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battery electric bus, public transport, alternative drive

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URBAN PUBLIC TRANSPORT WITH THE USE OF ELECTRIC BUSES – DEVELOPMENT TENDENCIES

Summary. The programing documents of the European Union determine the direction of transport systems development, including large cities and agglomerations. The context of these actions which aim to transform into ecologically clean and sustainable transport system is a significant reduction of greenhouse gas emissions. Assuming that public transport will significantly reduce the use of combustion-powered buses, studies on urban logistic enabling the use of electric buses for public transport are needed. The article presents the variants and scenarios for electric buses implementation in urban public transport, as well as the decision algorithm to support electric bus implementation based on technological, organisational, economic and ecological variables.

TRANSPORT PUBLICZNY W AGLOMERACJACH Z WYKORZYSTANIEM AUTOBUSU ELEKTRYCZNEGO – TENDENCJE ROZWOJU

Streszczenie. Dokumenty programowe Unii Europejskiej wytyczają kierunki rozwoju systemu transportowego także w dużych miastach i aglomeracjach. Kontekstem tych działań, mających na celu przemianę systemu transportowego w transport ekologiczny i zrównoważony, jest znaczące ograniczanie emisji gazów cieplarnianych. Zakładając, że w transporcie publicznym nastąpi znaczne ograniczenie wykorzystania autobusów z napędem spalinowym, niezbędne są badania nad logistyką miejską, umożliwiające wykorzystanie autobusów elektrycznych do transportu publicznego. W artykule przedstawiono warianty i scenariusze wdrażania autobusów elektrycznych w publicznym transporcie zbiorowym oraz zaprezentowano algorytm wsparcia decyzji na podstawie zmiennych technicznych, organizacyjnych, ekonomicznych i ekologicznych.

1. INTRODUCTION

For many years, there were worldwide concerns about the impact on air pollution caused by road transport [1]. Dynamic development of road transport entails negative consequences for society. It creates a significant dependence on imported energy and fuels, resulting in transportation being more burdensome on the environment [2]. The global trend towards clean and energy- efficient vehicles is because of the concerns for fossil fuels vehicles' usage on public health, climate change and energy security of European Union states and beyond (e.g. China) [3]. Gradual elimination of conventional vehicles from cities will contribute significantly to the reduction of oil dependence, greenhouse gas emissions, local air pollution and noise pollution [4].

Despite European Union's decreasing carbon dioxide (CO_2) emissions, transport share in harmful substances emissions (CO_2, CH_4, N_2O) has increased from 8% to 10%, between 2000 and 2012 [5]. In view of this, efforts are being made to reduce the emissions of harmful substances from transport vehicles. According to the White Paper [6], a 60% cut in transport emissions will be made by the middle of the century. These objectives should be read in conjunction with the document entitled 'A resource-efficient Europe – Flagship initiative under the Europe 2020. The document states that European economic growth must be decoupled from the use of resources by reducing CO_2 emissions, promoting greater energy security, and reducing the resource intensity of what is consumed and used across the European Union [7]. Attention should be paid to the European Green Cars Initiative [8] as it is a long-term roadmap for implementation of the electric vehicle market.

Ehrler and Hebes [9] consider electromobility as one of the technologies that would contribute to the realisation of the European Union's targets presented above. Electromobility should be viewed in a systemic perspective to assess whether it is an economically viable option reducing greenhouse gas (GHG) emissions in the transport sector [10]. Market requirements expressed by passengers' expectation, as well as European Union policy on transport development and environmental protection, force research and development on technological strategies of battery charging or exchanging, and economic and organisational aspects of electric buses implementation [Fig. 1].

