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Analysis of the current state and prospects for public electric transport development in Russia (on the example of electric buses)

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Abstract. The article considers current problems and prospects of public electric transport development in the aspect of electric buses. Modern realities dictate new trends in transport infrastructure, namely the replacement of the usual buses with internal combustion engines that use combustible fuel with a more profitable mode of transport powered by an environmentally friendly and renewable resource, electricity. Such vehicles are electric buses, which are rapidly becoming a part of passengers' lives. This fuel-free transport enables large numbers of people to travel quietly in megacities, while minimising pollution. The rapid introduction of electric buses around the world is making it possible to replace aging buses with internal combustion engines and clean up the environment with electric motors, but this cannot be done quickly due to the high cost and poor infrastructure in many cities around the world. Factors limiting the development of electric buses are identified, and possible solutions are described. Government investments and projects provide an economic solution to the problem. An analysis of the public electric transport market is carried out and prospects for the development of electric buses in Russia are formulated. Widespread introduction of electric buses in megacities will significantly reduce environmental costs for the population.

1 Introduction

The first prototype of this newly fashionable electric bus was made in 1886 in London. The average speed of an innovative bus at that time was 11 km/h. In Russia, however, the first electric bus was built according to the design of Ippolit Romanov from St. Petersburg in 1901. In his design, Ippolit tried to embody many of his ideas, successfully adopting the experience of foreign partners.

The initial examples of electric buses were obviously not perfect: a huge amount of usable space was taken up by cumbersome vertical batteries, which significantly reduced the space available for passenger use. It wasn't until a few years later that the problem was solved. Russian engineer-inventor Ippolit Romanov produced a fundamentally new type of battery, the main advantage of which was compactness. The batteries could now be located both in the floor and on the roof, increasing the space available inside the vehicle. After a

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successful test on the roads of St. Petersburg, the City Duma approved the project and allowed regular runs on ten city routes. Ten electric buses were manufactured at the Moscow "Dukes" plant, had a range of 64 kilometres and reached speeds of up to twenty kilometres per hour.

Performance and eco-friendliness are among the notable advantages of electric buses over internal combustion engine buses. An electric bus is a quiet and financially viable solution, as the need for petrol is fully exhausted. The durability and low maintenance costs are also worth noting. The life cycle of an electric bus is 15 years, after which the only thing that should be done for its correct operation is to change the battery.

Eco-friendliness is an important factor in urban areas, where the huge amount of exhaust fumes affects people around. However, this transport mode also has its drawbacks which do not allow it to reach its full potential in the current realities.

1.1 Relevance

The relevance of the study is determined by the fact that in the modern world there is a need for an environmentally friendly mode of transport, as the amount of harmful substances emitted into the environment is increasing inexorably every year. The alternative to buses is electric buses, which have low noise level and no harmful emissions into the atmosphere. The objective of the study is to identify the key challenges in the development of electric transport infrastructure and technologies that hinder the growth of this sphere, as well as to analyse the prospects for electric transport and its improvement.

As Boud Verbrugge, Mohammed Mahedi Hasan, Haaris Rasool, Thomas Geury, Mohamed El Baghdadi and Omar Hegazy write in their study, "In recent years, bus operators have started focusing on the electrification of their fleet to reduce the air pollutants in cities, which has led to a growing interest from the scientific community. [1]

The above-formulated objective requires the following tasks: analysis of the current state of electric transport in Russia and the experience of foreign countries, collection and analysis of statistical data, analysis of the impact of electric buses on the environment, technical shortcomings of lithium-ion batteries, as well as characterizing the prospects and opportunities of this type of transport.

1.2 Literature review

This paper reviews and studies the works of foreign authors who study the possibility of replacing buses with internal combustion engines by environmentally friendly electric buses. A significant number of works are devoted to the research in the field of electric bus infrastructure, environmental and economic impact [1-10].The work by Boud Verbrugge, Mohammed Mahedi Hasan, Haaris Rasool provides a detailed overview of the current state of electric buses and the progress of their implementation in cities [1]. Vallera A. M., Nunes P. M., Brito M. C. in their work detailing the power cells and explaining the need for battery replacement technology [4].

