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GEOGRAPHIC FEATURES OF ZERO-EMISSIONS URBAN MOBILITY: THE CASE OF ELECTRIC BUSES IN EUROPE AND BELARUS

Abstract. This article reviews the emerging phenomena of electric buses' deployment in Europe and Belarus within the general framework of the concept of sustainable and electric urban mobility. The author offers a brief overview of electric bus technologies available on the market and a spatial analysis of fleet deployment in Europe. The analysis of the spatial structure of the distribution of e-buses in Europe indicated that, in terms of the number of vehicles in operation, the UK and the Netherlands are the regional leaders, while in terms of the number of cities testing e-buses – Germany, Sweden, and Poland are the leaders. The analysis showed that the main factors supporting the distribution of innovative technology and public support are legislative and regulative framework as well as clear strategic planning and cooperation between local administrations and transportation authorities. Other important aspects, such as network building features, and the location of the charging infrastructure were also discussed. The analysis of the case study of Minsk (the first city to introduce electric buses in Belarus) outlined the typical limiting factors for all types of markets: high battery costs and dependency on infrastructure; recommendations are given to emphasise bus fleet replacement (instead of trolleybus) and to develop a comprehensive sustainable urban mobility strategy.
Key words: electric buses, new mobility, public transit, sustainable transportation, infrastructure, Minsk, Europe.

1. INTRODUCTION

Public transportation is considered as an integral component of everyday urban logistics routine, which meets the growing needs of citizens in private and business mobility. Over the past decades, the share of the global urban population had increased significantly, strongly affecting the way people move within and

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beyond city limits. In 1950, 30% of the world's population was urban, and, by the year 2050, it will reach 68% (UN, 2018). That trend is causing a significant increase in general mobility: by 2050 an additional 1.2 to 2 billion cars will be on the roads globally, which is double of today's global vehicles park (World Bank, 2017; C40 Group, 2017). Urbanisation and motorisation have a negative impact on the economic, social, and environmental dimensions of urban life, including (but not limited to): increased traffic congestion, air and noise pollution, freight and passenger flows, causing lack of space, and deteriorating safety and security (EC, 2007). Considering the main challenges that many urban authorities, planning agencies and stakeholders face (e.g. how to improve mobility while avoiding the problems named above), it is clear that cities must take action and look for more sustainable transport policy options and measures (REC, 2008). In recent years, the "sustainable mobility paradigm" had emerged (Banister, 2008), and many cities of developed and developing countries already joined the discourse of transition to sustainable urban mobility (C40 Cities Climate Leadership Group may be an example), which is understood as the "ability to support the need for people, cargo, and information to move around while doing minimal damage to the environment" (Rodrigue, 2017).

Transportation is considered a significant contributor to global climate change, accounting for 23–27% of total greenhouse gas (abbreviation GHG is also used in the text below) emissions (with the share of buses accounting for approximately 8%, World Bank, 2012; ZeEUS, 2017). With the expected global addition of 1.2–2 billion cars by 2050, the emissions related to the transportation sector may grow within the range between 120–230% (C40 Group, 2017).

In Europe, transportation is a major contributor to climate change and air pollution. Since 1990, carbon dioxide (CO2) emissions from European road transportation have increased by 17% (it is the only sector that has seen an increase in GHG emissions). Road transportation now accounts for roughly one-fifth of the EU's GHG emissions (Miller, 2016). Transportation is the second biggest GHG emitter in the EU (24.2% of total emissions in 2010). It receives special attention regarding the policies of emissions reduction at various spatial scales, from the EU regulations and directives to local cities' initiatives. The EU is committed to the reduction of GHG emissions, aiming at a 20% reduction (to the level of 1990) by 2020 and 80–95% reduction for all sectors combined – by 2050. The 2050 reduction target for transportation is about 60% (CIVITAS, 2013). The EU has clear objectives to increase the share of public transportation in the structure of general mobility. With the introduction of new CO_2 regulations for vehicles, European municipalities will face new challenges making cost-efficient and environmentally friendly decisions.

Reducing emissions, energy efficiency, improving air quality, and reducing noise pollution are priorities for the sustainable development of many states and cities. More than 20 EU policies, strategies, and measures provide the regional legislative framework for the development of cleaner public transportation in Europe. Some reflect the general vision on European urban mobility; other address noise levels, air quality, reduction of GHG and CO_2 emissions, and energy security (CIVITAS, 2013). In 2009 the Electric Vehicles Initiative (includes Germany, France, United Kingdom, Netherlands, Sweden, Norway, Finland) was established. It is a multi-governmental policy forum dedicated to accelerating the distribution of electric vehicles worldwide (IEA, 2018).

