by methodological considerations. Furthermore, diverse opportunities and possible developments in urban centres of different sizes are also indicated.

The authors used varied methods of data collection ranging from the systematic query of secondary sources (i.e. scholarly and press articles, transport industry documents and development strategies) to in-depth interviews. Information on public transport vehicles (in towns & cities with more than 10,000 inhabitants) was collected from diverse, dispersed sources, that include websites of companies and transport organisers as well as from articles in the trade and technical press. Interviews were conducted with decision-makers responsible for public transport in Poland and finally statistical and cartographic methods were used. The first task was to compile a database of means of public transport that include:

- electric buses of various types,
- hybrid buses,
- in addition, the database also includes (not used in this article):
- vehicles powered by gas or biofuels. These types of vehicles appeared in the database due to their substitution with "zero-emission" vehicles within the framework of EU funds,
- electric rail vehicles, SKM (urban rail) and metro in Warsaw were included, as well as trams,
- trolleybuses.

The database was compiled over several time periods. Information (from the Polish Central Statistical Office) on the size of towns & cities was also included. Already at the stage of its construction, there was a number of challenges related to both the availability and quality of the data and its comparability. For example, each vehicle was counted as one, even though in real terms they may differ in capacity. An exception was made for the Warsaw metro and SKM Warsaw, where the concept of 'vehicle' is not unambiguous and at the same time the differences would be too great, so carriages were counted rather than

trains. It was the intention of the authors to identify the phenomenon for each city separately, but this was not always possible, especially in the case of complex relationships in large urban transport authorities covering many cities, such as in Warsaw – where the entire ZTM (Public Transport Authority) rolling stock was assigned to the capital of Poland. The GZM (The Górnośląska-Zagłębiowska Metropolis or Katowice agglomeration) area, on the other hand, was treated as a single city, which can partly be justified by the existence of this metropolis in the Polish legal system.

The remaining part of the article is structured as follows: in the first section, the current state of research is analysed. Then the development of second-generation electromobility on the example of Polish towns & cities in four time period (2016, 2017, 2020, 2022) is analysed. In the next part, an attempt is undertaken to identify the dynamics of the phenomenon under study. Important part of this section is the discussion on the varied strategies adopted by towns & cities of different sizes and reasons behind. The final sections summarises the main findings.

1. Literature review

The implementation of the second generation electromobility into urban public transport is a complex issue which is connected with numerous challenges of different character. They can be divided into four groups: technological-operational, technological-environmental, energy supply and economic.

One of the crucial issues among the technological-operational challenges is the range of electric buses – also identified as autonomy of the vehicle – which is the result of their limited on-board energy storage capacity (Varga et al., 2019; Bi et al., 2018; Kambly, Bradley, 2015). Range anxiety is perceived as one of the major user concerns for electric vehicle utilisation (Adhikari et al., 2020; Nan et al., 2022). This issue is strictly connected with two factors: batteries and charging facilities. The battery technology is being continuously developed but still in some cases batteries are reported to have shorter range than announced (Li, 2016). It should also be highlighted that electric bus range is influenced by different factors of operational character such as use of air conditioning or driving behaviour (Li, 2016). Electric buses have to be charged at charging stations. It can be done in three ways: by plug-in, using a pantograph or utilising induction (Dobrzycki et al., 2017). The required charging time is one of the main challenges here (Rogge et al., 2018). It is important to emphasise that charging facilities and their location are crucial for a proper functioning of an electric bus network (Schmidt et al., 2021; Jóźwiak et al., 2018). One of several ways to solve these problems is to charge

vehicle batteries from overhead wires. Such in motion charging is utilised by battery-assisted trolleybuses (BATs) which can extend their routes on sections without a catenary (Stavropoulou, Iliopoulou, 2022; Grygar et al., 2019; Połom, 2018). However, as classical trolleybus technology is indispensable here, we treat this solution as belonging to the first-generation electromobility and we do not discuss it here.

Technological-environmental issues apply to the batteries lifecycle and to their recycling. The batteries lifecycle depends mainly on the temperature of the environment and on discharging (Gandoman et al., 2021). The ongoing development of the batteries is delivering new solutions. At present electric vehicles utilise Li-ion batteries which are characterised by high energy and power density and whose degree of development is still higher in comparison to other battery technologies (Benveniste et al., 2022). However, for some years a new technology has been very promising – Lithium-sulphur batteries stand out not only for their higher theoretical capacity and energy density but also for a presumably lower environmental impact (Benveniste et al., 2018; Benveniste et al., 2022). Moreover, sulphur is cheaper and easier to produce if compared with cobalt and nickel used in Li-ion batteries (Ye et al., 2023; Nakamura et al., 2023). Although prototype lithium-sulphur batteries have already been produced but some problems still remain unsolved, one of the crucial being their low cyclability (Benveniste et al., 2022; Sun et al., 2022). Indeed, even the most long-lasting batteries will have to be replaced at one point. This creates an important challenge for the environment, because batteries – which are characterised by a complex chemical composition – “constitute hazardous waste that is difficult to manage and must be recycled in modern technological lines” (Sobianowska-Turek et al., 2021). This problem was recently addressed by the European Council and Parliament which proposed an agreement to strengthen sustainability rules for batteries and waste batteries regulating the entire life cycle of a battery – from production to reuse and recycling (Council and Parliament strike..., 2022). What is more, the growing scale of electric vehicle production results in the increase in the demand for materials needed for battery production such as lithium, cobalt, nickel, graphite and manganese (Bernagozzi et al., 2021; Chan et al., 2021). Consequently, a question about sustainability of battery technology may arise (Beaudet et al., 2020). As Abdollahifar et al. (2023) notice, the high number of batteries “that are produced or discarded every year is growing exponentially, which may pose risks to supply lines of limited resources”. Moreover, apart from materials mentioned above in the near future also some new materials like silicon, germanium

or graphene may be needed for battery production (Kwiatkowski, Kras, 2021).

Similar questions may be asked as far as energy supply challenges are concerned. Growing electric vehicle use has to lead to the increase in energy production and can result in difficulties for the energy supply system. In fact, a large-scale diffusion of electric vehicles will cause an enormous power demand and consequently will have a deep impact on the existing electric grid infrastructure with overloads, voltage instabilities, and increased power losses (Lazzeroni et al., 2021; Hussain et al., 2021). On the other hand this increase in energy demand may be a chance to develop renewable energy sources which can be used for charging electric vehicles (Badea et al., 2019; Fasięcka, Marek, 2018). A great change may be connected with hydrogen which seems to be a chance for solving the problem of energy storage and which consequently can enable to operate vehicles with much longer range avoiding problems with battery degradation (Uhl, 2020).