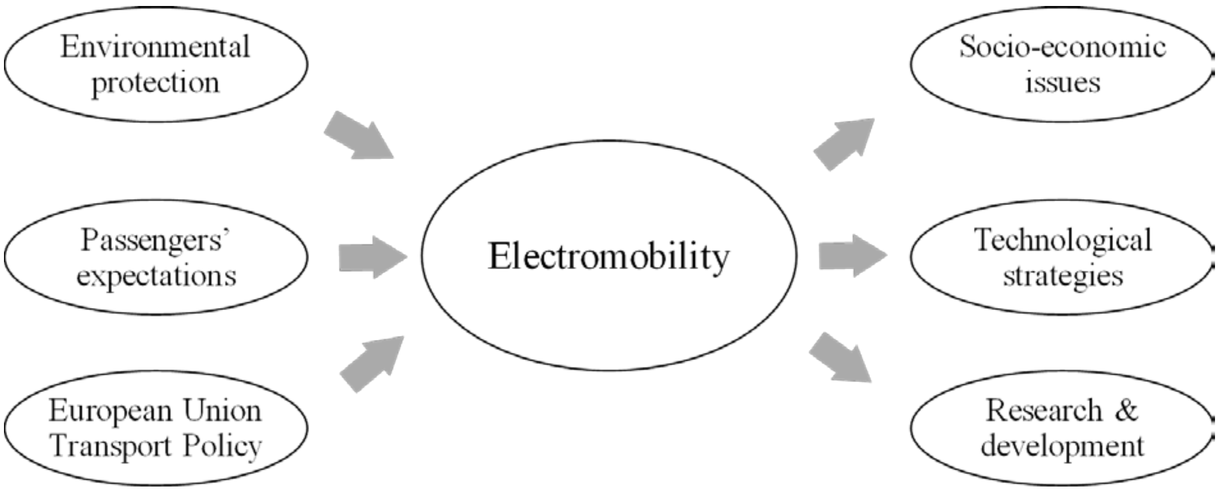


Fig. 1. Factors affecting the development of electromobility
Rys. 1. Czynniki wpływające na rozwój elektromobilności

At present, the overwhelming majority of bus fleet operated by public transport companies are conventionally-fuelled diesel buses, which are a source of toxic substances emitters [11, 12]. In 2011, European urban mobility consumed about 140 million tons of oil, and emitted about 470 million tons equivalent of CO_2 [13]. Due to the data presented in [14], any significant reduction of the impact of city public transport on the environment can only be achieved by applying alternative drive systems. Battery Electric Vehicle (BEV), may have different emission and energy advantages [15]. Electric vehicles are much more environmentally friendly, as their engines consume less energy, have greater efficiency as well as use the phenomenon of energy recovery [16]. For several years, pilot implementations of electric buses were carried out which resulted in 1.2% share of electric buses, according to the survey in [17].

2. ELECTRIC BUSES IMPLEMENTATION SCENARIOS

The decisions concerning conducting the process of electric buses implementation to urban public transport must be made by entities that provide public transport service, e.g., public transport companies. There are many problems and challenges associated with electric buses implementation in urban public transport: battery charging or exchanging stations location, choice of bus routes to be electrified, likewise questions related to electric buses implementation management. All these factors will implicate new solutions within technological, economic and organisational aspects of their business activity.

An enterprise may adopt various scenarios of fleet exchange, taking into account financial capacities and the date limits described in the White Paper [6], or another national or international strategy paper. In the White Paper, there are two important date limits: half the use of conventionally-fuelled cars in urban transport by 2030 and phase them out from cities by 2050, as well as achieving CO_2 - free city logistics in major urban centres by 2030.

