Dynamic charging of electric buses as a way to reduce investment risks of urban transport system electrification

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Abstract. Night charging and fast charging are currently the two most common systems for charging electric buses. Despite the fact that numerous trial installations were started, neither of these two systems has obtained unqualified approval of the users. The alternative is to charge vehicles in motion - dynamic charging which combines the advantages of trolleybus transport and of electric buses. One of the advantages is the reduction of risks associated with the electrification of urban transport. The investment in the construction of the traction network allows you to reduce the costs associated with the purchase and replacement of traction batteries, as well as increase the flexibility of the transport system. The article presents the financial benefits resulting from the use of a dynamic charging system.

Keywords: Electric bus, trolleybus, traction batteries, dynamic charging, in motion charging, LCC, investment risk

1 Introduction

Despite the continuous development of electrochemical batteries technology and the multitude of electric buses on offer, it is still not possible to exploit electric buses in urban transport on all-day basis without the necessity of charging them. Therefore it is necessary to build point-to-point contact charging stations or induction charging stations at the terminals. This results in substantial financial outlays connected with the construction of charging stations, and in the necessity to extend the stopping time at the terminals; there are also problems which arise in the situation where the route is changes. The alternative solution is the so-called Dynamic Charging, also called In Motion Charging (IMC). It consists in building an infrastructure allowing for charging vehicles in motion, most often with the use of overhead contact line (Fig. 1) [1 - 3]. What is more, in the cities where tram network is already exploited, there is a possibility to use the elements of the tram infrastructure when constructing the catenary for the Dynamic Charging system.

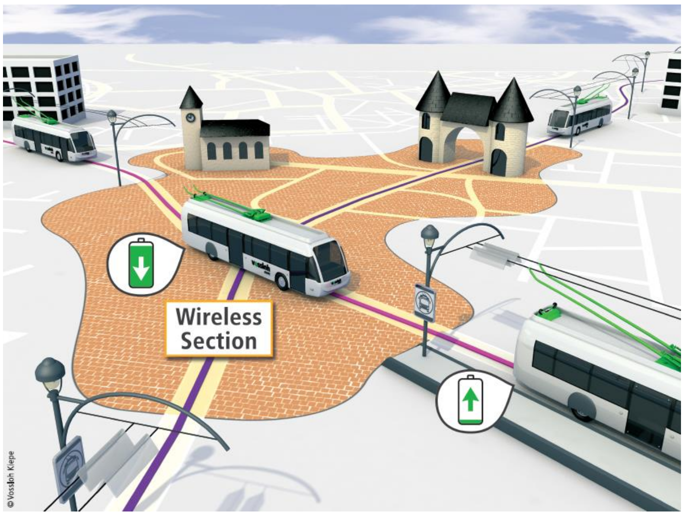

Fig.1. The idea of In Motion Charging system (IMC) [© Vossloh Kiepe]

In the dynamic charging system, part of the route is covered with a trolleybus traction network, which allows for the charging of traction batteries during movement (Fig. 2). The vehicles cover the rest of the route, i.e. the part in which there is no contact line, using traction battery power. This allows for the charging of the vehicle without stopping, increasing the flexibility and functionality of the system. In addition, covering a section of the route with a traction network reduces the length of the route to be travelled in battery mode, which in turn allows for a reduction in the capacity of the traction batteries.