Finally economic issues constitute a large set of challenges for electric vehicle implementation. The question about vehicle purchase and operational costs of electric buses if compared to hybrid and diesel vehicles is one of the most crucial (Pelletier et al., 2019; Drábik, Krnáčová, 2018). A key issue among the purchase costs are batteries. In fact, Nakamura et al. (2023) emphasise that high prices of cobalt and nickel used in Li-ion batteries are a threat to electric transport implementation. Besides the costs of the vehicle itself the lifecycle costs of electric buses are heavily impacted by the costs of charging devices (Lajunen, 2018). A. Jagiełło (2021) notices that the operating costs of conventional and electric buses are most often examined in the light of total cost of ownership (TCO) or life cycle cost (LCC) which makes it possible to compare the operating costs of different types of buses in terms of vehicle costs, maintenance, operation and decommissioning, but it does not take into account the non-cost differences in operation between electric and conventional buses such as passenger capacity or level of technical readiness. Similarly, A. Harris et al. (2020) criticise a conventional vehicle-by-vehicle comparison between conventional and electric buses pointing out that it “neglects the influence that passenger capacity and range limitations have on fleet and infrastructure sizing, underestimating capital costs and greenhouse gas emissions of these phases”. Hence, a broader view of electric bus implementation in the context of the entire given transport system is needed. Going even further, charging costs cannot be neglected either. They require – especially in the case of large electric bus fleet – that an appropriate charging strategy is developed in order to save charging

costs and improve the operation efficiency (Liu et al., 2021). However, costs can – and should – be seen in a broader context. S. Borén (2020) points out lower societal costs of electric buses if compared to diesel or biogas vehicles. This is the result of much lower noise and emissions of electric buses. Moreover, an interesting observation in long-distance perspective was made by U. Motowidlak (2020) who suggested to utilise electromobility can be a tool for implementing circular economy.

the first purchases of new buses started a few years later: in 2012 the national capital Warsaw purchased the first new hybrid buses (Solaris) and in 2015 the first electric vehicles were acquired by medium-sized towns of Jaworzno and Ostrołęka. Slightly earlier, in 2014, the first line operated exclusively with battery-powered rolling stock was launched by the second-largest Polish city of Kraków, but by using buses that were being tested (Solaris, AMZ and Rampini Carlo). At the beginning of 2016, 13 Polish towns & cities²

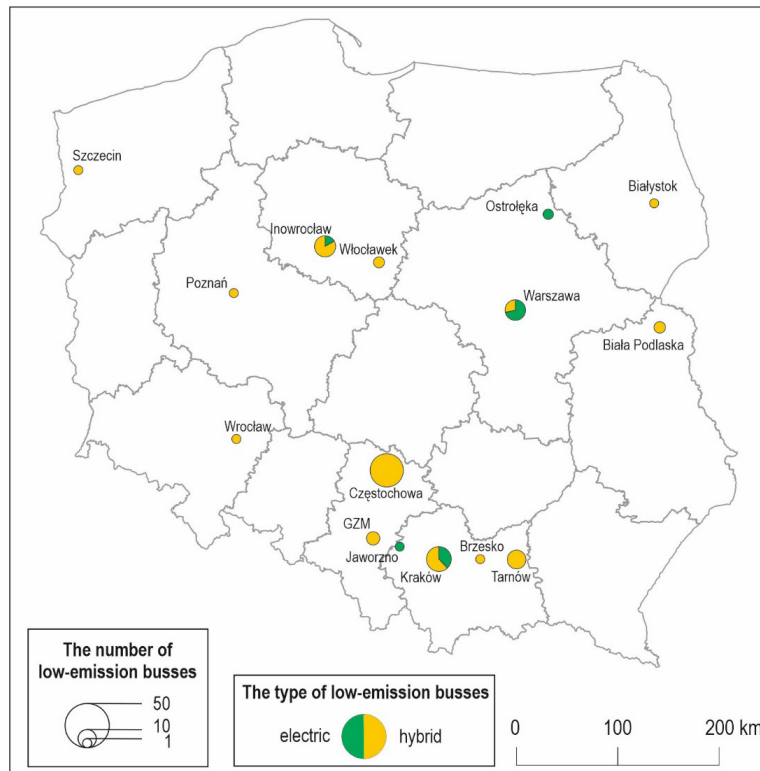


Fig. 1. The distribution of electric and hybrid buses in Polish towns & cities in 2016.

Source: Domański et al. (2016); changed.

The existing electromobility literature is mostly concentrated on selected technological, environmental or economic issues whereas spatial aspect seems to be less common. In particular, analyses of spatial expansion of electric bus urban transport systems covering the whole country and the entire development process are rather rare. This article seeks to fill that gap.

2. The rise of the second generation electromobility in Poland

The introduction of low emission vehicles (LEV) in Polish cities and towns was a rather slow process (Domański et al., 2016). The first tests of low-emission vehicles took place at the end of the first decade of the 21st century in the Poznań metropolitan area in western Poland,

were operating 96 hybrid vehicles (some of them had purchased used buses), and 23 electric vehicles in 5 urban centres (Fig. 1).

At the end of 2017, in 18 towns & cities 138 hybrid buses were used and another 57 vehicles were commissioned. As far as fully electric buses are concerned, 71 vehicles were in operation in 7 cities whereas another 7 cities were waiting for the delivery of 93 vehicles

² In fact, in 2016–2017 there were 14 and 19 centres with hybrid buses. This was due to the separate counting of PKM Świerklaniec, which was the operator of MZKP (Intercommunal Passenger Transport Union) Tarnowskie Góry and PKM Sosnowiec (then operator of KZK GOP). Of course, these buses also served other cities, so after the formation of the GZM we treated them as a single centre (cf. Domański et al., 2016, Taczanowski et al., 2018).

(of which Zielona Góra was planning a one-off purchase of as many as 47 vehicles³) (Fig. 2).

At the initial stage, two territorial concentrations of particular electromobility development could be identified: one in central Poland (Warsaw but also some towns & cities around Poznań, interestingly – without Poznań itself) and the other in the south (with Kraków, Częstochowa and the Katowice urban region).

were also linked to their overall strategies – such as in Inowrocław, where rolling stock replacement was part of ensuring a clean environment in this spa town. A similar strategy was also adopted by small towns, where this often meant implementing public transport altogether. One can point to the case of Września (2018) or Środa Śląska (2018) – and a little later in 2020, by way of imitation, Miechów and Ząbkowice Śląskie.