Leila Ghadbeigi, Brandon Day, Kristina Lundgren, Taylor D.Sparks in their work evaluate the performance and efficiency of lithium-ion batteries in low temperature conditions, and reason about the temperature control system as a possible option to reduce the consequences in the winter seasons [8]. In their study, authors Yuping Lin, Kai Zhang, Zuo-Jun Max Shen highlight the need for electric bus infrastructure and its layout, taking into account the existing trolleybus infrastructure [9].

These authors describe certain aspects of electric buses in great detail, coming to the same conclusion: electric bus is an efficient, clean and promising mode of public transport, despite the obvious shortcomings in the form of low travel time and high production costs.

1.3 Problem statement

Analysis of scientific papers has shown that the main problems preventing the introduction of electric buses on Russian roads are: partial or complete lack of infrastructure, including power grids and charging stations. Many Russian cities lack charging stations due to a lack of budget funds; rapid loss of battery charge at low temperatures; high production and development costs; due to the novelty of the technology and low demand, the price of electric buses is too high; and the small number of companies capable of recycling batteries.

1.4 Aim, objectives and hypothesis of the study

The aim of the study is to analyse the problems and prospects of electric buses and their impact on the economy and the environment.

The objectives of the study are:

- to analyse the current status of electrically-powered buses;
- identification of factors limiting the development of electric buses and description of possible solutions;
- market analysis and formulation of future prospects.

Hypothesis can be formulated as follows: it is to be expected that with a deeper introduction of electric buses, carbon dioxide emissions and noise levels in cities will be significantly reduced. However, there are challenges to the successful use of electric buses, such as: harsh climatic conditions affecting lithium-ion batteries, lack of battery recycling facilities, partial or complete lack of infrastructure, and the high cost of manufacturing and maintaining electric buses.

2 Methods

Materials from various sources relevant to the topic were selected with a view to writing this paper. On the basis of these, an analysis of the problem was carried out, ways of solving it were identified and conclusions were drawn. Empirical-theoretical research methods were used, in particular the method of analysis, the method of analogy, the method of comparison and induction. In order to analyse the current state and implementation of electric buses on Russian roads, materials from different sources were found. Based on the data obtained, problems were identified and analysed, solutions were identified and conclusions were drawn.

3 Results

In 2021, buses and trolleybuses are the main means of passenger transport, accounting for about 99% of the public fleet. Electric buses account for the remaining share of passenger transport. Table 1 shows the number of electric buses in regular service. There are about 1,300 electric buses throughout Russia, most of them produced by KAMAZ. The rest are produced by LiAZ and Volgabus, etc.

Table 1. Models in regular service in Russia.

KAMAZ-6282	LiAZ-6274	Volgabus-5270.E0	Next Electro 7720	GAZ-A65R3E	BKM E321 «Olgerd»
>1000 pcs.	206 pcs.	14 pcs.	5 pcs.	2 pcs.	1 pcs.

Table 1 clearly shows that PJSC KAMAZ is the leader in electric buses, with the largest number of active vehicles, LiAZ is second in the number of electric buses, while Next, GAZ and BKM are just starting to develop their own electric buses. Their projects are test vehicles.

Not all regions can afford the use of a relatively new type of transport due to extremely limited budget and underdeveloped infrastructure, so the majority of electric buses are located in the most developed cities of the country (Moscow and St. Petersburg). Researcher Elena Romanova raises this issue in her paper "Many cities refuse operation of urban electric passenger transportation. Basic reasons of it are high cost value and expensive operation". [2] In Moscow, a reduction in the share of diesel transport purchases and a gradual transition to buses with electric power units is planned by 2025, however, the purchase of a large number of electric buses will not solve a number of infrastructural problems. The capital is replacing the fleet inefficiently in terms of transport logistics and economics by duplicating trolleybus routes and sending conventional buses along them. The most efficient solution would be to remove diesel buses from the routes, replacing them with electric vehicles. St. Petersburg is using and developing the trolleybus infrastructure for the possible introduction of electric buses powered by the contact network. This will avoid large budget expenditures.