With the growth of urban population and the increase in rates of urbanisation, the adoption of sustainable mobility has become central to the processes of urban planning (Montero, 2017). Sustainable urban transportation systems will play an increasingly critical role in driving responsible climate action and reducing global emissions (C40 Group, 2017). Nowadays urban transportation is responsible for a quarter of the total CO_2 emissions from transportation in the EU (EC, 2011). It is possible to state that the political target to reduce this share correlates with the shift of public opinion towards the values of sustainable development. Under the influence of such factors as the negative consequences of motorisation, the situation at the energy markets (especially in Central and Eastern Europe), technological progress, and availability of cheaper and greener transportation modes (i.e., electric vehicles), the transformation of public transit is already happening across the region (Fig. 1).

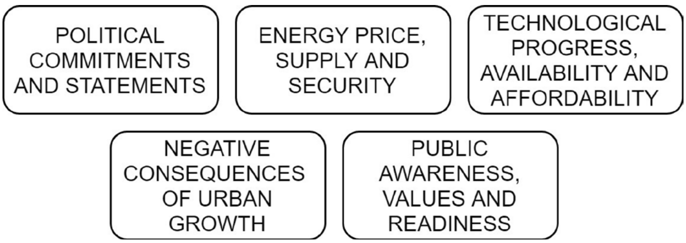

Fig. 1. Factors supporting emissions reduction in public transportation

Source: adopted from FCH JU, 2015.

At the local (urban), level cooperation between cities is trending. More than 80 cities worldwide have joined the network of C40 Cities Climate Leadership Group, focusing on tackling climate change, and initiating practices and actions that reduce the negative impacts of urban socioeconomic activities. The key approaches and strategies the cities use to reduce emissions from transportation include switching to effective modes (e.g. public transit or non-motorised transportation) and enhancing the efficiency of fleets via shifting to zero-emission technologies (C40 Group, 2017). The “Clean Bus Declaration of Intent”, signed by 26 cities representing C40 Cities Climate Leadership Group and supported by 10 Latin American cities (Fig. 2), is a good example of an interregional and international commitment to efforts. Its goal is to improve air quality by introducing low and zero emission vehicles in urban bus fleets. A geographical analysis of the spatial distribution of the signatory cities shows the leading role of Europe in promoting practices and measures to reduce the negative impact of urban transportation. 31% of C40 "Clean Bus Declaration of Intent" signatory cities are located there (Fig. 2).

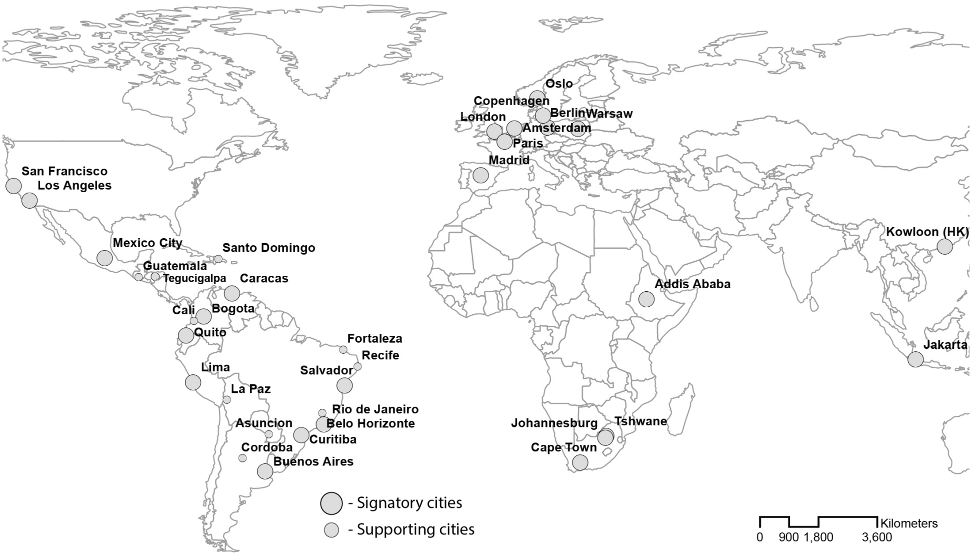

Fig. 2. C40 Climate Leadership Group cities, supporting "Clean Bus Declaration of Intent", 2017
Source: own work, data obtained from C40 Cities Clean Bus Declaration of Intent, 2017.

2. THEORETICAL FRAMEWORK

Notwithstanding the fact that 40–50% of public transportation in Europe is already electrified (UITP, 2015), buses with internal combustion engines (the main pollutants) are the most economical vehicles in terms of the lowest total cost of ownership. The market price of the Belarusian diesel bus "MAZ" Model 215 is \$198,166 USD. It is cheaper than the Belarusian trolleybus "Belkamunmash" Model 321 (\$281,000 USD) or electric bus (\$450,000 USD). They still serve as the core elements of numerous contemporary urban transportation systems (CIVITAS, 2013). In Europe, 80% of buses have diesel engines, including 50 % with Euro III or older models (ZeEUS, 2017). In less economically developed countries of Eastern Europe, those numbers are higher, especially in smaller and peripheral regional centres. However, the shift in public awareness and environmental concerns, technological progress, and the growing affordability of cleaner bus technologies (i.e. hybrid or electric buses) change the way urban mobility stakeholders favour the low and zero-emissions transport systems. Over 40% of the operators and transportation authorities surveyed in Europe are keen to switch to electric traction options (ZeEUS, 2017).