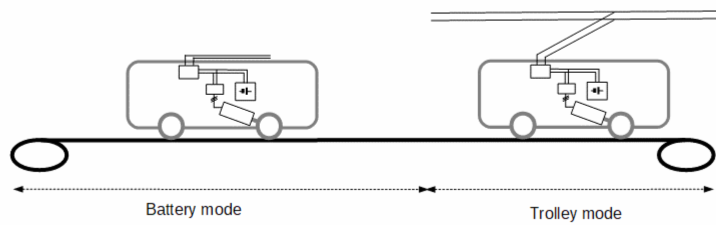

Fig. 2. Idea of dynamic charging system (In motion charging)

The construction of a traction network is associated with significant financial outlays and is the most expensive element of dynamic charging system. For this reason, it is advisable to limit its length. The length of sections accompanied by contact line must be sufficient to charge the traction batteries with energy at least equal to the energy necessary to cover the catenary-free section. With currently used vehicles, the minimum degree of coverage with the traction network is at a level of 40% - 50% [3]. This value can be reduced by increasing charging power to 25%. In the case of a supply system of 750 V DC it is possible to decrease this rate to 20% [1-3]. In the case of a reduction in the heating power of the vehicle or use thermal pumps, it is possible to reduce the degree of coverage below 20%. Fig. 3 shows an estimation of the minimal coverage rate in function of charging power, based on, the energy consumption for a standard vehicle was assumed to be 3 kWh/km (winter) and, correspondingly, for an articulated vehicle 3,9 kWh/km [1].

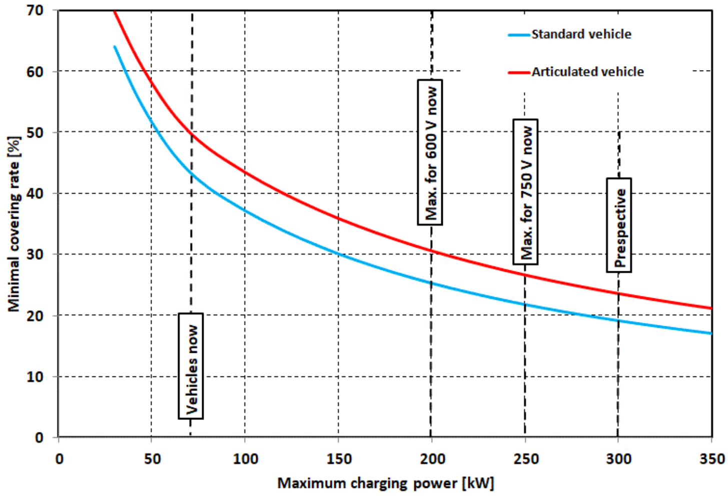

Fig. 3. Minimum catenary coverage in function of maximal charging power [1]

2 The benefits of dynamic charging

The benefits of using dynamic electric bus charging will be illustrated by an example of line with a length 10 km, which is operated by standard length electrical buses. Maximal energy consumption at the level 3 kWh/km is assumed.

There are analyzed 3 alternative systems of line electrification (Fig. 4):

- operation by standard electrical bus with one charging station and Terminus 1. The charging power is 400 kW,
- operation by dynamic charged battery bus with one 3 km wired section (variant 1),
- operation by dynamic charged battery bus with two wired sections: 1 km and 2 km (variant 2).

The average charging power of dynamic charging system is 140 kW, the average velocity in wired section is 20 km/h. The minimal charge level is assumpted at 50%. It table x there are shown the energy balances of analyzed variants. In case of standard battery bus the maximal discharge level is 60 kWh. With a minimal discharging rate 50%, this requires a 120 kWh traction battery. In fist variant of dynamic charged bus the battery is discharged with energy 42 kW, what allows the required battery capacitance to 84 kWh. In the second variant battery is maximally discharged with power 15 kWh. As a result of that, the traction battery with capacitance 30 kWh will be enough to fulfill transportation route conditions. The Fig. 5 presents the graph of battery charge level of analyzed variants.