In their research paper, Mohammed Mahedi Hasan, Nikos Avramis, Mikaela Ranta, Andoni Saez-de-Ibarra, Mohamed El Baghdadi and Omar Hegazy write about calculating the total cost of a bus fleet "A TCO analysis of a bus fleet must always be made on a system level to include all the relevant costs. As a first step, the productivity of the bus fleet must be confirmed, i.e., that the buses are able to fulfil the required duty cycles without failure. In the second step, the total cost of the operation can be evaluated. The total cost of ownership of an electric bus fleet consists of the capital expenses as well as the operational expenses. The capital costs arise from owning a bus fleet, i.e., purchasing the vehicles and the required charging infrastructure, while the operational costs arise from the energy, service, and maintenance, as well as as salary costs.

In 2021, Elektrotransport Tekhnologii developed and produced an electric bus powered only by domestic components. "Elektrotransportnye Tekhnologii together with the National Research University of Moscow Power Engineering Institute created a unique traction engine, and the batteries were produced by the Novosibirsk company LIOTECH. Domestic developments are undergoing sea trials and are distinguished by their high performance. The electric bus has a mass of about 18 tonnes and accelerates to 90 km/h, and has a cruising range of 150 km, which is excellent. In terms of maintenance costs, electric buses in St. Petersburg have low running costs and only use night charging. This allows the vehicles to be charged at night. The cost of electric buses themselves is 4-5 times more expensive than diesel buses, but the 12-year maintenance cost of electric buses is 12.5% lower than that of diesel buses.

While the introduction of electric buses in Russia has been very slow, China is becoming a leader in their number. For example, in 2018, the Chinese city of Shenzhen became the first city in the world to switch completely to electric buses. This is what the Portuguese researchers A. M. Vallera P. M. Nunes M. C. Brito, "Battery swapping found a new impetus in China, with relevant investment from carmakers." [4].

As of early 2022, there are around half a million electric buses worldwide, 90% of which operate in China, making it the fastest-growing electric vehicle market. All electric bus manufacturers in China produce about 2,000 units per week, making the country a near monopoly in this field. For Russia, China is a positive example of electric transport infrastructure development, but Russia does not have the budget and technology to actively implement electric buses on the country's roads. This requires a specific strategy, as stated in their paper by Cambridge University researchers Dietmar Göhlich, Tu-Anh Fay and

Sangyoung Park "Therefore, a profound assessment strategy is necessary to find a "most suitable system solution" under given strategic and operational requirements" [5].

In 2019, there were only around 3,000 electric buses in Europe and the US, but that number will grow significantly in the coming years. For the past decade, Chinese manufacturers have received subsidies from the state, and now many other countries, such as Russia, Sweden and India, are also offering them to support the growth of electric buses. At the same time, a number of other major cities, including London and Los Angeles, have pledged to exclusively purchase zero-emission buses starting in 2025.

Diesel-powered buses contribute to climate change and threaten public health by emitting pollutants. Since diesel buses have a lifespan of more than ten years, any new diesel buses purchased now will continue to pollute the environment for years to come. In their study, Marcus Gustafsson, Niclas Svensson, Mats Eklund, Joel Dahl Öberg and Aner Vehabovic note: "battery-electric buses show a large reduction of GHG emissions compared to diesel buses" [6].

Air pollution from buses causes an enormous risk, as buses are constantly on the busiest roads and places. Vulnerable groups such as the elderly, children and people with disabilities are particularly exposed to the negative effects of air pollution. As Enrico Toniato, Prakhar Mehta, Stevan Marinkovic and Verena Tiefenbeck write in their study, "The transport sector is responsible for 25% of global CO2 emissions" [7]. However, not all electric buses are a completely clean mode of transport, because the heating systems of some electric buses use diesel fuel to heat the interior. This compromise significantly reduces electricity consumption. Electricity is also generated not only by environmentally-friendly power plants like solar panels and wind turbines, but also by the use of coal, oil and gas which release CO2 emissions into the atmosphere as a side effect. Measurements of the noise pollution levels of electric and diesel buses at fixed speeds in urban areas show a difference of 5 to 9 decibels, making electric buses extremely quiet.