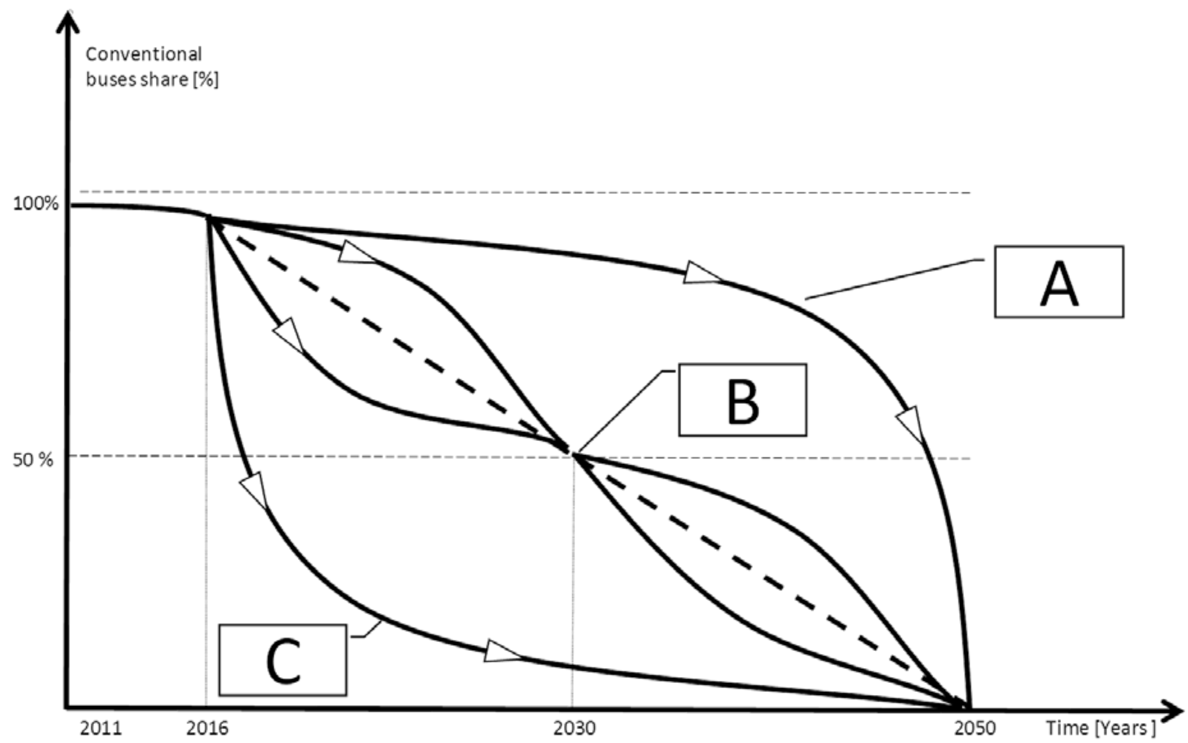


Fig. 2. Bus fleet exchange variants to be conducted by public transport companies
Rys. 2. Warianty wymiany floty autobusów, które są możliwe do przeprowadzenia przez przedsiębiorstwa komunikacji miejskiej

These two important dates are highlighted in Fig. 2, which depicts three possible scenarios of bus fleet exchange resulting in decreasing share of conventionally- fuelled buses:

- variant A – a passive scenario wherein a public transport company protracts the process of fleet exchange awaiting expected effect of electric buses' technological maturity,
- variants B – normative scenarios, assuming linear or quasi-linear financing and execution of fleet exchange wherein 50% of conventional fleet is replaced by electric buses in 2030,
- variant C – an active scenario wherein the fleet is exchanged, as soon as possible, by getting a grant for innovative, environmentally-friendly activity.

All these variants have advantages and disadvantages involving opportunities and threats, for the particular public transport company. These include perspectives to gain funding, which affects the total cost of the exchanging process, the level of fleet homogeneity in the sense of a bus brand and technological generation of the fleet, the complexity of the exchange process.

The variants A, B, and C of bus fleet exchange can be elaborated more specifically in terms of how to exchange the fleet:

- scenario I – one-off exchange to be carried out as soon as possible,
- scenario II – experimental exploitation of one electric bus to test the technology, and posterior one-off exchange of the rest of the fleet,
- scenario III – successive replacement of subsequent batches of buses,
- scenario IV – awaiting electric buses technological maturity and execution of the exchange process in the most advantageous moment.

Scenario I corresponds to the active scenario (variant A) of bus fleet exchange. In Fig. 3, exemplary characteristics ($x_n = x_1, x_2, \ldots, x_i$) of scenario I are given. There are three points put on the timeline (x- axis): x_1, x_2, and x_i that describe the moments of one-off exchange of bus fleet owned by these companies. The specific moment of the exchange differs according to organisational, technical, economic and ecological factors, defined by the local conditions in which a company operates.

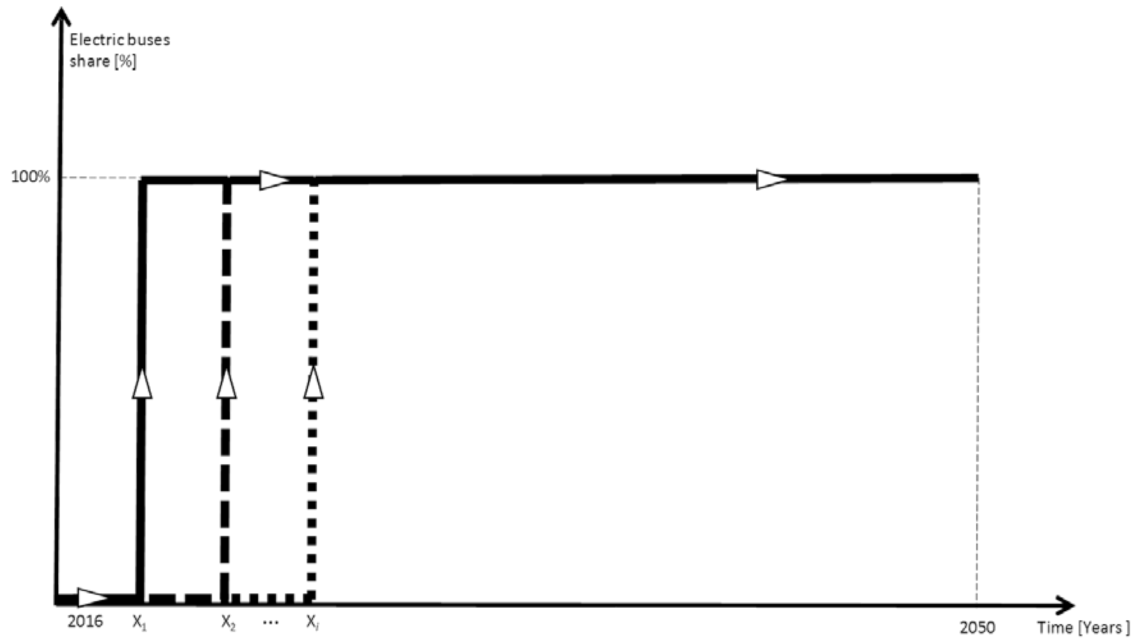


Fig. 3. Scenario I – one-off exchange to be carried out as soon as possible
Rys. 3. Scenariusz I – jednorazowa wymiana, przeprowadzona najszybciej jak to możliwe

The decision to execute the one-off replacement of current fleet by electric buses presupposes many consequences for public transport companies. As the technology is still in infancy, and further development is assumed by the industry, there is a risk that the buses acquired at initial phases of technology development will have inferior technical properties. Another threat is the risk of acquiring buses at a higher price, it is expected that the prices would decrease. This risk can be depreciated by national or international funds for innovation actions related to the implementation of environmentally- friendly technologies.