According to the estimations and forecast of the Institute for Transportation & Development Policy, the world today is on the cusp of three revolutions in transportation: vehicle electrification, automation, and shared mobility. The scenario, considering all three trends, produces impressive global results by 2050, such as: a) reduction of global energy use from urban passenger transportation by over 70%; b) reduction of CO_2 emissions by over 80%; c) reduction of the measured costs of vehicles, infrastructure, and transportation systems operation by over 40%; and d) savings approaching $5 trillion per year (Fulton *et al.*, 2017).

Electric mobility is considered an effective mechanism of urban transportation transformation and reduction of GHG emissions (Nikitas *et al.*, 2017). Its future depends on the degree of the penetration of renewable energy sources into power systems. If the energy source mix used to produce the electricity that will supply EVs has low (or even zero) GHG emissions, the transition from conventional vehicles to electric will also lead to a reduction of emissions (Millo *et al.*, 2014). As the electric energy supply changes and moves towards electricity production from cleaner sources, the carbon content of the electricity powering electric buses will continuously decrease. This aligns with the goals set at the United Nations climate change conference in Paris (Kinsley, 2017) and in the European Union 2030 climate and energy framework (CIVITAS, 2013).

The benefits of electric mobility include a reduction of GHG emissions, health benefits through improved air quality, decreased noise pollution (like in Shenzhen, China, the first city to electrify 100% of its bus fleet, BNEF, 2018), increased energy security, and a potential for grid balancing. However, despite the potential benefits of electrification, the geographic spread of electric vehicles' deployment is limited by such factors as cost, infrastructure (charging points, grid modification), consumer education, and awareness (C40 Group, 2017). In developing countries, local governments, transportation agencies, and planners are facing enormous challenges finding consensus between receiving secure funding for infrastructure investments and delivering comfortable transit services (Hiroaki *et al.*, 2013).

The nature of the existing technologies (modern diesel buses, trolleybuses, dual modes (trolley/diesel), hybrids) and the emergence of new ones (electric buses, hydrogen fuel cells) means that there is a wide range of options that can replace the aging diesel bus fleet (GWRC, 2014). Among low-emission vehicles, *electric buses* can contribute to the future de-carbonisation of mobility. They can overcome the existing disadvantages of conventional fossil fuel buses (Nikitas *et al.*, 2017). A rechargeable electric battery powers electric buses; there are two types of e-buses currently in use – *opportunity buses* (recharge at stopping points en-route and carry lightweight battery – thus, increasing passenger capacity) and *overnight buses* (carry heavier batteries and can operate all day without recharging). Opportunity buses depend on the charging infrastructure, and they have a limited geographical route flexibility within the existing network (usually inside city limits where the stations are available). Then, overnight buses have complete *flexibility* within the existing network; it is typical to use them on selected suburban and intercity destinations (GWRC, 2014).

E-buses produce zero direct emissions, they are relatively easy to integrate into existing infrastructure (although, additional infrastructure adjustments are usually required), and they are environmentally and customer-friendly (low-floor, CCTV surveillance, USB charging ports). However, due to expensive technology, the life-cycle costs of e-bus deployment are much higher than of diesel or hybrid buses. The price may vary from $450,000 to $1,1 million USD, excluding charging infrastructure and battery replacement costs (Mahmoud *et al.*, 2016; GWRC, 2014). Transportation planning agencies and authorities should also carefully consider the shorter battery life (especially under low temperatures) and the logistics of the disposal of aging batteries.

3. LITERATURE REVIEW AND METHODOLOGY

3.1. Literature review

This study utilizes the existing academic literature and enhances the existing discourse with a geographic perspective. Some ideas of this article interpret the concepts and methodological approaches of contemporary transportation geographers, planners, and multidisciplinary researchers towards the sustainable mobility paradigm (Banister, 2008; Montero, 2017), the general spatial aspects of urban mobility (Rodrigue, 2017), and sustainable electric mobility (Miller, 2016; Kinley, 2017). Hanson (2003) discussed emerging issues of changing transportation context of sustainable mobility, related to the costs and benefits of transportation investments, including social costs of externalities (air, noise and water pollution, death and injury from accidents, loss of open space). Hiroaki (2013) discussed the spatial aspects and limitations of the distribution of technology due to the financial constraints of sustainable transportation planning (typical for developing countries). Hopkins and Higham (2016) discussed the transition to low carbon mobility. Fernando-Sanchez and Fernandez-Heredia (2018) studied sustainable bus mobility and delivered a detailed review of 10 strategies for sustainable bus mobility for selected cities, including New York, Memphis, Muscat, Montreal, Santiago de Chile, Bogota, Melbourne, London, Singapore, and Madrid.