One of the most important issues for electric buses is their adaptability to low temperature conditions. According to the KAMAZ's experts, thermal conditions were fully taken into account during the design of the vehicles, which means they are fully adapted and prepared for Russia's harsh winters. According to the statements of specialists, KAMAZ electric buses are capable of operating in the range from -45 C to +45 C, however, there are some difficulties: exposed to severe frosts, the batteries lose their rated capacity and deplete the battery reserve by about 30-40%, which significantly reduces the operating time of the electric bus, forcing drivers to make more cycles of charging. It is also confirmed in a paper by American scientists from the Department of Materials Science and Engineering, University of Utah Leila Ghadbeigi Brandon Day Kristina Lundgren Taylor D.Sparks, "Li-ion batteries need to operate in a temperature range of 20°C to 40°C in order to prevent thermal runaway and poor life cycling at high temperatures as well as avoid high resistance at low temperatures" [8].

While the stated temperature range of electric buses is reassuring, based on Moscow's experience, the problem is acute and not limited to the loss of battery capacity during the cold season. For the third winter in a row, Moscow's electric buses are facing low temperatures and failing.

Based on that, comparing the facts and analysing the situation, it would be correct to make the following proposals to solve this problem:

1. Development of a completely new type of lithium-ion batteries, fully adapted to the harsh Russian weather conditions, compatible with already existing electric buses and with sufficient capacity to take into account possible emergency situations. It will take more than one year to develop and implement, but the new type of battery could permanently eliminate the problem of electric buses adapting to bad weather.

2. On the subject of passenger comfort and cabin heating, the only possible solution at the moment is heating the bus using the fuel we are accustomed to. This solution is not an environmentally friendly vehicle because it produces harmful emissions, but it can still solve the problem to a certain extent. Some bus manufacturers include a diesel propulsion system for passenger heating, which may well be efficient, but it generates emissions.
3. The use of trolleybus networks to charge electric buses on the move. This solution is the golden mean. Buses would remain environmentally friendly and be able to provide passengers with heat.

The planned replacement of internal combustion engine buses with electric buses has been underway since 2018, but with further growth in demand and increased volumes of electric buses, infrastructure needs to be planned in advance. Charging stations, the use of trolleybus tracks and smart route planning are all essential for the stable operation of electric buses. However, without government support, the process of integrating electric buses will be stalled. The ever-increasing demand not only for electric buses but also for electric vehicles encourages businesses and authorities to take measures to develop and improve electric vehicle infrastructure capable of covering people's needs.

By early 2022, three types of charging are common in practice: slow, dynamic and fast charging. Not all electric buses are equipped with ultra-fast charging; some models are charged exclusively at night. Reducing battery charging times will considerably increase battery life, avoiding emergency situations and reducing the load on the power grid. This will lead to a profound optimisation of the electric bus system. Using this concept and reducing the charging time to 25-45 minutes, the need for a large number of cumbersome depots will disappear, with only "spot" stations with a minimum amount of space to keep electric buses operational. Table 2 shows the main characteristics of electric buses operating in Russia, including the charging type.

Table 2. Main characteristics of electric buses in use.

Features	Model name		
	KAMAZ-6282	LiAZ-6274	Volgabus-5270.E0
Maximum speed	70 km/h	80 km/h	90 km/h
Battery capacity	80 kW/h	77 kW/h	115 kW/h
Power reserve	Up to 70 km	80 km	200-220 km
Full charge time	25 mins (ultra-fast charging)	15 mins (ultra-fast charging)	6 hours (night-time charging)
Curb weight, t	12.2 t	18 t	12.9 t
Total capacity	85 people	110 people	90 people

The types of electric buses shown in Table 2 have different characteristics. "Volgabus" has the highest top speed, but differs from the others in type and charging speed. All models in the table have similar characteristics, but can be used in different regions depending on the type of infrastructure.