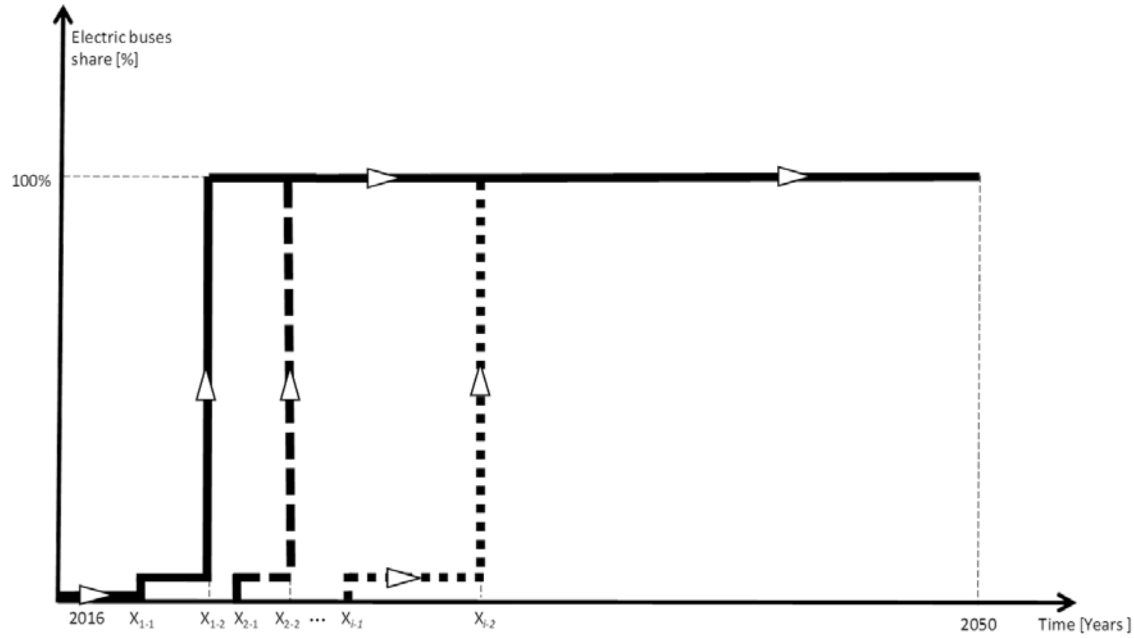


Fig. 4. Scenario II – experimental exploitation of one electric bus to test the technology and posterior one-off exchange of the rest of the fleet
Rys. 4. Scenariusz II – eksperymentalna eksploatacja jednego autobusu elektrycznego w celu przetestowania technologii i późniejsza jednorazowa wymiana floty

The excellent characteristics of scenario II, assuming acquisition of one electric bus for test exploitation and one-off posterior replacement for the rest of the fleet are presented in Fig. 4. There are two key points in each characteristic ($x_{n:(1,2)} = x_{1-1}$, x_{1-2}; x_{2-1}, x_{2-2};…,x_{i-1},x_{i-2}): the first is a moment of electric bus acquisition for experimental exploitation while another is a moment of exchange for the remaining conventional buses.