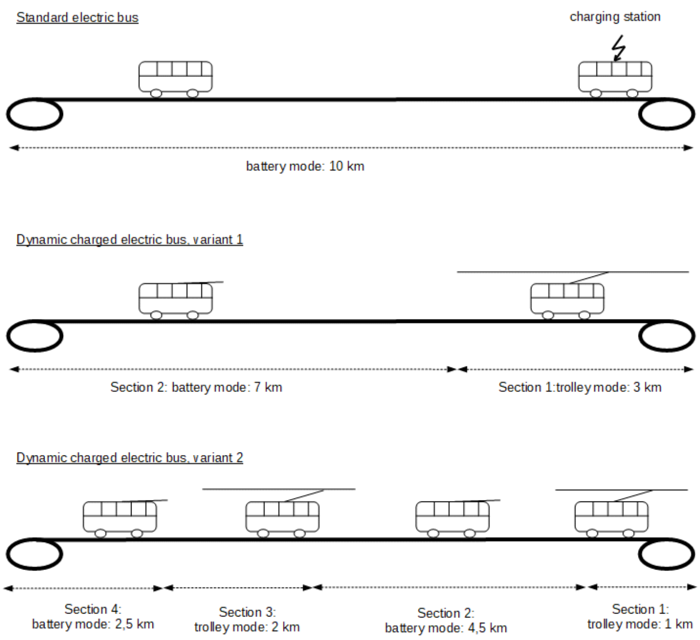

Fig. 4. The scheme of an example of route operated by standard electrical bus and two variants of dynamic charged buses

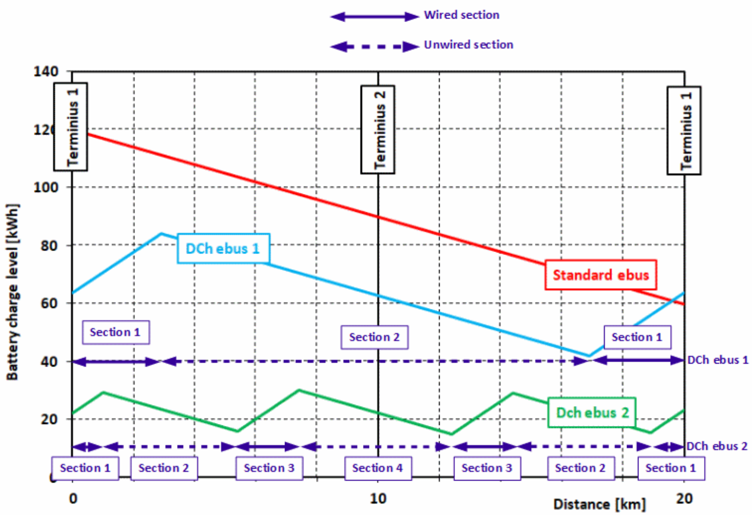

Fig. 5. Diagram of battery charge level during operation of route by standard electrical bus and two variants of dynamic charged buses

Covering part of transportation route allows to reduce the required traction battery. The capacitance reduction is bigger in case of using more than one wired sections. This allows to alternate work in mode charging - discharging - charging - discharging. Thanks to this, the depth of discharge is significantly reduced. Considering that the price of the battery is 1000 to 1500 euro for 1 kWh of capacity, the use of overhead contact line saves 90 000 euro on one vehicle. In addition, the dynamic charging system does not require stops for charging the vehicle, therefore the number of vehicles necessary to operate the line is smaller than in the classic electric bus.

Stationary charging involves the necessity to stop the vehicle while it is being charged so for charging time vehicle is unavailable for user. Time is money - so we are losing money while vehicle is charged. What is more, it may result in the need to increase the number of vehicles necessary to operate the line. The table presents the exemplary charging times when we operate route 15 km and charging stations are localized at both terminuses.

Table 1. The comparison of charging time of electric bus with opportunity charging system

Type of vehicle	Charging time*
12 m vehicle	9 min.
15 m vehicle	10 min.
18 m vehicle	12 min.
24 m vehicle	16 min.

