Applied Energy 377 (2025) 124585

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Electrifying the bus network with trolleybus: Analyzing the in motion charging technology

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HIGHLIGHTS

- the battery cost is a key element of the operating costs of the transport system,
- investing in infrastructure allows to reduce the demand for batteries,
- IMC: it is sufficient to cover only 25–35 % of the route by the trolleybus catenary,
- the technical conditions for the IMC charging corridor were determined,
- the impact of traffic congestion and battery aging process were taken into account

ARTICLE INFO

Keywords:
Electric bus
Electromobility
Trolleybus
Bus rapid transit system
Battery degradation
Open-sesame

ABSTRACT

Currently, electric buses are becoming more and more popular, and their number in operation is increasing. The range of electric buses is also increasing and solutions that seem to be working almost without fixed infrastructure are being promised. However, this requires the use of high-capacity batteries, which increases the weight and price of the vehicle and causes high costs of battery replacement during operation. Moreover, if we take into account the growing demand for batteries, limited raw material resources, and the environmental impact of the battery production process, the optimization of battery capacity in vehicles may turn out to be a key issue. In this light, trolleybus becomes a sustainable and economically efficient bus electrification technology, if considered in an international scope and a medium- to long-term approach. The article provides a comprehensive study of challenges and potential solutions related to electric buses, which covers the theoretical analysis, technical aspects and practical applications, thus making a valuable resource for readers interested in sustainable urban transport systems. It presents the trolleybus technology, especially with modern solutions, as a sustainable and economically efficient tool for bus electrification. The article shows that the In Motion Charging (IMC) system reduces the need for high-capacity batteries under 100 kWh, which allows to extend their service life up to 15 years and, consequently, to reduce the number of buses needed for operation. The research was based on real measurement data from the transport system in Gdynia (Poland).

1. Introduction

The cost of the battery is a significant part of the purchase cost of an electric vehicle, reaching up to 40 % of its price, and is the main reason for price difference between a combustion engine vehicle and an electric vehicle. Moreover, if the subsequent replacement cost is also taken into account, the cost of batteries can be a key component of the total cost of a transportation system. Therefore, taking into account the increase in the use of electric buses in transport and the increase in demand for batteries, optimizing the battery capacity in buses can be considered a key issue for urban transport.

1.1. Stationary charging and IMC charging

Electric bus battery charging can be realized in two forms: opportunity (OPP - Opportunity charging system) and overnight (ONC - Overnight charging system), which differ in terms of travel range and charging time [1]. The OPP charged electric bus has a smaller battery package that offers a limited range (10–20 km) and its full charge

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https://doi.org/10.1016/j.apenergy.2024.124585
Received 22 May 2023; Received in revised form 29 July 2024; Accepted 24 September 2024
Available online 1 October 2024
0306-2619/

Nomenclature

BRT	Bus Rapid Transit system
C-rate	battery current rate
DDM	Data Driven Model
DOD	Depth of Discharge
ECM	Equivalent Circuit Model
EFC	Equivalent Full Cycles
HVAC	Heating, Ventilation, Air Conditioning
IMC	In Motion charging system
LFP	Lithium iron phosphate
LTO	Lithium-titanate batteries
NMC	Nickel Manganese Cobalt
OHL	Overhead line (trolleybus catenary)
ONC	Overnight charging system
OPP	Opportunity charging system
SM	Semiempirical Model
SOC	State of Charge
SoH	State of Health
SoR	State of Resistance

(80–100 %) can be achieved within 5–15 min. In contrast, the ONC electric bus contains a relatively large battery package with a range of up to 250 km and a has much longer charging time (2–4 h). Despite their popularity, these main solutions have many disadvantages, mainly high battery cost (ONC) and limited flexibility (OPP). Batteries used in OPP systems usually have a capacity of 80–200 kWh, but due to additional requirements, e.g. high charging power, their capacity in some systems may increase up to 400 kWh [2]. In the ONC system, due to longer driving distance, the required capacity is larger, of even 800 kWh.

When comparing the total life cost of the operation of a bus line with electric vehicles, the cost related to batteries plays a key role [3]. Therefore, the cost of infrastructure construction and the cost of replacing batteries, taken jointly into account, are crucial when designing the bus electrification system [4].