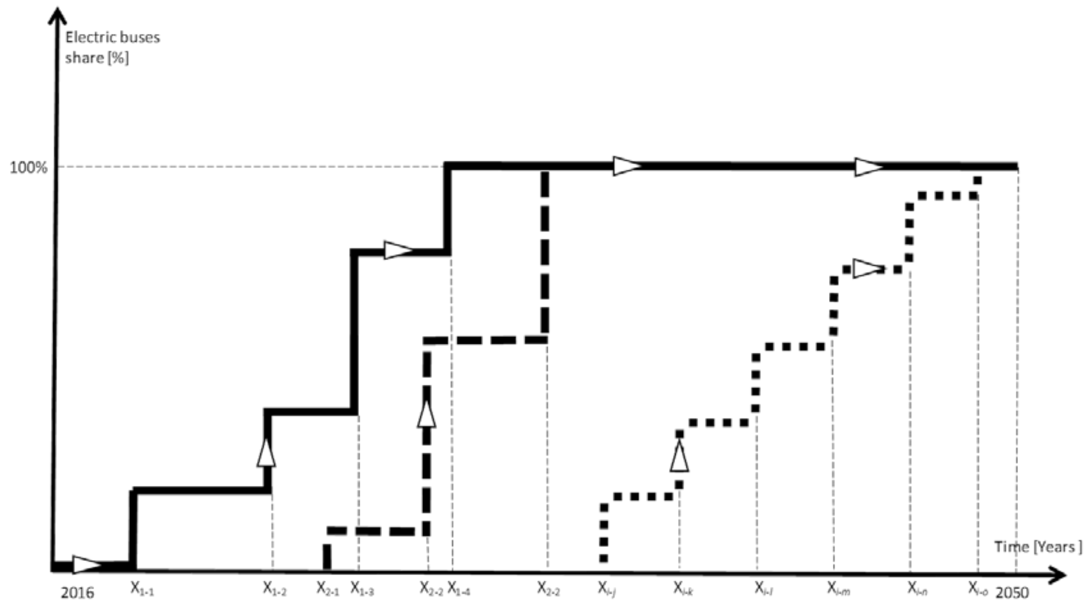


Fig. 5. Scenario III – successive replacement of subsequent batches of buses
Rys. 5. Scenariusz III – następujące po sobie wymiany kolejnych partii autobusów

Periods of time between these two moments are not constant and depend on local conditions. The choice of scenario II seems to be reasonable as it can help public transport companies to exploit technologically new buses. As a result, public transport operators could be better prepared for a huge challenge of fleet exchange.

Scenario III, which is depicted in Fig. 5, assumes successive replacement of subsequent portions of buses. This scene represents a quasi-linear variant of fleet exchange. Steps corresponding to the number of subsequent batches of buses acquisition must be subjected to analysis. It should be noted that these batches are not necessarily equal; however, there must be at least two batches to differentiate scenario III from other strategies.

Application of scenario III will probably take place in those companies where purchasing decisions depend mostly on current financial possibilities, rather than on long-term development scenario adopted. With the implementation of this scenario, an au courant company can respond to changes on the market, but at the cost of a less homogenous fleet.

Scenario IV is the inverse of scenario I, and corresponds to a passive scenario (variant C) of fleet exchange. This involves waiting for the most advantageous moment to conduct the process of fleet exchange. Such an action increases the chances to purchase more technologically-advanced electric buses, but has negative consequences in terms of propitious financing conditions. The choice of this scenario is the least environmentally friendly as conventional buses are in operation longer than they would have been if another scenario had been chosen. On the other hand, the risks from technological immaturity are the least.

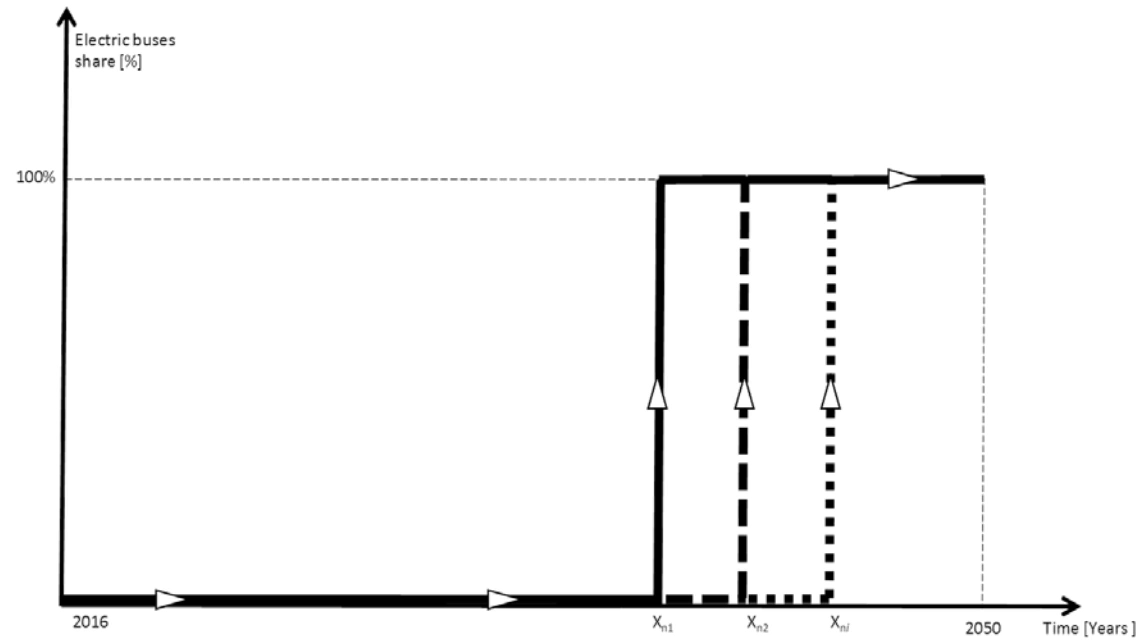


Fig. 6. Scenario IV – awaiting electric buses' technological maturity and execution of process in the most advantageous moment

Rys. 6. Scenariusz IV – oczekiwanie na dojrzałość technologiczną autobusów elektrycznych i przeprowadzenie procesu wymiany w najbardziej korzystnym momencie

The dynamics of fleet exchange process depend on public transport companies' potential as well as external financing possibilities. The company's potential volume necessary for entire fleet exchange should be examined from an economic, human and technological context. For each of the potentials, specific indicators describing the fleet exchange process can be defined. Programming particular process dynamics for a specific company can be considered as an optimisation problem.