** Assumed energy consumption Energy consumption: 2,2 - 2,6 - 3,2 - 4 kWh/km*

3 The elements of risk in transportation systems with electric buses

Electric buses are a relatively new means of transport, so there is not enough experience in operation. The electric vehicle market is developing very dynamically and it is very difficult to determine trends in changes in the purchase price of electric vehicles in the future. In addition, there is no experience related to the operation of traction batteries with a large capacity. The key factor here is the battery life, which is currently difficult to assess. As a result, there is a high risk associated with the entry into service of this kind of transport. The following main elements of risk can be distinguished:

- the risk related to the purchase price of new vehicles,
- the risk related to the cost of replacing the battery,
- risk related to traffic congestion and its influence on charging process.

3.1 The risk related to the purchase price of new vehicles and the cost of replacing the battery

.Currently, the cost of the battery can be up to 50% of the vehicle price. Moreover, during the entire lifetime of the vehicle it will be necessary to replace the battery at least once. A decline in battery price can be expected, but the size of the reduction is very difficult to assess. What is important, the increase in the development of electromobility and the increase in demand for energy storage can negatively affect the battery prices. What's more, for example in Poland the increase in interest in electric buses has caused their prices to rise recently.

3.2 The risk related to traffic congestion and its influence on charging process

Stationary charging requires an increase in the number of vehicles servicing the transportation line due to the need to provide an adequate time reserve for vehicle charging. This results in an increase in the number of vehicles in service and the number of drivers. This additional cost is difficult to estimate due to the differing ways of organizing driver service in various transport systems, but currently the cost of drivers accounts for up to 50% of all maintenance costs of the transport system. Thus even a slight increase in the number of rolling stock can cause a significant increase in costs. For this reason, this factor can also be treated as a random element.

The necessity of stopping the vehicle during the time of charging is of primary importance in the context of traffic disturbances caused by traffic congestion. They cause a delay in the arrival time to the final stop (Fig. 6), which shortens the time left to recharge the vehicle. In the case of stationary charging, this may cause situations where the remaining stop time is too short to charge the vehicle and it becomes necessary to use on the reserve vehicle. An exemplary situation is shown of Fig. 7.

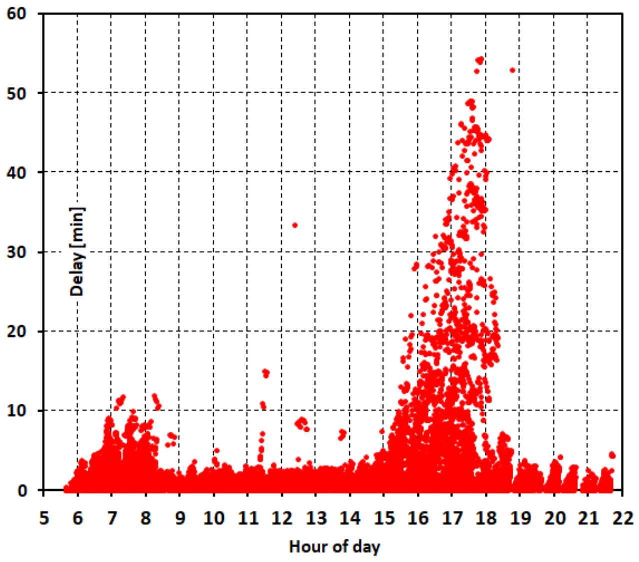

Fig. 6. Examplary delays of arrival to final stop on bus route

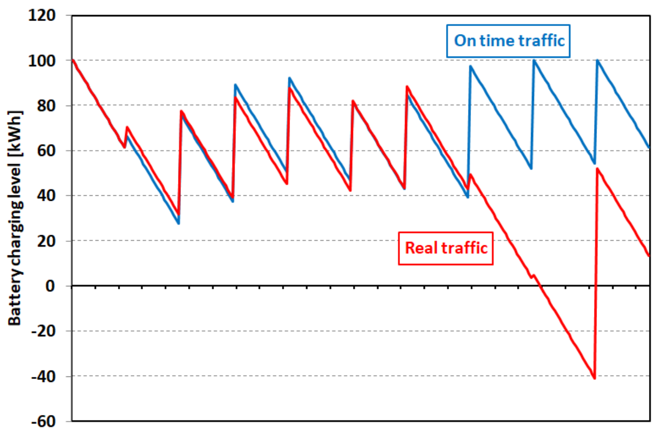

Fig. 7. Influence of traffic delays on battery bus operation - during peak hours delays can cause reduction of stopping time, which can be too short for fully charging