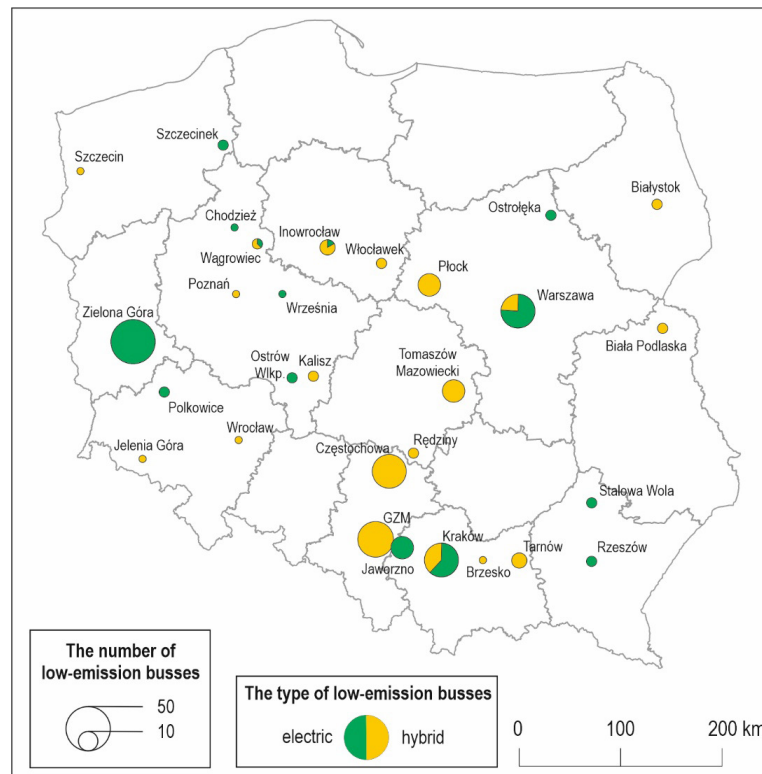


Fig. 2. The distribution of in-service and contracted electric and hybrid buses in Polish towns & cities in 2017.

Source: Taczanowski et al. (2018); changed.

At the initial stage of the development of the second-generation electromobility in Poland, three strategies could be distinguished: “ambitious”, “cautious” and “let’s wait and see” (Domański et al., 2016; Taczanowski et al., 2018).

The most aggressive strategies aiming at a majority (and intended total) replacement of rolling stock were adopted by medium-sized cities (Inowrocław, Jaworzno, Zielona Góra⁴, Częstochowa⁵). These strategies

Warsaw and Kraków – Poland’s two largest cities – have adopted a cautious strategy. These cities introduced zero-emission buses into their fleets quickly and with enthusiasm, however, it was only a few per cent replacement of the fleet. In 2015 four hybrid buses and ten electric buses were in operation in Warsaw (a mere 0.8% of the entire fleet), while in Kraków it was 18 vehicles (2.8%). In retrospect – the troubles of battery traction caused by congestion in large metropolises – this strategy should be considered sensible.

Most towns and cities (including both large, medium and small ones) decided to wait this first period of time to first assess the effects of the electrification of bus transport. This was the case in Poznań, Wrocław, Łódź, the coastal agglomeration of Tricity (Gdańsk, Sopot and Gdynia) and Lublin, among others. Representatives of these cities pointed to the underdevelopment of the technology, not fully known operating costs

³ This particular contract was not fulfilled in its entirety and the supplier – Ursus Bus – eventually went bankrupt.

⁴ At the time, Zielona Góra had the most ambitious plan to replace its entire rolling stock. However, it was significantly slowed down by problems with the supplier of electrobuses.

⁵ Częstochowa purchased 40 hybrid buses with CNG gas engines. Unfortunately, the Solbus design turned out to be underdeveloped (fire hazard), with the result that to this day (2022) some of these vehicles are not in service and the manufacturer has ceased operations.

or, finally, having already developed first-generation systems (Połom, 2018; Bartłomiejczyk, Połom, 2021; Kołoś, Taczanowski, 2016). They also pointed to the greater importance of the mere growth of public transport than its technological upgrading.

In the first period of the introduction of low- and zero-emission buses, four types of factors that influenced the possibility and speed of innovation adoption could be identified (Domański et al., 2016).

The most important determinant was obviously the technological one. It was crucial to develop a bus with a minimum range of 200-300 km. This condition was achieved, but – it has to be highlighted – only under optimal operating conditions. In winter and during congestion the performance decreased significantly (Li, 2016; He et al., 2018). What is more, performance at the limit of the minimum resulted in a strong dependence of the ability to adopt the innovation to local conditions (relief, road layout, etc.).

The second determinant and the one of national importance (not differentiating between cities) was the formal and legal context, related to EU and Polish regulations. In practice, one should point first of all to the regulations related to the acquisition of EU funds (Połom, 2015) and, somewhat later, also to the Polish law on electromobility (Ustawa z dnia 11 stycznia 2018 r. o elektromobilności i paliwach alternatywnych; Dz.U. 2022, 1083), which obliged cities to at least justify not introducing electric rolling stock⁶. According to this act (Article 68, point 4), local government units with a population of up to at least 50,000 should provide or contract the provision of public transport services to entities that collectively ensure a share of zero-emission (electric) buses or biomethane-powered buses in the fleet of vehicles in use on the territory of that local government which sums up to at least: 5% as of 1 January 2021, 10% as of 1 January 2023, 20% as of 1 January 2025 and 30% as of 1 January 2028.

Another group of factors are local economic and organisational conditions, both institutional but also social. Studies carried out at the time (Domański et al., 2016; Taczanowski et al., 2018) demonstrated that local factors perhaps had the strongest influence on the differences in the rate of introduction of the second generation electromobility. Firstly, this innovation was realistically implemented by local governments which were the organisers of public transport. It was observed that this happened most easily in cities characterised by a public transport system which functioned according to the model of competition “for the market” where there was a municipal authority

owned public transport company (operator) enjoying a long-term contract. In such conditions the company felt the need to innovate (because there was competition) but at the same time was not afraid of new and risky solutions as it had a sufficiently strong position on the market (e.g. Kraków, Warsaw).

In addition, the general approach of the towns & cities to the implementation of sustainable development, particularly in terms of environmental protection, was important. Cities strongly emphasising these challenges in their strategies were at the same time the ones most interested in implementing electromobility (Inowrocław, Kraków). Interestingly, the personal attitude of decision-makers managing the city or its public transport (Jaworzno, Inowrocław) was also a differentiating factor (Guzik et al., 2021). This was clearly evident especially if unambiguously positive economic or organisational indicators were missing.

Finally, it is interesting to note that in the period 2015-2017, neither the existence of a hierarchical diffusion nor the importance of geographical proximity to the plants producing these types of vehicles (notably Volvo in Wrocław, Solaris in Bolechowo (Poznań metropolitan area), and at that time also Ursus in Lublin or AMZ in Kutno north of Łódź) was found at the local level. On the other hand, the presence of manufacturers was a factor of national importance (Guzik et al., 2021).

3. The developments of the second-generation electromobility in 2020-2022

At the end of 2020, there were 923 electric or hybrid buses operating in 65 Polish urban centres⁷: the highest number (230) in Warsaw, 62 in Kraków and 54 in the GZM metropolis (Katowice agglomeration). Nearly half of these vehicles (426) were electric, operating in 34 towns & cities (most in Warsaw – 160, Jaworzno – 44 and Zielona Góra – 43). Hybrid buses (497) were in use in 40 towns & cities, with Warsaw (70), GZM metropolis (41) and Kraków (34) being the leaders. By the end of 2020 low-emission vehicles appeared in towns & cities in every voivodship except Pomerania (Fig. 3). However, the number of towns & cities using these vehicles in each region of Poland was similar to the distribution in 2017, with the largest number in southern and central Poland and few in towns & cities in the north of the country.