Resource use function should be maximised:

$$F(P_e, P_h, P_t, \Delta t, \Delta z, c_l, c_e) \rightarrow \max, \tag{1}$$

P_e – economic potential; P_h – human potential; P_t – technical potential; Δt – period of time for which public support is considered; Δz – periodic financial funding from external funds; P_t – technical potential; c_l – local conditions; c_e – ecological conditions.

The formula above (1) is general definition of subsequent variables for each public transport company or public transport organiser should be made in every case. Any company owns different resources, has various potential, dissimilar financial standing as well as different local and ecological conditions.

Construction of multi-criteria decision support model for the choice of the most favourable scenario requires defining finite set *D* of investment variants as:

$$D = \{d^n : \ n = 1, \ldots, N\}\,, \tag{2}$$

where *N* is number of all variants, taking into account acceptable solutions of decision problem. The set of evaluation criteria should be defined as follows:

$$K = \{k_i : \ i = 1, \ldots, I\}\,, \tag{3}$$

where K is number of evaluation criteria. In the next step, every investment variant is to be evaluated from the perspective of each criterion.

Implementing buses with alternative propulsion to urban public transport is a long-lasting process which can be supported by the simulation [18]. Development of specialised computer programs based on decision support algorithms is predicted. These programs should also be concerned with the issue of implementation strategies, based on variants and scenarios presented in this paper. An algorithm example of a decision support programme is presented in Fig. 7.

As neither technical approach being offered in the market, nor implementation scenario presented in the article will be suitable for all public transport companies, a precise definition of local conditions should be made. Transportation model should analyse the bus route network including topography of the road network sections, bus stops and bus depots localisations, bus schedules and vehicle operation plans. The model will be subject to significant fluctuations, depending on the nature of public transport network.

Collection of these data is necessary for analysis in the technical model, which contains all the information about characteristics of professional vehicles, e.g. driving unit, energy consumption, behavioural characteristics (driving style) and charging strategy are to be defined at this stage. The technical model should also collect and process information about the current allocation of buses to routes. The aim of the technical model is to optimise:

- vehicle allocation to specified schedule,
- strategy for battery recharging or replacement,
- location of charging and switching stations,
- possible variants of the fleet (mixed or fully electric).

The output is the optimal distribution of charging and switching stations, optimal strategy for battery recharging or replacement for either full electric bus variants, or mixed fleet.

From this point, the analysis should be conducted collaterally taking into account the balance between the economic and ecological aspects. The goal of the green model is to analyse the impact of proposed solutions (both local and global) on the environment, especially its compliance with European laws on air quality, based on fleet composition. The goal of the economic model, however, is to evaluate acquisition, infrastructure, operational and external costs.

The final stage of the decision algorithm is to decide whether an analysed solution should be accepted or not. If the outcome of the model is unsatisfactory, the procedure should be repeated beginning from defining new input data, looking for another variant of electric buses implementation in urban public transport company. The feedback should be repeated until an acceptable solution is found, and approved solution implemented by public transport company.