The analysis of the existing literature on electric bus mobility revealed the major study directions that influenced the general research methodology of this paper. Numerous works provided a general overview of technology, market analysis, and an overview of motors and barriers for the deployment of e-buses (Fulton, 2015; Nikitas *et al.*, 2017), especially in the European Union (Borghei, 2016). Mwasilu (2014) provided an economic analysis of the infrastructure for electric buses. Some publications delivered findings based on partial spatial analysis carried out for route planning in selected European cities – Perrotta (2014) carried out an analysis of the electric bus performance on three different routes in the city of Oporto, Portugal.

A number of studies applied a geographical approach and a spatial-temporal analysis. They explain the essential infrastructural requirements, required for the electrification of the urban bus network. The research of Xulia (2017) delivered a model for the optimal placing and sizing of fast charging stations for electric vehicles in Stockholm. The study of the urban bus network in Berlin presented an advanced optimisation model for planning a fast charging infrastructure (Kunith, Mendelevitch, Goehlich, 2016). The study of Aachen (Bohnen and Louen, 2017) answered the question of how different charging locations for electric buses affect route planning and travel time for public transport, and how to modify the existing public transportation.

The study of mixed bus fleets of electric vehicles and their conventional counterparts, conducted in Porto, Portugal (Santos, 2016), discussed the general performance, peculiarities of fleet balance (i.e. how many vehicles of each type should be allocated and where), and network optimisation (i.e. energy consumption, environmental impact, overall economic impact, and service quality).

There were quite a few geographic academic works which analysed the emerging phenomena of the new forms of urban electric mobility, including electric buses. However, a study by the Polish geographers identified the main factors and mechanisms behind the development of low-emission public transport vehicles in Polish cities (based on the case studies of Jaworzno and Cracow). They included energy challenges, environmental requirements, governance strategies, and manufacturing capacities (Taczanowski, Kolos and Gwozd *et al.*, 2018).

So far, none of the Belarusian transportation geographers covered the problems of electric urban mobility and the deployment of electric buses in the urban environment, particularly in Minsk, the first city to introduce the new transportation mode. The purpose of this paper was to fill the existing gap and to analyse the spatial structure of the development and distribution of electric buses in Europe. Another goal was to study the factors that influence the spread of this emerging technology. With consideration of demographic trends and the peculiarities of socio-economic development, the results, findings, and recommendations can serve as the basis for further urban transportation development in Minsk, the capital of Belarus.

3.2. Research methodology

The logical structure of this geographical analysis and review of the peculiarities of electric buses distribution in Europe consists of the following steps: a) a general overview of the concept of sustainable electric urban mobility; b) a brief overview of electric buses technology available on the market; c) spatial analysis of the e-buses distribution in Europe; and d) case study of Minsk and the analysis of practical exploitation of electric buses.

The statistical and analytical data on the current state of electric buses market discussed in the article was collected from open access publications and reports provided by the following international agencies and institutions: International Energy Agency, ZeEUS eBus Project, C40 Cities Leadership Group, the official publications of the World Bank, UTIP, Bloomberg New Energy Finance, etc. Other relevant academic publications (see literature review), industry reports, and policy papers provided the author with a better understanding of the emerging phenomenon of bus fleet electrification.

The spatial analysis of the electric bus market applied the open data from the sources named above. The official website of the Minsk transportation agency and Yandex Transport application provided the network data on the routes of electric buses, including configuration, evolution, and stops location. The maps presented in this article were designed in ESRI ArcGIS software using a standard geographical approach towards spatial data visualisation. Measurement units of the indicators studied are provided in the standard metric system.

4. GEOGRAPHIES AND TRENDS OF THE CURRENT MARKET

Although electric buses are an emerging technology, they are improving in commercial feasibility at global markets. The value of the global electric bus market was over $37 billion USD in 2018 (BMA, 2018). The decrease in the price of components (mainly, batteries) leads to the global spread – the global stock of electric buses almost doubled in 2015–2017, from 175,000 to 385,000 vehicles. In many cities, public transit operators and authorities demonstrate commitment to fleet electrification (C40 Group, 2017). Following the pioneers, i.e. the densely populated megacities of China (with severe pollution threats), local officials across the planet have begun working onprocurement plans and tenders to support the introduction of cleaner zero-emissions electric buses for public transport services (ZeEUS, 2017).

The last decade has seen progressive and positive developments in the distribution of e-bus technology, led mainly by China, and followed by Europe and the USA. The successful deployment of the first full battery e-buses during the Olympic Games in Beijing in 2008 (followed by the launch of a long-range (250–300 km) 12 m full-battery electric bus in 2010) opened up the e-bus market for Chinese manufacturers (ZeEUS, 2017).