As of 2022, Russia does not have the capability to produce and use domestic batteries, but development in this area is underway. The leading companies in the development of domestic batteries are KAMAZ and OOO Liotech-Innovations. In the future, new distribution stations and transformer substations will be needed to succeed in building an optimized infrastructure.

The Chinese research team, represented by Yuping Lin, Kai Zhang, Zuo-Jun Max Shen and Lixin Miao, examining the issue of charging network planning, cites the following in their paper: "Since large-scale electricity-consuming stations will result in an intense burden on the power grid, it is necessary to consider both the transportation network and the power grid when planning the charging infrastructure." [9]. In June 2019, KAMAZ and ABB launched cooperation on the development of municipal transport infrastructure at the international economic forum, which includes the supply of new electric buses as well as charging stations. The companies have also agreed to work together to improve existing charging stations and optimise them.

Despite the challenges posed by the introduction of electric buses, the transition to green transport is inevitable. Thanks to improvements in technology and more operating experience, electric buses will be a more profitable solution than diesel buses. At the same time, the regions that are already introducing them provide the impetus for local industry development not only in the production of electric buses, but also in a number of related segments: charging stations, electric components, batteries, etc. In order to successfully develop electric infrastructure, cities, purchasers and equipment manufacturers need to adopt the experience of other companies in operating electric buses and developing related industries.

All of the above is confirmed by Norwegian scientists Rebecca Jayne Thorne, Inger Beate Hovi, Erik Figenbaum, Daniel Ruben Pinchasik, Astrid Helene Amundsen, Rolf Hagman "Since urban buses reflect a market that is almost 100% controlled by public tenders, by weighting the environment highly (reduction of GHG emissions) or requiring zero emissions, authorities can de facto push towards full electrical public transport operation" [10].

Based on extensive experience with electric transport and urban development, the following key points should be highlighted:

1. assessing the current energy and transport infrastructure for targeted electric bus solutions and adjusting the development plan. For example, with night-charging buses, the city may need to consider strengthening the power grid so that it can provide sufficient capacity to charge a large fleet of electric buses at the depot. Night-time charging also requires additional space, as a charger for each electric bus needs to be placed, as well as power converters and transmission lines at the depot.
2. Integrating the electric bus fleet with other environmentally friendly transport, taking into account their characteristics and the availability of the necessary infrastructure.
3. Switching to electric buses may require significant fleet expansion, especially with electric pantograph buses. They need to be recharged at their terminals and therefore have shorter running times. For example, on trial routes, Moscow electric buses had to use almost twice as many buses as before to provide the same service.
4. Entering into agreements with equipment manufacturers on the terms of a maintenance guarantee. This will reduce the risks associated with the use of imperfect and new technologies and allow the development of the necessary expertise in electric vehicles while working closely with equipment manufacturers.
5. Contracts with equipment manufacturers should stipulate responsibility for battery disposal. Ignoring this issue may lead to conflict between the manufacturer and the city.

The only barrier to quality recycling and disposal of lithium-ion batteries in electric buses is the near absence of recycling facilities, but this problem will be solved with greater demand for electric buses and electric vehicles. The problem is unlikely to affect manufacturers and bus fleets in the next five years; universal recycling will begin sometime in the 1930s, as batteries have a lifespan of 10-15 years.

The government monitors the development of electric buses and approves certain ordinances for development. One such decree dated 23 August 2021 includes two development phases until 2030. The key concepts for Stage 1 are: production of at least 25,000 electric vehicles; commissioning of at least 9,400 charging stations, of which at least 2,900 will be fast charging stations. Key indicators of implementation of Stage 2 of the concept are: production of electric vehicles in the amount of at least 10 percent of the total volume of vehicles produced; launch of production of cells for traction batteries as well as cathode and anode materials; commissioning of at least 72 thousand charging stations, of which at least 28 thousand are fast charging stations; commissioning of at least 1,000 hydrogen filling stations; creation of at least 39 thousand additional highly productive jobs throughout the technological

By 2025, sales of electric buses outside China are expected to reach 14,000, up from 5,000 in 2020. Many cities in China have already replaced 99% of diesel buses with electric buses, with plans to replace all diesel vehicles nationwide with electric ones by 2030. The leader in electric buses in China is BYD, which produces electric vehicles not only for sale domestically, but also for the world. In 2022, the company will send its electric buses for trials in Moscow and St. Petersburg to further develop the electric transport market.