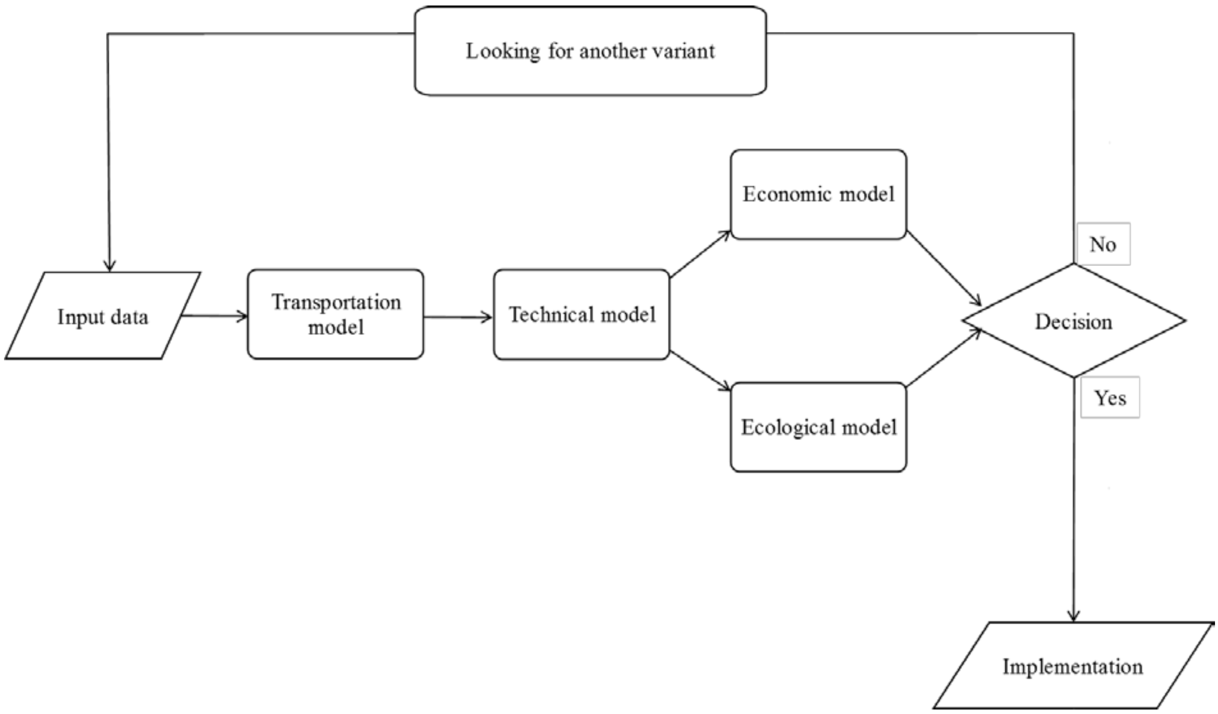
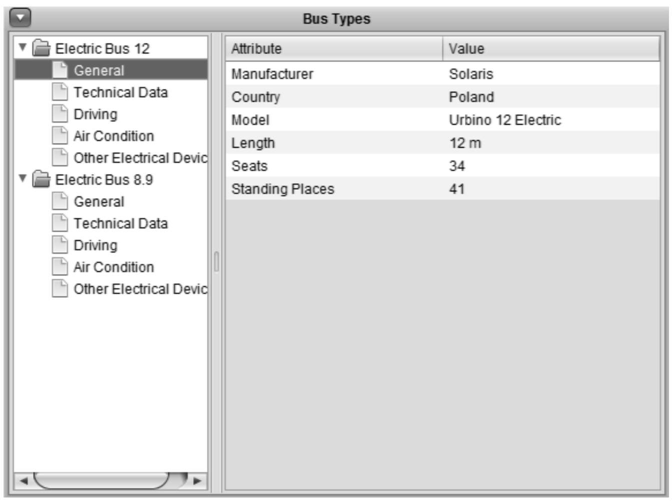


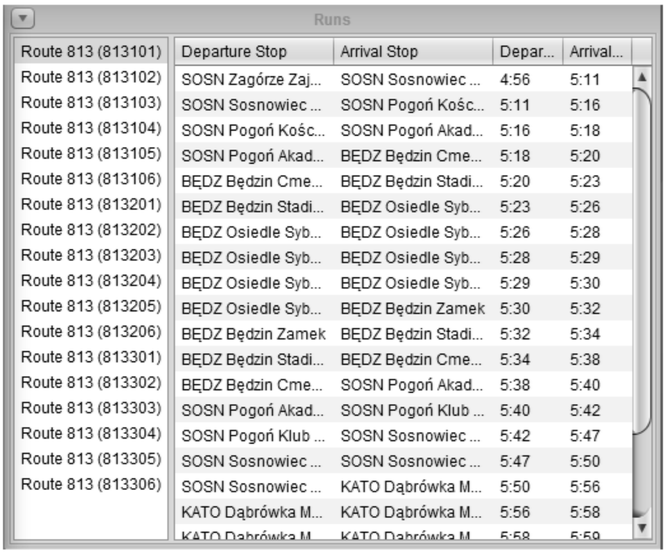
Fig. 7. The decision algorithm to support electric bus implementation
Rys. 7. Algorytm wsparcia decyzji w sprawach związanych z wdrażaniem autobusów elektrycznych