Chinese e-bus manufacturers dominate the current global market in terms of vehicles sold. The e-bus industry in China is fragmented: Yutong, the biggest manufacturer, has a share of 19% of the market. The second biggest e-bus manufacturer is BYD. This company invests in electric vehicles and lithium-ion batteries manufacture, both in China and in Europe (BNEF, 2018).

In Europe, the total estimated electric bus stock reached 1,273 units in 2016 (an increase of 100% over 2015), and approximately 1,600 – in 2017. Additional 1,600 vehicles are being on order by mid-2018; since the delay between orders and deliveries is usually 9–12 months, all these electric buses are expected to be on the road by mid-2019 (Transport&Environment, 2018). The increase in European stock suggests that the European market is moving beyond the demonstration phase into commercial development, and by 2030, the share of battery-electric buses will reach 50% (ZeEUS, 2017). The United Kingdom, the Netherlands, Germany, Spain, Sweden, Poland, and Lithuania are the major European markets that order and operate fleets of electric buses (Fig. 3).

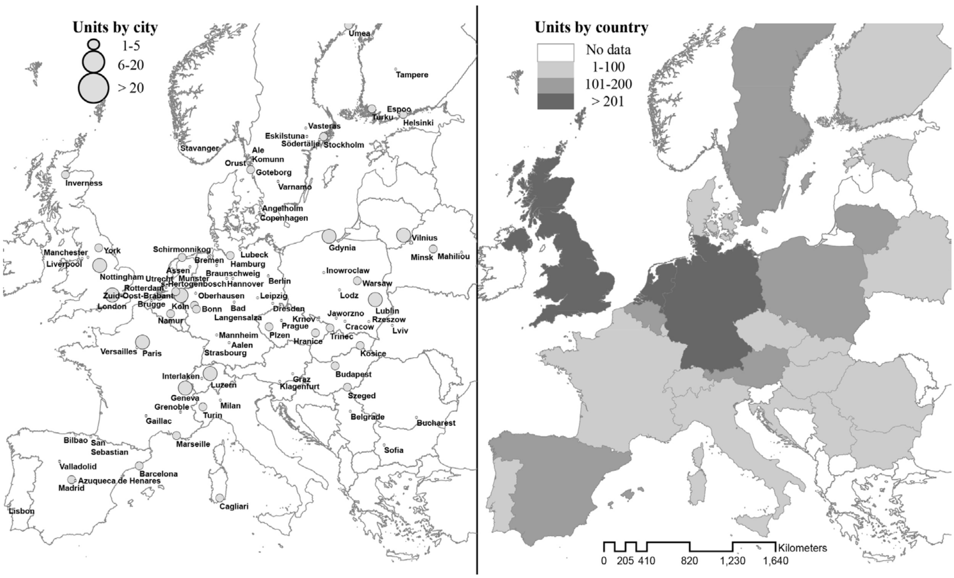

Fig. 3. Geographical distribution of electric buses in Europe, 2017
(note: transit systems with EVs operating in airports only (i.e. in Geneva or Nice) are excluded from the map)

Source: ZeEUS, 2017; Minsktrans, 2018; BNEF, 2018.

Germany (has 19% of European cities, deploying the electric buses technology), Sweden (11%), and Poland (9%) are the leaders by the total number of cities with electric buses. Vilnius, London, Nottingham, Lublin, and Eindhoven have the largest fleets of electric buses (ZeEUS, 2017).

The principal factors that support the deployment of electric buses into the existing urban transportation systems include: availability of additional funding (most of the e-buses in Europe were financed by national and regional grants), existing manufacturing base, liberal industrial policies (supporting local manufacturers), and political aim to reduce dependence on imported energy sources – particularly for the cities of Central and Eastern Europe (BNEF, 2018).

The contemporary geographical picture of the manufacturers' distribution highlights the Chinese domination – more than 98% of all electric buses sold worldwide in 2017 were manufactured in China (mostly for the domestic market). The three major Chinese bus manufacturers are Yutong, BYD, and Zhongtong (all have sold more than 20,000 vehicles in 2015–2016). The recent trend is that those companies have been actively present at the international electric bus markets. For instance, in 2018 Yutong supplied electric buses to the intercity bus company Flixbus (BMA, 2018). Nevertheless, the Chinese companies are facing strong competition in Europe with local manufacturers of electric buses. These include both incumbent bus companies (i.e. VDL, Solaris, Scania, Volvo, MAN, and Iveco) that have begun to offer electric models, and many new entrants focusing on electric buses (BNEF, 2018; IEA, 2018). By mid-2018, the following manufacturers delivered the majority of electric buses in Europe: BYD (approximately 38% of total deliveries), VDL (31%), and Solaris (21%, Transport&Environment, 2018).