4 Financial analysis of the IMC system

The biggest difference between stationary charged electrical buses and dynamic charged electrical buses from the economic point of view is the cost structures – with the latter having a higher level of fixed costs and a lower level of variable costs.

In order to compare the costs of stationary charged buses and dynamic charged buses a financial analysis was done – analysis of costs, including maintenance costs and costs of assets. A financial comparison of stationary charged electric buses and dynamic charged electric buses will be carried out on the basis of a discounted life cycle cost analysis - LCC. It shows total discounted costs (infrastructure and vehicle):

$$NPV = C_i + \sum_{n=1}^{n=T} \frac{C_{op}(n)}{(1+r)^n} - \frac{SV}{(1+r)^T} \quad (1)$$

where:
C_i - initial costs,
T - entire period of analysis,
n - given time periods (years),
i - financial discount rate.
$C_{op}(n)$ - operational costs in a given period n (year),
SV - residual value of infrastructure and vehicles after period T of analysis.

The purpose of the financial analysis was to find the extreme life cost values for various input values: the purchase price of a new vehicle, the price of battery replacement and the impact of traffic conditions on the charging process. To analyze the varied settings of given input data parameters, the Monte Carlo Statistics modeling method was used. The Monte Carlo method is based on the continuous repetition of a statistical experiment, which performs an analysis of the condition of the object using random input factors. The result is a distribution of probability of the output variable. The simulation model is based on the randomized input data:

- price of purchase of the new vehicle,
- price of exchange of the battery during lifetime of the vehicle,
- additional charging time caused by traffic delays.

The schematic diagram of testing the impact the parameters on LCC by means of Monte Carlo method has been presented in Fig. 8.

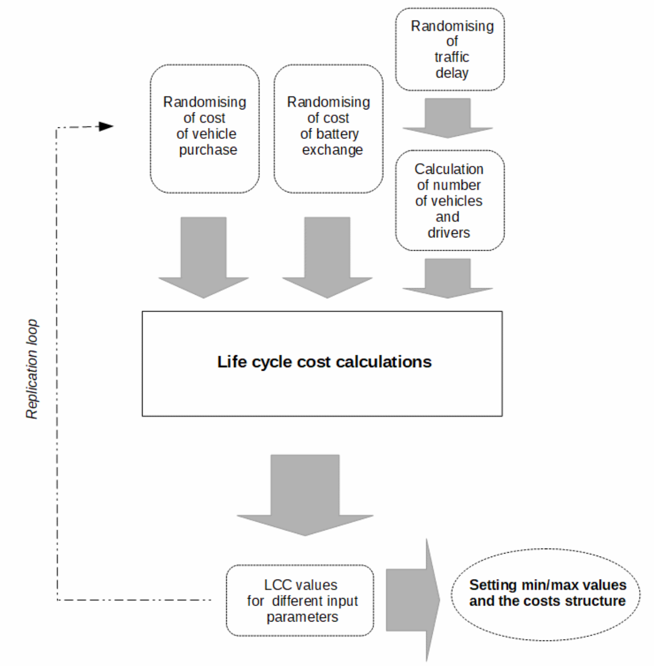

Fig. 8. The scheme of Monte Carlo calculation model

The investment and operational costs are shown in table 6.1. The cost of battery is the most uncertain element influencing the life cycle costs of transportation systems. The actual price of battery storage systems can be estimated at level 1 000 euro / kWh [4]. In 2017 a 25% reduction in battery price was observed. If this trend continues, the price of battery systems may decrease several more times. On the other hand, many experts are of a different opinion [4]. For this reason, the risk analysis assumes a drop in the price of the battery to 25% of the present value in the optimistic variant and maintenance of the current prices in the pessimistic scenario. Due to the lack of experiences in the field of battery systems lifespans, one and two battery changes were assumed during the lifetime of the vehicle (number of battery exchange was also randomized).