3. VALIDATION OF THE METHODOLOGY

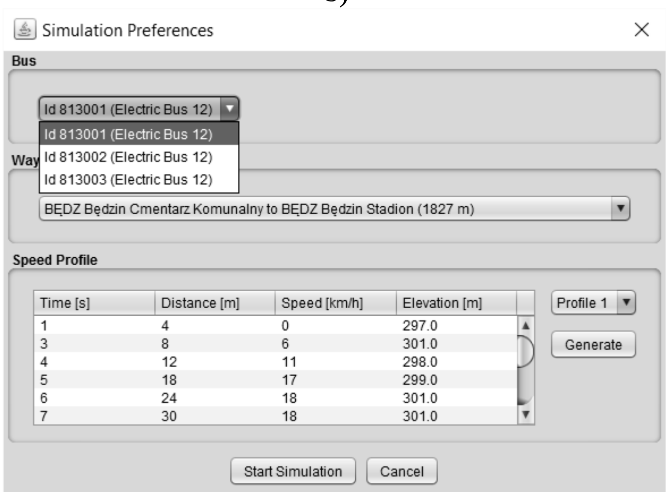
The method has been validated under Era-Net Electromobility+ international scientific project CACTUS in cooperation with Polish public transport company PKM Sosnowiec that provided the data. The authors have analysed bus line No. 813, which is 35 km, and is operated by three vehicles a day. This bus line is a roundabout line that runs only on weekdays to and from Katowice Piotra Skargi, via Sosnowiec and Będzin. It is one of those considered for electrification in the future. The calculations were conducted in the CACTUS tool.



a)



b)



c)

Fig. 8. The interface of CACTUS tool
Rys. 8. Interfejs narzędzia CACTUS

The technical characteristics of Solaris Urbino 12 Electric for which the calculations were carried out are presented in Fig. 8-a, a snippet of the bus schedule is presented in Fig. 8-b and a fragment of distance, speed and elevation profiles of the bus are presented in Fig. 8-c. The above are the print screens of the CACTUS tool.

The process of fleet exchange will be conducted in accordance with Scenario II [Fig. 4] that assumes experimental exploitation of one electric bus to test the technology, and posterior one-off exchange for the rest of the fleet. A twenty-year lifetime for a bus and a seven-year lifetime of a battery are assumed. The loan repayment period is eight years.

Fig. 9 depicts the comparison of costs generated by both types of buses: electric and diesel. In this case, electric bus operation involves increased expenses for public transport company. The total includes costs of acquisition, operations, external resources, and infrastructure. In Fig. 9, one can see two sharp changes in costs generated by electric bus, occasioned by acquiring two extra batteries after 7^{th} and 14^{th} year of exploitation.

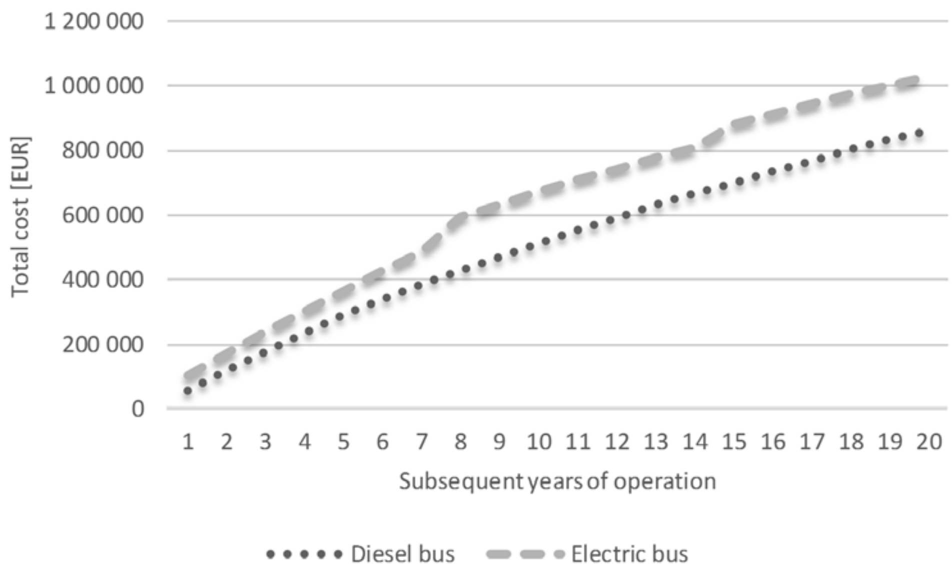


Fig. 9. Cost comparison generated by electric and diesel bus in subsequent years of operation
Rys. 9. Porównanie kosztów generowanych przez autobus elektryczny i autobus z napędem Diesla w kolejnych latach eksploatacji

4. SUMMARY

It seems that under the current passengers' expectations, increasing ecological requirements and European Union transport policy, the process of replacing buses from conventionally-fuelled to electric ones is inevitable. There is, thus, a challenge of how to introduce new types of buses in an optimal way.

The process of electric bus implementation is complex, in terms of technical, transport, economic and ecological issues. These issues have a significant influence on the choice of bus fleet exchange variant and scenario. Local conditions considered in technological, human and economic senses are significant to select optimal variant and scenario of the fleet exchange process.

Due to the multitude of variables affecting the process of fleet exchange, decision support algorithms development is expected. The algorithm which is presented in the article can provide technical, operational, ecological and economic data to public transport operators and organisers to ensure an optimal method of electric buses implementation in urban public transport.

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