In the largest cities, electric vehicles tended to predominate among low-emission vehicles (e.g. Wrocław, Poznań, Warsaw, Lublin). A slight predominance of

⁶ However, it is worth noting that, in its first period of operation, the law did not recognise trolleybuses, trams and electric trains as zero-emission vehicles.

⁷ The GZM (The Górnośląska-Zagłębiowska Metropolis, i.e. Katowice agglomeration), which comprises 41 municipalities, is treated as a single city.

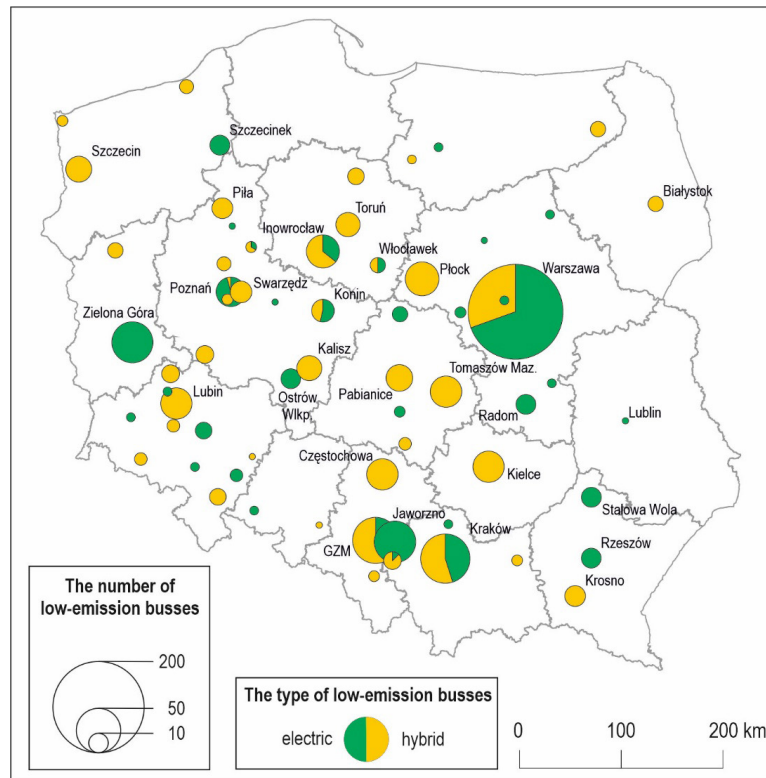


Fig. 3. The distribution of electric and hybrid buses in use in Polish towns & cities in December 2020.

Source: Own study.

hybrid vehicles can be observed in Kraków and GZM, no electric buses were used in Szczecin and Białystok and there were no low-emission vehicles at all in Łódź and Gdańsk. Medium-sized cities invested in hybrid vehicles, although in a few of them there were also electric vehicles (in Jaworzno and Zielona Góra they constituted the majority of the fleet). The most interesting situation concerns some smallest towns, where often while introducing low-emission vehicles it was immediately decided to purchase electric buses (e.g. Bolesławiec, Ostróda).

At the end of 2022, low-emission buses were used in 86 towns and cities in the total number of 1389, of which 768 (55%) were electric and 621 (45%) hybrid. In total, the highest number of them were still running in Warsaw (232), GZM metropolis (127) and Kraków (113). There was almost a doubling of the number of electric buses. Most were running in Warsaw (162), Kraków (79) and Poznań (58). The number of hybrid buses in use also increased in less than two years. Most were used in the GZM metropolis (78), Warsaw (70) and Częstochowa (39).

At the end of 2022, low-emission buses were being used in many towns and cities across Poland – most often in the area south of the Szczecin–Warsaw–Lublin line (Fig. 4). The lowest use of this type of vehicle can be observed in the cities of Podlaskie Voivodeship

(only in Białystok and Łomża) and Lubelskie Voivodeship (only in Lublin).

Undoubtedly, such an impressive increase in the number of low-emission vehicles, and in particular electric vehicles, was influenced by the Act on electromobility and alternative fuels (Ustawa z dnia 11 stycznia 2018 r. o elektromobilności...). Considering only electric vehicles, by the end of 2022, the requirements of this law in force from 2023 are met by 38 cities (regardless of their size), the requirements required from 2025 – 19 cities, and from 2028 – 15 cities.

The largest cities that do not meet the above requirements at the threshold of 2023 are Łódź, Wrocław, Gdańsk, Szczecin and Bydgoszcz. In small towns of Koźnice, Lidzbark Warmiński and Miechów all vehicles in the public transport system are electric. However, it should be noted that in all these towns only two vehicles are in operation. Among cities with the share of the second-generation electric public transport vehicles greater than 50%, the leaders are Jaworzno (74%) and Zielona Góra (51%), in cities with more than 500 vehicles – Poznań (17%), and in those with more than 1000 vehicles – Kraków (11%)⁸.

⁸ However, it should be added to the whole paragraph that, especially the larger cities (e.g. Wrocław, Łódź, Gdańsk, Lublin) have extensive electric transport, but the 1st generation one.

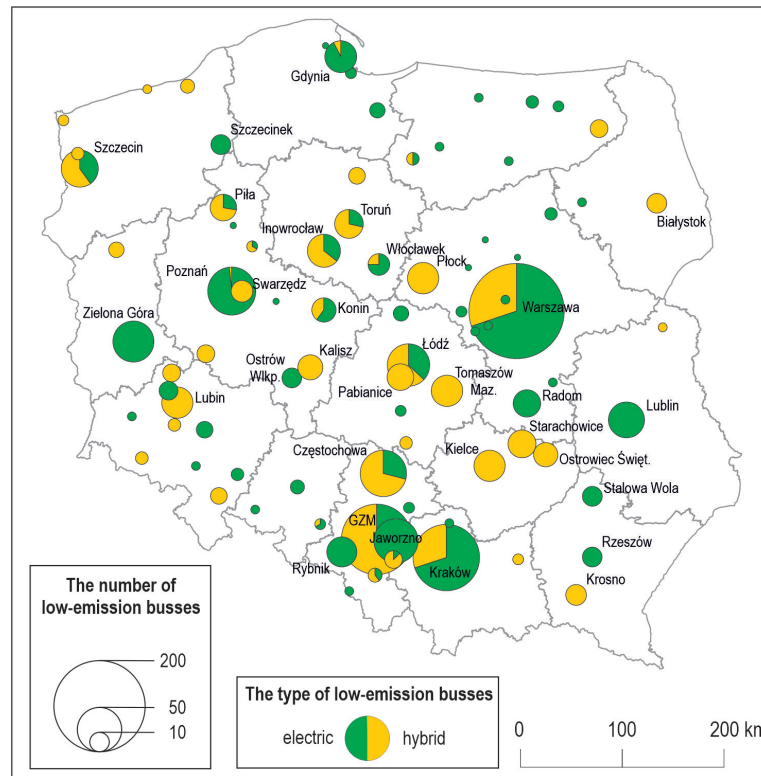


Fig. 4. The distribution of electric and hybrid buses in use in Polish towns & cities in December 2022.