5. CASE STUDY: MINSK CITY, BELARUS

In May 2017, with deployment of the first electric bus "E433 Vitovt MAX Electro" on route 59el (instead of the existing trolleybus route), the Belarusian capital, city of Minsk (2 million inhabitants), joined the list of European cities that test the new transportation mode – electric bus (Fig. 4).

The initial length of the first route, operated by four electric buses in trial mode, was 12.3 km. The daily mileage of each electric bus was about 280 km. The battery specifications defined the route selection with the necessary recharging infrastructure located at the final stops of the routes. In August 2017, with the launch of an electric bus on route 43, the network of this type of transport in the city of Minsk expanded to 19.8 kilometres. The reconstruction of the second transportation ring justified the replacement of the closed trolleybus communication with electric buses. However, according to the position of the Minsk transportation agency "Minsktrans", it makes more sense to replace the existing bus routes for environmental reasons. In 2018, after the deployment of electric buses on route No. 1 instead of existing diesel buses, the network had grown to 29 km, and it connects the geographical, economic, and transportation city centre (main bus and railway terminals) with residential areas and sports infrastructure facilities (Minsk-Arena on route 1).

Fig. 4. Electric bus “E433 Vitovt MAX Electro” in Minsk, Belarus
Source: phot. by A. Bezruchonak.

It is worth mentioning that the city master plan, designed and approved in 2014–2016 (with projections until 2030), does not consider the development of electric buses as a new transportation mode, and has no consistent strategy for their development (Minskgrado, 2016). Nor the city has the approved sustainable urban mobility plan (SUMP), so it may seem that low-emission transport is not an important issue, according to the official documents. That may mean that the first trials were the promotion of the production of the existing manufacturer, “Belkamunmash”, with the goal of marketing and selling it (mostly to Russia).

However, the analysis of the current and planned network shows that, despite the absence of electric buses in the official planning documents, the city considers them as a potential replacement of the existing conventional buses. In 2019, “Minsktrans” plans to trial e-buses on additional seven bus routes, aiming to unload the passenger traffic from the city's major arteries (*avenues*) or to feed them (Fig. 5). That partly corresponds with the development strategy of conventional buses and trolleybuses, presented in the masterplan (Minskgrado, 2016).

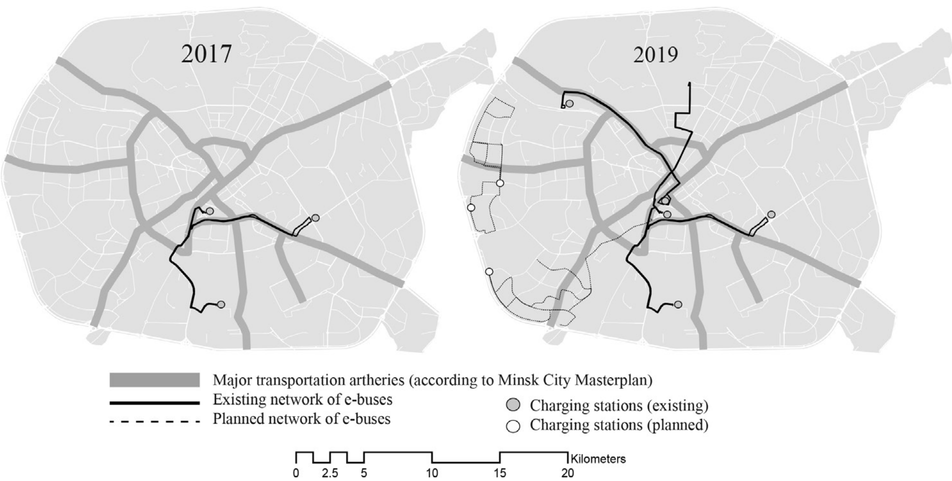

Fig. 5. The evolution of electric buses network in Minsk, 2017–2018

Source: own work.

The total number of electric buses operating in Minsk in 2018 was 20. However, according to the plan, this number will increase to 80 in mid-2019, with 60 electric buses purchased for the Second European Games by June 2019 (BMA, 2018). It is logical to assume that the extended network will reach the venues of the European Games. It is a vivid case of a top-down approach in transportation planning when political will of the senior governing authorities (i.e. the Minsk City administration) is a factor which defines the implementation rate of new strategies and steps in urban transportation development.

It is worth noticing that Belarusian-manufacturing Company "Belkamunmash" (that manufactures electric buses) holds a considerable amount of share in Eastern Europe and is planning to establish a factory in Georgia to meet the increasing demand from Eastern Europe and the Middle East (BMA, 2018). However, the company, targeting mostly regional post-Soviet non-EU markets, endures strong competition from Chinese and EU companies.