Another element with a randomly determined value is the purchase price of a new vehicle. The reason for this is the fact that in the currently dynamically changing market of electric vehicles it is very difficult to determine the purchase price of an electric bus.

The third factor of random character taken into account in the simulation model was the impact of traffic congestion on the charging process. In the case of static charged electric buses there is a need to ensure a guaranteed charging time at end points. This increases the required number of vehicles and the number of drivers. This charging time is influenced by random road congestion conditions and the organization of work by individual transport operators. For this reason, it should also be considered as a random factor. The maximum increase in the number of vehicles due to charging time k_{charging} can be expressed as:

$$k_{charging} = \frac{2 \cdot T_r + T_{charg}}{2 \cdot T_r + T_{res}} \tag{2}$$

where:
- T_{r} - driving time in one direction,
- T_{charg} - required charging time,
- T_{res} - time of minimal break at final stop.

The minimal value of k_{charging} is 1, which means no need to ensure additional charging time. Charging station is localized on the one terminus. The value of k_{charging} was randomizing between the value calculated according to (2) formula and 1.

The calculations were made with the following additional assumptions:

- share of rides in peak hour is set at 25%, which is used to estimate the number of vehicles needed to serve the connection [4], lower share of rides in peak hour means that less vehicles are needed to serve the line, which influences total costs; share of rides in peak hour is defined as relative to the increasing frequency of transportation in peak hours in comparison to average all day frequency;
- 3 rush hours per day were assumed;
- number of workday equivalents per year is set at 310 [4], which equals 255 workdays and 110 non-workdays, with 50% daily supply of workdays;
- rolling stocks reserve at 10%,
- two ways of electrification by dynamic charging were compared: variant 1 (DCh ebus 1) and variant 2 (DCh ebus 2) according to fig. 5.

The influence of battery cost reduction is presented in Fig. 9. The calculations were made with an assumption of the same vehicle price for standard electric bus and dynamic charged electric bus 1 800 000 PLN. Figures 10 present life costs analysis and risk value of life costs for 20% coverage rate by catenary and traffic interval 8 min. Calculations were made with assumptions presented in table 2. The structure of costs is presented on Fig. 11 It should be summed up that the investment in the traction network allows to reduce risk related to operating costs. This benefit is particularly visible in the high frequency of running vehicles.

Table 2. The investment and operationl cost of electric buses (C - certain cost, U - unceitain cost, HU - highly urceitain cost, S - static charged bus, D - Dynamic charged bus) [4, 5]

		Type of costs	Applicable for	Value, min. and max. values	Annotation
Investment costs	Vehicle purchase	U	S, D	Standard electric bus: 300 - 500 k EUR DChar Bus, variant 1: 350 - 550 k EUR DChar Bus, variant 2: 325 - 525 k EUR	- max. price: actual results of tenders and market analysis - min. price: assumption 75% reducing of battery price
	Traction substation	C	D	300 k EUR	actual results of tenders
	Overhead catenary	C	D	300 k EUR/km	actual results of tenders
	Charging station	C	S	300 EUR	technical analysis
Operational costs	Drivers personal costs	U	S, D	0,7 EUR/km	
	Battery exchange costs	HU	S, D	Standard electric bus: 35 - 150 k EUR DChar Bus, variant 1: 25 - 100 k EUR DChar Bus, variant 2: 10 - 40 k EUR	- max. price: assumpted pride 1 k euro /kWh - min. price assumption 75% reducing of battery price - the calculation were made for two variants: battery exchange one time and twice per vehicle lifetime
	Vehicle maintenance cost	U	S, D	0,30 EUR/km	
	Overhead catenary maintenance cost	C	D	25 k EUR/km	
	Energy	C	S, D	0,08 EUR/kWh	