Source: Own study.

An important factor was the presence of rolling stock manufacturers in Poland – especially companies that visionarily and consistently decided to start production of low-emission and hybrid buses, especially Volvo based in Wrocław and Solaris headquartered in Bolechowo (Poznań metropolitan area) should be mentioned here⁹ (Guzik et al., 2021).

An important factor influencing the willingness to increase the share of electric buses in the fleet of transport operators was also the price of electricity in relation to the purchase price of diesel fuel until the beginning of 2022. According to K. Grzelec and D. Okrój (2016), the cost of energy consumption in 2016 in electric buses compared to diesel-powered buses was more than seven times lower. In the analysis of

the costs and benefits of using zero-emission buses in the provision of public transport services in the capital city of Warsaw from September 2021, the authors indicate that the cost of energy consumption in relation to diesel is three times lower and in the following years this difference will decrease to the disadvantage of electricity (Mroskowiak et al., 2021). The energy market crisis that erupted in 2022 resulted in an almost threefold increase in electricity prices in relation to the one taken into account in the aforementioned analysis (including prices regulated by the Act on special solutions to protect electricity consumers; Ustawa z dnia 7 października 2022 r. o szczególnych ...). In view of the above, the energy price argument does not currently support the purchase of electric buses.

The general affluence of the city and its inhabitants, who are highly educated, have a high level of professional activity and frequently participate in cultural and artistic events, is also a factor encouraging the implementation of electromobility (Guzik et al., 2021).

After several years of operation of electric vehicles, it has become apparent that what can now be called "classic" battery vehicles do not function in the same way everywhere. Their relatively short ranges result in the need for longer charging breaks during the day and, in special cases (such as high congestion), emergency exits from lines. The vehicles themselves

⁹ According to Marcin Żabicki (2022), development director at the Chamber of Commerce of Urban Transport: „The development of electromobility in Poland would not be so intense if it had not been for the activity of one more key player: the rolling stock manufacturer Solaris Bus & Coach. The company's founder, Krzysztof Olszewski, realised quite quickly that electric buses would be the future of public transport. With bold business decisions, Solaris gained an advantage over other key bus suppliers of at least 5 years in the implementation of electric bus production. It is no coincidence that the experience of this particular company has radiated to many Polish public transport operators, as Solaris buses are very popular in Poland and have been in widespread use for years.”

have also fewer seats for passengers (their place being “taken” by batteries). Cases of reduction of the number of lines or courses due to lack of space for charging stations on loops have also been reported. Of course, in small towns and even in medium-sized cities, these problems do not occur or are secondary or, as one manager responsible for the implementation of electric transport in a medium-sized city expressed it “... it’s just a matter of good organisation...”. In large centres, however, this means at least the need for more (by about 20-30%) buses to serve the lines and consequently higher operating costs (in Warsaw in 2021 by 29%; Urbanowicz, 2022).

When thinking about the future of electric buses, it is worth mentioning a particular type of electric bus, namely hydrogen electric buses. They do not require the presence of batteries in the vehicle, as electricity is produced in them on an ongoing basis. This is a new technology and in Poland only the municipal transport company in a medium-sized city of Konin has leased one such bus. However, hydrogen electric buses have been tested in many cities, such as Warsaw, Lublin,

4. Discussion: The dynamics of electromobility development in Polish towns & cities and reasons behind

In the period under study, a clear trend in the development of the second-generation electromobility in Polish cities can be observed in the context of implementing buses with alternative powertrain into urban transport systems. The structure of low-emission vehicles has changed – while in the first years purchases of hybrid vehicles dominated, currently their total number is smaller than that of electric buses (Fig. 5). Bearing in mind the development process of automotive technology, this is an understandable phenomenon – hybrid vehicles are often regarded as a transition between an ICE powered bus and an electric bus (Mahmoud et al., 2016). Other pro-environmental propulsion systems (gas, ethanol, hydrogen) were marginal in the studied period in relation to electric and hybrid vehicles, although it cannot be excluded that some of them will become more popular in the future.

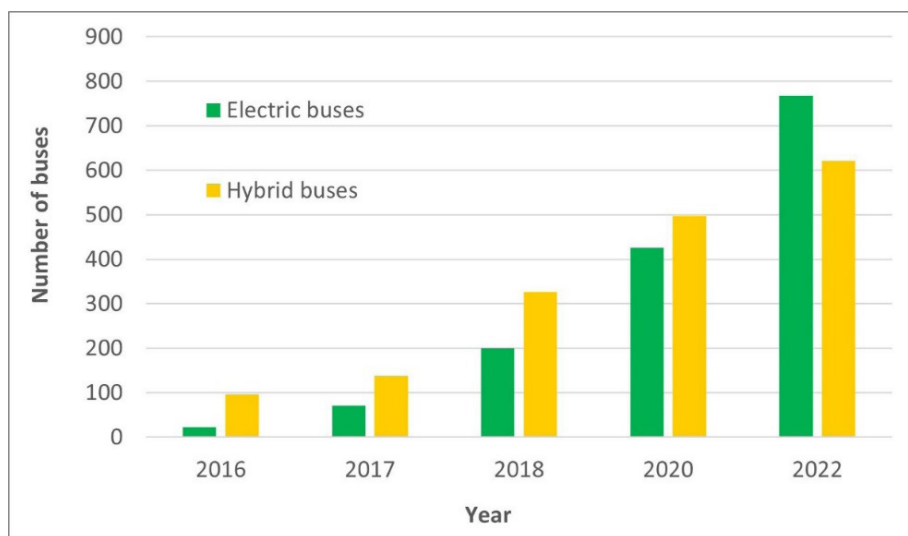


Fig. 5. The number of electric and hybrid buses between 2016 and 2022 in Polish towns & cities.

Source: Own elaboration; data for 2018 after (ZDG TOR, 2018).

Konin and Kraków. In the latter, a mobile hydrogen refuelling station has been in operation since June 2022 and the bus runs on a regular route. In 2022, several cities launched tenders for the purchase of hydrogen electric buses. These were medium-sized cities of Rybnik (20 units of 12 metre buses) and Konin (1 unit, 12 m). In 2022 tenders for the purchase of hydrogen electric buses with a delivery date in 2023 were also awarded in Lublin (1 unit, 12 m) and Poznań (15 units, 12 m)

Although the total number of electric and hybrid buses in Poland’s urban transport systems increased substantially between 2015 and 2022 and reached a share of more than 10% (Fig. 6), the spatial distribution of leaders among centres with this type of rolling stock is similar between the beginning and end of the period under study. This refers to several medium-sized cities that have adopted an „ambitious” strategy from the beginning (e.g. Zielona Góra, Jaworzno or Inowrocław), as well as the largest metropolises

(Warsaw, Kraków and GZM). This is a natural result of both the mobility strategy adopted about a decade ago and the desire to maximise the efficiency of the existing infrastructure accompanying electrically-powered vehicles (e.g. chargers). The availability of this infrastructure causes high fixed cost and, consequently, it can be seen as a threshold for entering the second-generation electromobility system.