The design of e-buses, based on the existing trolleybuses models due to practical reasons, facilitates the registration of technical documentation and permits for deployment. There are four models offered on the market, with the most popular models – E420 and E433 (12.7 m and 18 m respectively). Both versions have 160 kW engines, made of composite materials and equipped with climate control, video surveillance and USB charging systems (BKM, 2017). The technical specifications of Belarusian electric buses differ slightly from their foreign counterparts: the length of E420 model is 12.7 m (according to ZeEUS project estimations, 73% of all electric buses in Europe have that length), E433 model is 18 m long (as are 15% of all electric buses in Europe). The battery range of electric buses is enough for 12–16 km (it takes 5–7 minutes to charge the installed Chinese supercapacitor); although, it is significantly less than what is offered by foreign counterparts (the first electric buses deployed in China had the range of 250 km, ZeEUS, 2017).

6. DISCUSSION

This study explained some theoretical and practical aspects of electric bus deployment in Europe, including a brief analysis of the usage in the city of Minsk, Belarus. It demonstrated that the concept of sustainable electric urban mobility is trending among researchers (Fernando-Sanchez, Fernandez-Heredia, 2018), experts (Transport&Environment, 2018), urban officials (C40 Group, 2017), manufacturers (BKM, 2017), and transit companies.

Despite the advantages and benefits of electric mobility, outlined in the theoretical part of this article (Miller, 2016; Kinley, 2017), there are several barriers preventing the growth of vehicle units on the streets of European cities nowadays. The cost of a battery (still accounts for approximately 50% of the total e-bus cost) is still a limiting factor for the distribution of e-buses, not every city administration (especially in developing countries) can afford a fleet replacement (Hiroaki, 2013). Battery capacity and weight have a direct impact on the carrying capacity and the final cost of electric buses. On the one hand, electric buses are still several times more expensive for transit companies in terms of cost of ownership. However, on the other, the picture significantly changes if one calculates and includes the external costs. The calculation of health costs from air pollution and noise, which cause premature death, respiratory diseases, loss of productivity, and other negative impacts, shows that electric buses prove a cheaper option (Transport&Environment, 2018).

Electric buses have no direct emissions, but it is necessary to be careful with the selection of electricity sources. They can be considered as an environmentally friendly alternative to diesel buses only using energy from a clean and renewable source (Miller, 2016). There are several controversial issues regarding power sources for the electric buses of Minsk. Firstly, environmental activists wonder if the popularisation of electric mobility in Belarus is related to the ongoing construction of Ostrovets nuclear power plant (NPP) that can potentially supply electricity into the grid systems. Despite the positive environmental image of electric buses, one can hardly consider nuclear energy as a clean and environmentally friendly power source, especially after the disaster at the Chernobyl NPP. The second issue is about practical implications of electric buses in Minsk – unlike in the majority of models in the EU, the heating system during winter is working on diesel fuel (banned or planned to be banned in several European countries, like Germany or Norway), a conventional GHG pollutant.

In addition, the estimations show that the increase of battery capacity will significantly increase the weight of the vehicle, reduce energy efficiency and raise the final cost of the product (the current price of the electric bus starts from $450,000 USD, MUP, 2017). Electric buses in Minsk use supercapacitors from a Chinese manufacturer, with a 10-year life cycle (or about 100,000 charge-discharge cycles). That is not enough for the sustainable and self-sufficient financial performance of the transportation agency. Further research should evaluate the long-term economic effects of electric bus deployment in European cities (including Minsk). In Cracow, the deployment of the electric buses is still an experiment, and the city council with transit agency have a careful approach to the replacement of conventional buses (Taczanowski *et al.*, 2018). However, according to the estimations of the Minsk transportation agency, the operation of electric buses on routes 59 and 43 resulted in electricity savings (14% in comparison to the trolleybus usage) and network operational costs savings – the cost of 1 km of the network operation was 3.8% lower (MUP, 2017).

It is important to understand the spatial constraints of the infrastructure: the location of charging stations determines the geography of networks and the network-building features. For instance, the original feature of electric buses in Minsk was, unlike in many European cities (Fulton, 2015; Santos, 2016, Nikitas *et al.*, 2017), the incorporation into the existing trolleybus network and replacement of one environmentally friendly mode of transportation with another. The Minsk transportation agency should use the commonly applied network-building feature, i.e. to develop the network by integrating the zero-emission vehicles into the fleet of conventional buses, like in Porto, Portugal (Santos, 2016). It is necessary to consider the costs of replacing one expensive transportation infrastructure (i.e., the existing trolleybus contact network) with another (charging stations for e-buses).

The distribution of the charging infrastructure is also an important aspect when it comes to transit operations, as the charging of electric buses cannot affect the passengers during the provision of transportation services, so additional schedule planning is required. Regular charging of the opportunity buses can lead to traffic delays. Moreover, the noise from charging stations may cause inconvenience to passengers and residents of the nearby neighbourhoods (actual observation from the trials in Minsk). However, various concepts need to be adapted and reviewed individually for every city. Many factors may affect the decision-making process, such as the type of the battery, urban design, secured funding, and political commitment. The existance of the network infrastructure before the installation of a charging station is an advantage, and each integration of electric bus infrastructure should be verified, like in Aachen (Bohnen and Louen, 2017).