Belarusian researcher Andrei Bezruchonak in his work raises the question of the future in the field of electrification of motor transport: "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 transpor-tation by over 70%; b) reduction of CO2 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)."[11].

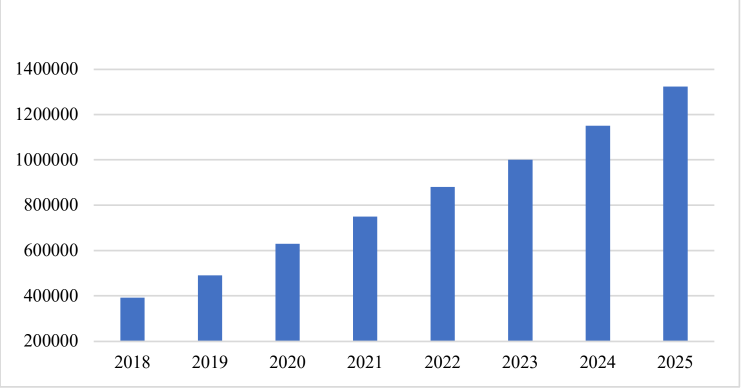

Fig. 1. Projected number of electric buses worldwide, according to BloombergNEF.

It is expected that by 2050, the vast majority of countries aiming for zero-carbon emissions will have completely switched to electric buses. Achieving this goal will require accelerated adoption of charging networks, expansion of existing power grids and the creation of a recycling structure for unusable batteries.

There is, however, the potential threat of rising prices of energy and brand new buses may be considered another threat due to the low popularity of the new mode of public transport, said Polish researcher Marcin Połom from the University of Gdańsk: "Increasing prices of energy and brand new buses could be considered another threat. The increased demands for fully electric vehicles, which are still niche products in Europe, have led to significant growth of their prices". [12]

Electric buses will have a steady growth due to the idea of reducing urban air pollution. (Fig. 1).

According to BloomberNEF, by 2040, electric buses will account for approximately 67% of the total number of buses worldwide. Electric buses will not take over the global market entirely, but they will confidently share it with hydrogen buses.

4 Conclusions

Despite the attractiveness of electric buses, the benefits in use and the minimisation of pollution, they also have significant drawbacks. This study has reviewed the statistics, compared the data and identified the following problems: partial or complete lack of infrastructure for stable operation of electric buses in most regions of Russia; lithium-ion batteries are not adapted to harsh temperatures; inability to dispose of unusable batteries; high cost of electric buses compared to diesel buses.

Based on the aforementioned challenges, the following suggestions for solutions are offered:

1. all existing routes should be studied in order to locate charging stations correctly, taking into account all territorial features. New, technologically advanced fleets for electric buses that use a night charging system are also needed. Getting rid of trolleybus power grids is out of the question; electric buses with cascade charging could well use them for recharging on the go;
2. lithium-ion batteries need to be upgraded for harsh weather conditions, or switch to a less common battery type: sodium-ion. Sodium-ion batteries are capable of storing energy at extremely low temperatures without reducing the capacity of the cells themselves;
3. development of a unified system for collection and recycling of used batteries as well as creation of private recycling companies. Construction of recycling plants all over Russia;
4. currently, the cost of electric buses varies from 30 to 40 million rubles, while the cost of diesel buses with the same capacity does not exceed 13 million rubles. This is due to the novelty of the technology. Price is a determining factor in the transition to a new type of public transport. The problem will be solved by improvements in batteries, through cheaper production of components. The price is also influenced by demand. Low demand for electric buses forces manufacturers to increase the price many times over in order to make a profit, hence, a large-scale transition to green public transport will lead to lower prices.

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