Between the years 2015 and 2022 it is noticeable that there has been a multiple increase in the number of public transport systems in Poland having at least one alternative-powered vehicle in their rolling stock (Fig. 7 and 8). Among this group special attention should be paid to some small towns, where the introduction of such buses was tantamount to launching public transport or replacing the entire

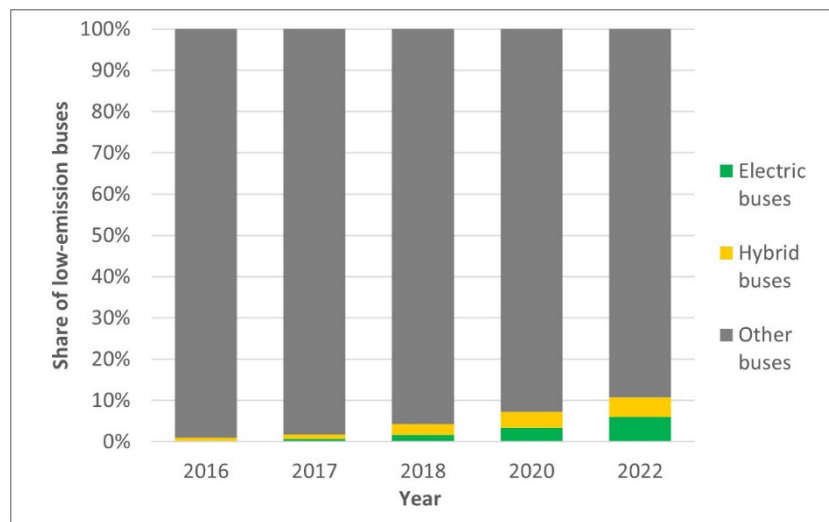


Fig. 6. The share of low-emission buses in the public transport fleet in the studied towns and cities.

Source: Own compilation; data for 2018 (ZDG TOR, 2018).

Meantime, the first electric and hybrid buses are gradually appearing in the remaining large and medium-sized cities, i.e. those that adopted the „let’s wait and see” strategy in the middle of the second decade of the 21st century. This is a consequence of the favourable external factors as low price of electricity before 2022 and the formal and legal requirements described above, which impose on the largest Polish cities the need to utilise this type of rolling stock, with tightening criteria for their share in the total fleet over time. However, among the largest cities, where the first-generation electromobility systems (i.e. tram or trolleybus networks) are in operation a preference to invest in them can be observed. This conclusion is relevant for the entire period studied. Indeed, among cities with tram and trolleybus systems, one can find many where electric and hybrid buses have not appeared at all (Olsztyn, Elbląg) or have appeared in a very small number and only in 2022 (Łódź, Gdańsk, Gdynia), but the overall share of electrically-powered vehicles in the public transport fleet is relatively large. It should be highlighted that significant investments in tram and trolleybus infrastructure and rolling stock have been undertaken in all Polish cities with these systems over the past several years (Kołoś, Taczanowski, 2018).

A particularly interesting case study is the Warmińsko-Mazurskie voivodeship, where urban transport systems operating only electric vehicles or having a significant share of alternative-powered vehicles in the fleet are becoming a certain standard – what were absent in 2016, 2017 and 2020, but started to be visible from 2022 onward in Lidzbark Warmiński, Giżycko and Szczytno, and announced for 2023 in Kętrzyn – with a complete lack of such buses in large and medium-sized cities in this part of Poland. There are more similar examples across the country (e.g. Miechów, Tomaszów Mazowiecki, Ząbkowice Śląskie). Apart from the marketing and environmental dimension, such actions may be considered as a way out of meeting the requirements imposed on public transport organisers as regards the share of emission-free rolling stock in the fleet – if they also concern the smallest urban centres (which is to be expected), the majority of them will automatically meet such a criterion.

Along with the dynamic development of the second-generation electromobility in Polish towns and cities the changes of their geography also take place (cf. Fig. 1-4). In particular, since 2017, two areas of concentration of centres where large-scale implementation of electric and hybrid buses has been undertaken

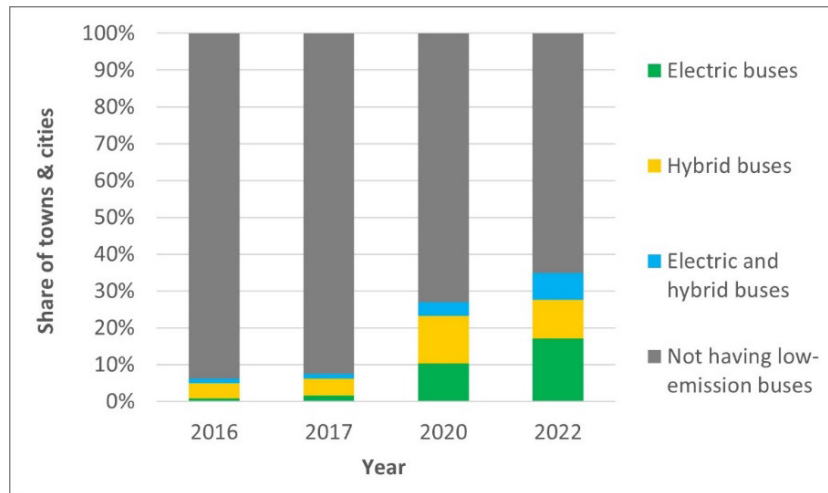


Fig. 7. The share of towns & cities operating low-emission buses.

Source: Own compilation.

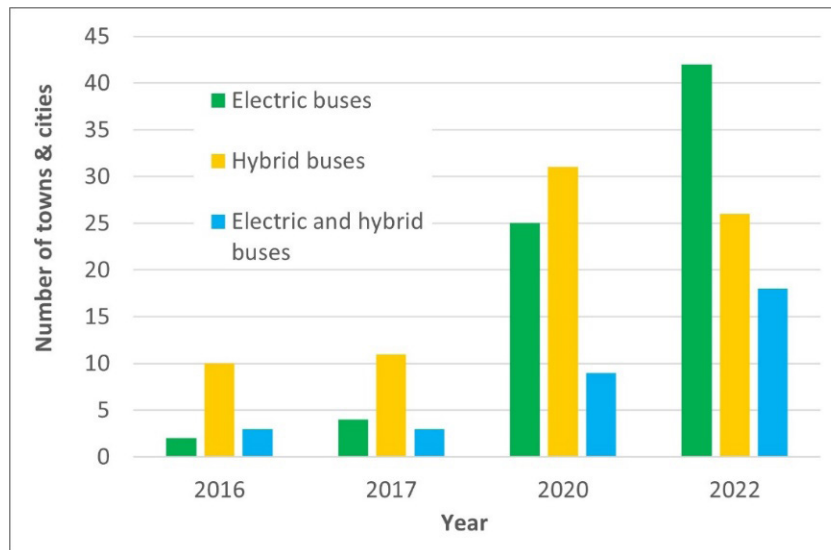


Fig. 8. The number of towns & cities operating low-emission buses.