Along with the battery cost, the bus line electrification cost may also involve the cost related to the increase in the number of vehicles necessary to operate the bus line. In the case of stationary charging, adequate time for charging should be provided, which involves the need to shut down the vehicle during the charging process [5]. This may result in the need to provide additional vehicles. What should be emphasized, is that the vehicle purchase cost and the personnel cost (bus drivers) also constitute a significant part of the total cost of an electric bus [6,7,8]. The need to provide additional vehicles for charging times increases these two costs.

In urban traffic conditions, ensuring the sufficient charging time is difficult due to the impact of traffic congestion, i.e. traffic delays caused by very stochastic nature of the urban transport [9-11]. Traffic delays can decrease the bus downtime at final stop and, consequently, the time available for battery recharging [12-14]. In the case of stationary OPP charging, this leads to the reduction of the amount of energy which can be delivered to charge the vehicle, and possible inability to recharge it to the full during the stop. As shown in [15,3], even with a large number of bus charging stations, insufficient battery charging can occur, which leads to disturbances in the transportation system (the necessity of using additional vehicles, or a delayed departure from the charging station). For this reason, in many situations, the operators of transport systems prefer to additionally protect themselves by oversizing traction batteries.

An alternative to stationary charging is charging in motion, without having to stop the vehicle. The concept of this dynamic charging [16], also called as In Motion Charging (IMC), is considered a promising technology for electric urban bus rapid transit systems. Its main advantage is the ability to reduce the battery capacity and the number of vehicles needed to operate the line [17,18]. Generally, charging the vehicles on the move (IMC) or increasing the number of charging points (OPP) allow for a multiple reduction in battery capacity, in particular in relation to overnight charging [19,20]. The advantages of charging electric buses in motion are often analyzed in the literature. Most analyzes are carried out assuming the use of non-standard linear charging systems, such as linear inductive transmitters [16,21]. Unfortunately, a technical solution which has been known for over a hundred years is overlooked in these analyses - it is the trolleybus catenary [22]. Nowadays, the trolleybus is often considered an outdated means of transport, but this opinion is far from the truth, as modern solutions provide new possibilities which greatly increase the attractiveness of trolleybus transport, in particular when trolleybuses are equipped with traction batteries enabling free catenary driving. Thanks to the use of autonomous power sources, primarily traction batteries, trolleybuses can become a modern transport mode [23-28]

1.2. Research gap

Currently, the available scientific literature in the field of IMC systems and trolleybus technology is focused on the following aspects:

1) optimization of the IMC system to obtain the optimal structure of the transport system based mainly on spatial aspects of optimization [5,29-31]
2) analyzing selected technical aspects of IMC, such as the selection of a charging strategy or batteries for a specific case study [22,32,33]
3) presentation of selected case studies [34,35]
4) IMC vehicles and their equipment [36-39]

However, there is a lack of detailed analyzes defining the multiaspect technical determinants of IMC. In particular, technical capabilities of the IMC system are relatively rarely analyzed in the literature. The trolleybus traction network is a well-known technical solution, but IMC is characterized by a different type of electrical load. Therefore, an analysis from a different perspective is highly desirable. Moreover, currently, several types of IMC charging are available, with powers ranging from 50 kW to 500 kW [32,33], and there are no publications taking into account technical limits and dealing with the influence of the type of charging and IMC system parameters on the lifetime of traction batteries. The type of the charging system and, in particular, the parameters of the IMC system have a key impact on battery degradation processes, and therefore on the total operating cost of the transport system. Consequently, a holistic approach is necessary here.

1.3. The aim of the paper

As presented above, despite their widespread use, stationary charged electric buses are not free from disadvantages. In this context, the aim of the article is to show that the dynamic charging of electric buses making use of the trolleybus traction network is a modern and promising solution, especially suitable for use in mass bus transport systems - e.g. BRT (Bus Rapid Transit system).