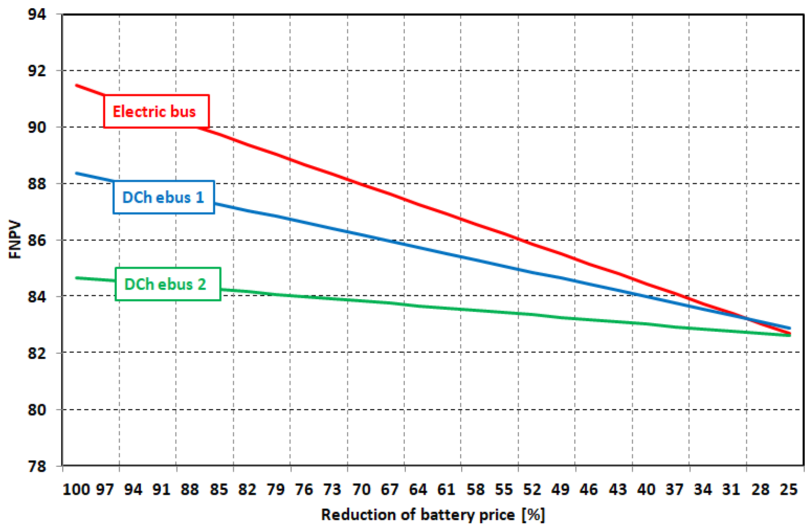

Fig. 9. Influence of the battery price reduction on life cycle cost (mln PLN) with assumption of one exchange of battery and transportation route interval 8 min

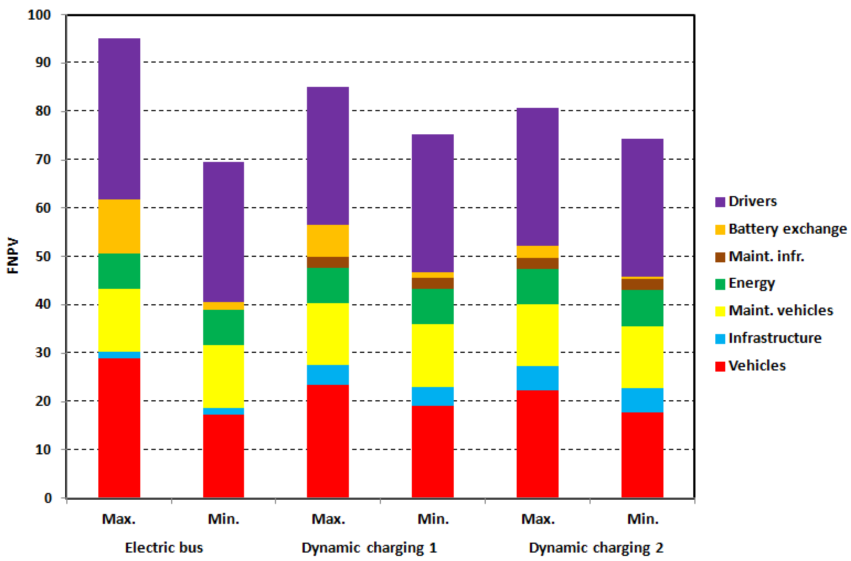

Fig. 10. Life cost analysis (mln PLN) with assumption of 20% coverage of transportation route by overhead wires (in case of dynamic charging) and transportation route interval 8 min