Source: Own compilation.

have been noticeable. The first one can be identified in Central Poland, covering the Wielkopolskie, Kujawsko-Pomorskie, Łódzkie and Mazowieckie voivodeships and the second in Southern Poland – in Silesia and Małopolska. Outside the concentration lies Northern and Eastern Poland where – although hybrid and electric buses have been appearing in recent years – a large delay in relation to the rest of the country can be observed. In fact, in 2017 not a single low-emission vehicle was present in the urban transport fleets of the cities of Pomorskie and Warmińsko-Mazurskie Voivodeships. Four years later such a situation was still the case in the former region. Consequently, in this part of the country it is impossible to identify at

least one large or medium-sized centre that would be labelled as a leader or early adopter in the implementation of the second-generation electromobility. This is probably due to the fact that pro-environmental measures in urban public transport in those cities are based on other solutions – the noticeable development of first-generation electromobility (trams – Gdańsk, Elbląg and Olsztyn; trolleybuses – Lublin and Gdynia) and the use of gas-powered vehicles (e.g. Rzeszów, Tarnów, Słupsk or Suwałki). A noticeable shift towards the second generation electromobility in these urban centres is only visible in Lublin and Gdynia, i.e. cities where the trolleybus systems existing for decades are somehow supplemented and developed.

5. Differentiation of electromobility development by town and city size

An interesting aspect – when following the development of the second-generation electromobility in public transport systems in Polish towns and cities – is to look at the issue of city size. Since in Poland the large metropolitan cities are the most important engines of economic development, blurring the previously important regional differences, it was assumed that they are the ones that are rich, modern and have high social capital so they are better equipped and prepared to adopt the second generation electromobility. On the other hand, by virtue of the fact that these large cities already have had the first-generation electromobility systems (tram, trolleybus and/or light rail), they may be less motivated to adopt such innovation. This trope seemed to be partially confirmed by the cases of dynamic and ambitious innovators recruited from medium-sized cities among the pioneers of the second-generation electromobility (e.g. Jaworzno and Inowrocław). However, the analysis by city size (Fig. 9) clearly shows that the larger the city, the greater the chance that electrobuses or hybrid buses will be in operation in the public transport system. Among the smallest cities (those with less than 25,000 inhabitants) in which urban public transport systems are present,

only 12.2% have adopted some form of electromobility by the end of 2022. This share rises to 80% for cities with more than 100,000 inhabitants and to 100% for cities with more than 1 million inhabitants. However, the process of change is dynamic and it is among the smallest urban municipalities that the highest dynamics are observed.

Having a specific system is important in itself, but the full picture is also completed by the level of intensity of electromobility development, measured either by the share of such vehicles in the fleet (Fig. 10) or by the ratio of such vehicles to the number of inhabitants (Fig. 11). Here the relationship to the size of the city is not linear. The smallest cities still have the lowest ratios, but the highest ratios are observed in medium-sized cities (50-100,000 inhabitants and 100-250,000 inhabitants). This is due to the fact that in this group of cities, the urban transport systems are smaller and, if they opt for the second generation electromobility, it makes economic and organisational sense to operate at least 10 or more such vehicles, which translates into correspondingly high rates of intensity indicator. In the case of larger cities, the number of such vehicles in relation to the total fleet is generally lower, as there are still many cities in this group which are only at the stage of testing this solution and, moreover, they often have disproportionately

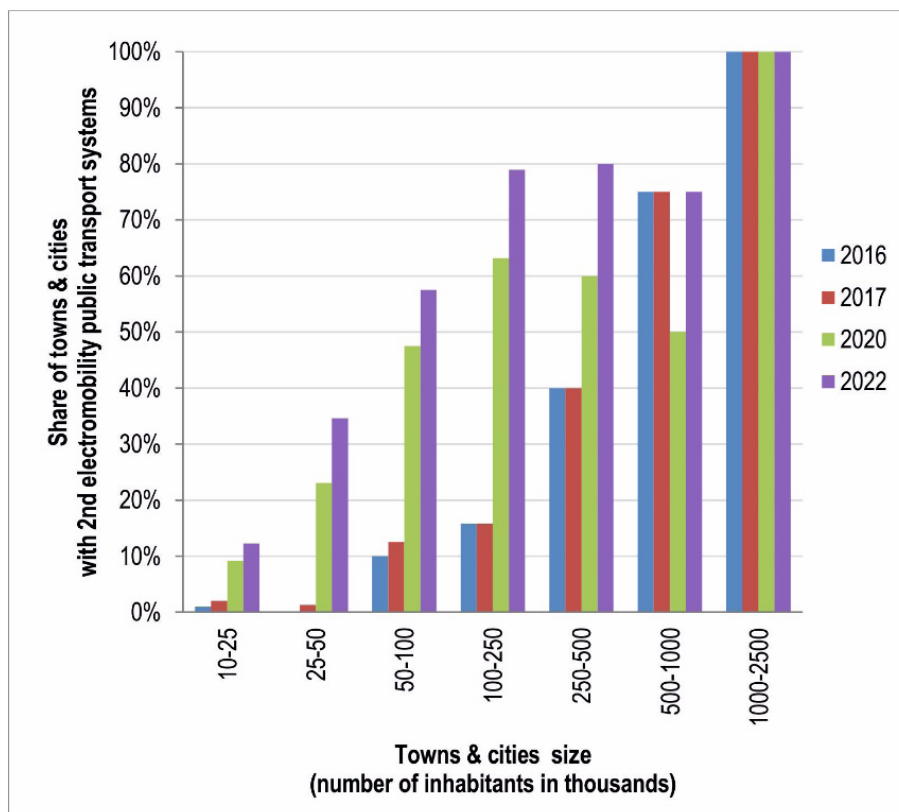


Fig. 9. The second generation electromobility development by town and city size.

Source: Own compilation.

large transport systems which serve agglomerations and suburban areas to a greater extent than in the case of medium-sized cities, not to mention small ones. An important factor influencing the number of electric vehicles in large cities is the presence of the

first-generation electromobility systems, which, on the one hand, reduces the need for the development of the second generation electromobility and, on the other hand, strongly influences the ratio relative to the size of fleets.