An effective regulation, a clear sustainable urban mobility plan (SUMP), and political support are important factors for the successful deployment of electric buses in a city. Several cities around the world have set clear goals for fleet electrification within the framework of urban transportation planning strategies: Montreal (have plans for 100% electric bus fleet by 2020), Madrid (40%), London, etc. (Fernando-Sanchez and Fernandez-Heredia, 2018). The case of the Polish city of Jaworzno proves the point that the city with clear goals and targets towards low-emission transportation becomes attractive in terms of the implementation of complex investment programs and public perception. According to local data, the share of inhabitants who use public transportation has grown over the trials, and municipal electric buses are perceived more often as an attractive alternative to a private car (Taczanowski, 2018).

The development of SUMP, with clear priorities set for low-emission vehicles and their popularisation among local residents, is recommended for the practical application in Minsk. That will increase the share of the population using public transit (in 2016, a significant percentage of Minsk residents – 59% – used public transportation to commute to work; 39% used it for general mobility (ODB, 2017)). The actions to promote electric buses among citizens may include an introduction of comfortable ticketing systems, a popularisation of the advantages of e-bus usage, and the installation of additional features (wi-fi, USB charging ports, bike racks, etc.). However, it is unclear if people are ready to pay more for cleaner transportation services. The field research proved that electric buses are quieter than their diesel equivalents – that also forms a positive image of the new technology in terms of creating a healthy urban soundscape.

7. CONCLUSIONS

Policymakers and city administrations consider the electrification of public transportation fleet and the reduction of greenhouse gas emissions as steps towards ensuring a healthy environment for the population. Electric mobility, and, in particular, the deployment of electric buses, is internationally recognised as an emerging technology, with strong attractive points and limitations. In recent years, numerous European cities have decided to incorporate electric buses into the existing public transit systems supporting the new technology. More cities have plans to initiate the replacement of diesel fleets with electric buses in the nearest future (ZeEUS, 2017).

The spatial distribution of cities, supporting e-buses, is defined by the consensus between authorities, planners, manufacturers, and citizens. It is typical that central cities (i.e., London, Paris, Madrid, Warsaw, Cracow, or Minsk) take a more cautious approach towards fleet replacements, due to higher costs of deployment. Yet smaller cities demonstrate fast and progressive dynamics (i.e. it is easier to design SUMP or to replace a smaller bus fleet). Polish and European cities with open public transportation systems and a strong position of the municipal transit agencies have favourable conditions for the introduction of electric buses. Then again, urban mobility in the cities with strong vertical planning systems (typical for post-Soviet countries) depends on the political will of the authorities and may ignore international environmental commitments.

The institutional environment together with the regulatory framework plays a dominant role in the development of electric bus systems. The EU 2019 low carbon economy strategy (anticipating the last diesel bus to be sold by 2030) is a good illustration of an international commitment towards the decarbonisation of economic development. The German court ban on diesel vehicles, the commitment of Dutch provinces to zero-emission buses, the zero-emission bus regulation of California – all serve as a good precedents to legislative controls and bans at regional levels.

Despite the fact that e-buses will likely remain expensive for at least one more decade, the general technology cost decline will support the geographical expansion of the promising technology. Altogether, with appropriate regulation improvements, that may have a synergetic effect and positively promote the global expansion of electric buses and low-emission public transit.

The analysis of the e-bus market indicates the leading position of China (manufacturing 99% of vehicles, mostly for the domestic market), followed by the EU and the US. In the EU, the spatial patterns of electric buses deployment have no equal distribution over the Member States: such countries as the UK, Germany, the Netherlands, and Poland have the largest fleets. They are the main markets with the most advanced and progressive practices and policies promoting distribution of electric buses. The projected increase in orders will have a positive impact on the development of the European bus manufacturing market (with BYD, VDL, and Solaris to be the largest manufacturers of electric buses).

Belarus is also trying to find its niche on the e-bus market, and "Belkamunmash" holds a considerable amount of share in Eastern Europe. The trials of e-buses in Minsk and the existing trends of the fleet and network growth show that the effectiveness of e-buses is still a matter of further detailed research and evaluation, but the available data shows that they can be more efficient in comparison to the existing public transit options. Though, at the international markets, the company will encounter heavy competition against the Chinese and European e-bus manufacturers. That will define the potential geography of sales in non-EU markets – Russia, Ukraine, and Moldova.

Finally, despite the fact that the deployment of electric bus vehicles and integration into urban transportation systems should be carefully analysed and evaluated individually for each city, it is vitally important to accept and understand the following: a successful electrification of public buses may not only improve urban life (by reducing air and noise pollution and providing better customer experience) but can serve as a role model for other cities and transportation companies.

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ADDITIONAL RESOURCES

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