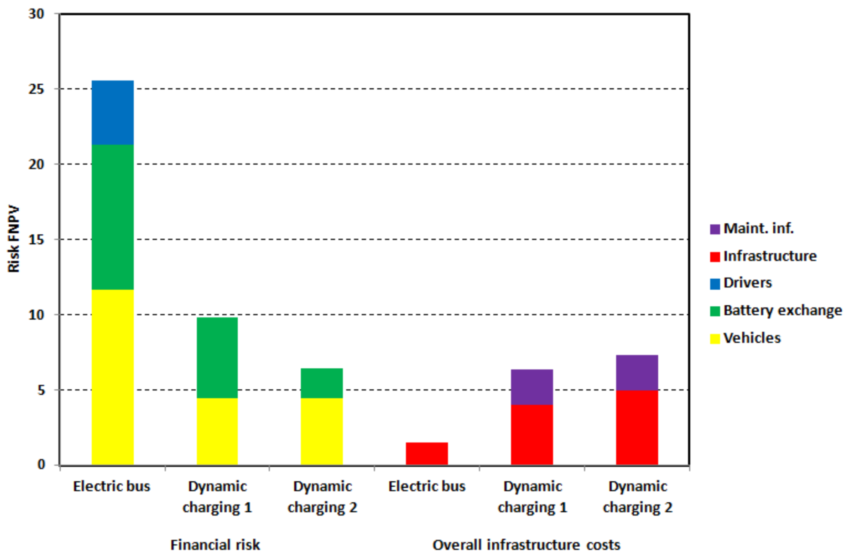

Fig. 11. Analysis of life cost risk (mln PLN) with assumption of 20% coverage of transportation route by overhead wires (in case of dynamic charging) and transportation route interval 8 min

5 Conclusions

Despite the fact that the number of cities exploiting electric buses in urban transport is increasing, the existing systems are test systems, and there is still no agreement among the users with regard to an optimal and universal solution for electric buses. The issue of charging is one of the biggest problems. On the other hand, trolleybus transport in numerous cities is considered to be outdated. Dynamic charging makes it possible to combine the advantages of trolleybuses and electric buses.

The main financial benefits of dynamic charging system are shown on Fig. 10 and Fig. 11. By investment in infrastructure (right side of Fig. 11) we can reduce the risks associated with costs of batteries and influence of traffic congestion on charging process (left side of Fig. 11). The battery price is up to 50% of the purchase price of a new vehicle. Taking into account the dynamically changing market of electric vehicles and the battery life which is difficult to determine, the costs associated with the purchase and replacement of batteries are an important source of financial risk. Thanks to covering the route with the traction network it is possible to reduce the size of the battery, and thus reduce the risk associated with their replacement.

The high cost of traction network construction is perceived as the main disadvantage of dynamic charging systems. However, it should be noted that it is incomparably smaller than the infrastructure costs for tram lines. What's more, the trolleybus overhead contact line for dynamic charging systems has a simpler structure than the classic trolleybus network, because there is no need to build crossing. This significantly reduces the price and makes it competitive for stationary charged electric buses.

Acknowlegment

The research was funded by a grant from the Polish National Science Centre (No. 2016/23/D/HS4/03085)

References

1. Bartłomiejczyk, M.: Dynamic charging of electric buses. De Gruyter Poland, Warsaw (2018).
2. Lenz, E.: Electric bus with IMC from Kiepe Electric: Reliable, simple and more cost effective", Fachmagazin V+T Verkehr und Technik, editions 8 + 9 (2017)
3. Bartłomiejczyk, M.: Practical application of in motion charging: Trolleybuses service on bus lines. In: 18th International Scientific Conference on Electric Power Engineering, 17-19.5.2017, Kouty nad Desnou, Czech Republic (2017)
4. Wolański M.: Economic Efficiency of Trolleybus Transport. In: Wołek M., Wyszomirski O.: The Trolleybus as an Urban Means of Transport in the Light of the Trolley Project, Wydawnictwo Uniwersytetu Gdańskiego, Gdańsk (2013)
5. Lindgren L.: Full electrification of Lund city bus traffic. A simulation study, Industrial Electrical Engineering and Automation, Lund Institute of Technology, Lund (2015),