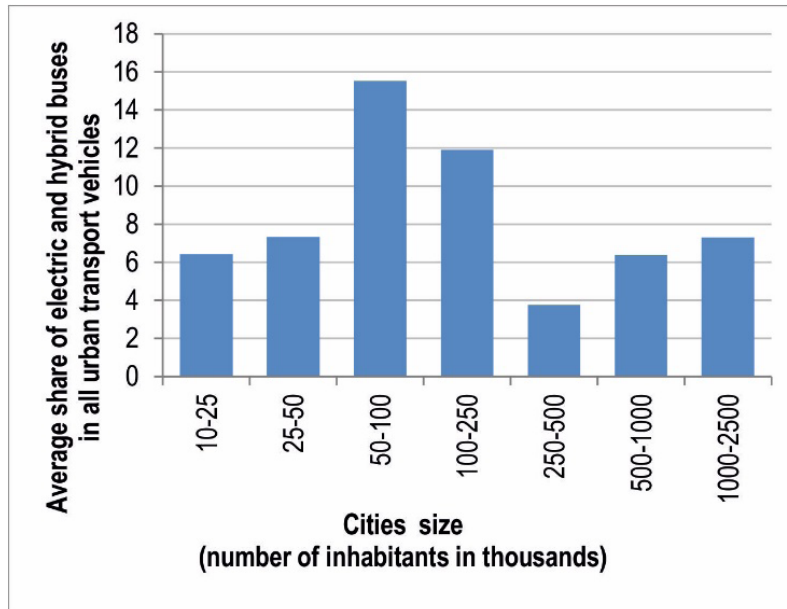


Fig. 10. The share of electric and hybrid buses in urban transport systems by town and city size in 2022.

Source: Own compilation.

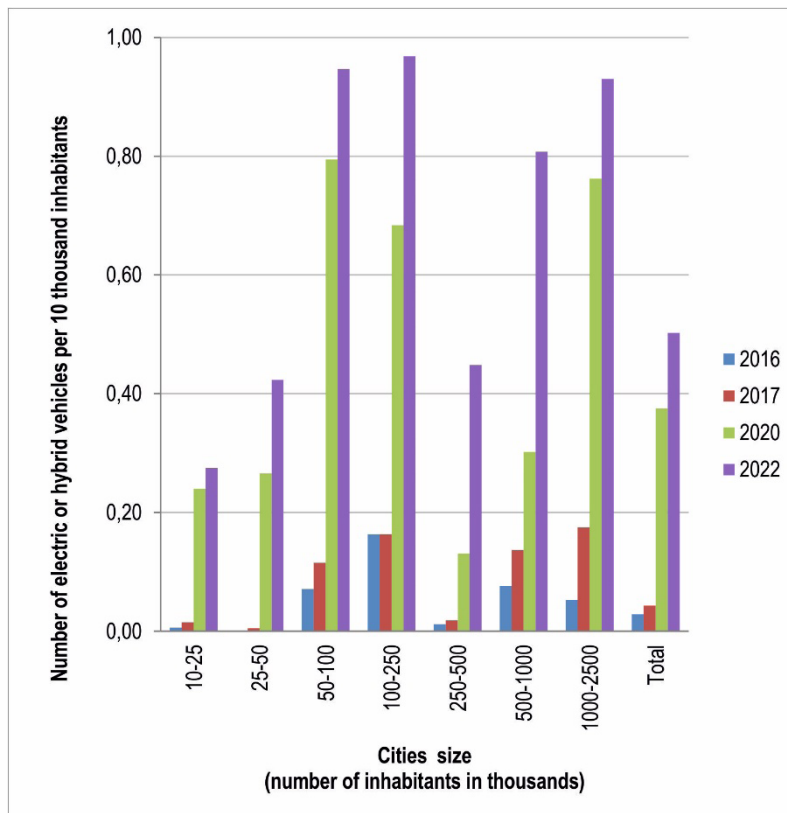


Fig. 11. The intensity of electromobility development by town and city size.

Source: Own compilation.

Conclusions

The implementation of the second generation electromobility in Poland has already departed from the initial phase. Both the share of towns & cities that have introduced low-emission vehicles (above 35%) and its market share (measured by the number of vehicles greater than 10%) suggest that Poland is positioned on the Rogers Diffusion of Innovation curve (1962) between the „early adopters” and „early majority” stage. It can also be seen that both advantages and shortcomings of the technology have already been recognised. Interestingly, it can be cautiously concluded that the possibilities for developing battery technology vary in cities of different sizes. The most serious technological problems apply to large cities, while smaller cities – especially medium-sized ones – are the most predisposed to its introduction. Obviously, in the initial phase it was easier to innovate in larger cities with adequate human and financial capital, as well as organisational capital.

In 2021, the share of electric vehicles among passenger vehicles in Poland was approximately 0.12% (PSPA, 2021). Even if we assume a significant share of surplus vehicles in the CEPIK state car register, the share of low-emission buses of over 7% in 2021 (and over 10% in 2022) has to be described as relatively high. This indicates that the Polish road to electromobility leads primarily through public transport. This is also due to the important role of zero- and low-emission bus manufacturers in Poland whereas an own-brand passenger car manufacturer is absent.

The most important general factor of national (and in fact EU) importance has been legislation and the regulation of EU funds, among which for example the Cohesion Fund, the Green Transport Programme or the Electromobility Act should be highlighted. A factor favouring the implementation of electromobility on the national scale has been the presence of manufacturers of rolling stock and electromobility equipment, especially Solaris. At the local scale, organisational, economic and social issues have been important differentiating factors. Interestingly, the second generation electromobility was more quickly implemented by cities whose public transport was organised according to competition for the market model and which – at the same time – had strong municipal companies. The strategic attitude of the municipal authorities to environmental issues and to sustainable development was very important. Especially in the initial phase and in smaller cities the attitude of local elites – especially those managing public transport and municipal transport companies – was a very important factor.

The second generation electromobility has been implemented faster by larger cities, although the most ambitious programmes (going in the direction of complete replacement of rolling stock by low-emission vehicles) have been implemented by medium-sized cities or even small towns (Inowrocław, Jaworzno, Zielona Góra).

It should also be noted that the implementation of the second generation electromobility is connected with the fact of having already the one of the first generation. However, this can be both a favourable and an unfavourable factor – the former as a result of having the appropriate knowledge and the latter because having a tram or trolleybus network may not necessarily be favourable for implementation of electric or hybrid bus system. It goes without saying that it depends on the individual characteristics of the city. Nevertheless, it cannot be stated that the first generation electromobility is inferior to the second generation one. Hence, there is some misunderstanding of the provisions of the Electromobility Act, which favoured this newer electromobility at the expense of the older one.

Electromobility and its implementation is promising and growing field of research. Further studies can be dedicated to the development, optimisation and stabilisation of the technology but also to the ways and factors of its implementation, primarily at the local level. It may be interesting to investigate whether the first and the second generation electromobility are more substitutive, complementary or perhaps competitive with each other.

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