When designing a dynamic charging system, due to the high cost of infrastructure, the optimization of the length of the overhead contact line plays a key role [29,40]. This was the basic inspiration to formulate the following research problems, discussed in the article:

1) what are the possibilities of the trolleybus overhead catenary as a linear charger for electric buses, in particular, what is the required minimum catenary length;
2) what charging power is optimal for the IMC system;
3) to what extent the dynamic charging using the trolleybus traction network allows to reduce the capacity of the batteries in the charged

vehicles and the number of battery replacements during the entire vehicle operation period.

The solutions to these problems will be provided using simulation methods, supported by data from a real transport system. The article has the following structure: Chapter 2 presents the theoretical basis of the methods used, while Chapter 3 is devoted to present the technical possibilities of the trolleybus network as a charging corridor for electric buses. Chapter 4 presents quantitative benefits of the IMC system from the point of view of reducing the impact of road traffic disturbances. The case study analysis is shown in Chapter 5, and the summary and discussion of the results are given in Chapter 6.

2. Methods

The article uses a multiaspect methodology to assess the technical capabilities of the IMC system. This methodology allows the user to examine the dynamic charging system taking into account (Fig. 1):

- technical possibilities of the trolleybus technology;

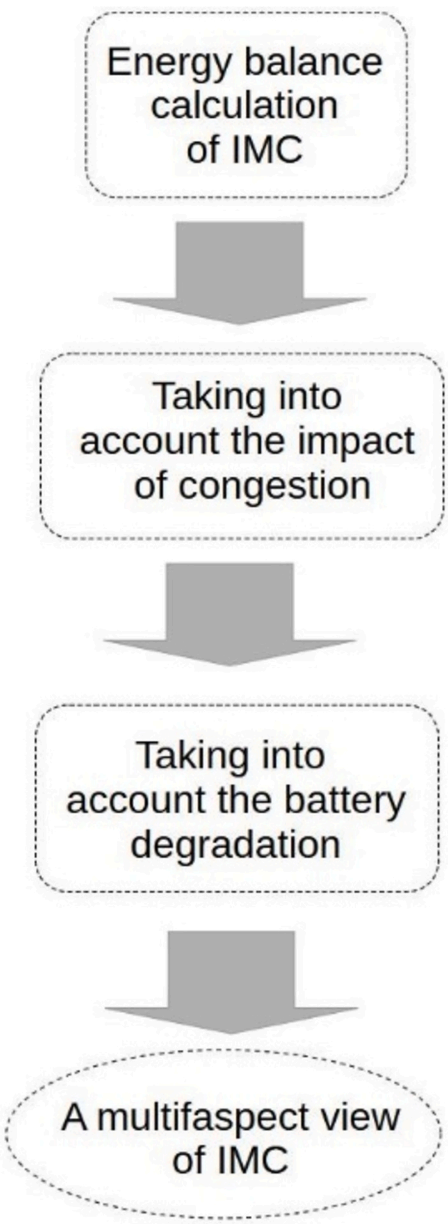

Fig. 1. Scheme of the applied methodology.

- the reliability of the charging system related to the impact of road traffic congestion;
- the battery aging processes.

The above elements make it possible to assess the demand for traction batteries as a whole - from the point of view of both the required electricity parameters and battery aging. The energy analysis makes it also possible to determine the technical parameters of the IMC charging corridor.

To achieve this goal, a three-step methodology was used:

Step 1 - Energy analysis: determining the IMC charging corridor boundary parameters, mainly based on the energy analysis. This step is intended to determine the technical capabilities of the IMC system.

Step 2 - Estimating the effect of road traffic congestion based on statistical data from road traffic. This step is intended to determine potential benefits of the increased charging reliability in the IMC system.

Step 3 - Battery performance and degradation model: determining the impact of the type of charging system on battery aging processes. This step is intended to determine the impact of the applied IMC system on battery lifetime increase.

To best reproduce the road traffic parameters, the data from the trolleybus transport system in Gdynia were used. Gdynia is a port city located in northern Poland, with an extensive trolleybus network operated by 100 vehicles. This is a rich source of data from real operation, which allows mapping of random aspects of the road traffic.

2.1. Energy analysis

The energy balance ΔE_{bat} of the battery during driving with dynamic charging on the move is equal to the difference between the energy E_{bat} supplied from the catenary when charging the vehicle and the energy E_{bat} consumed by the vehicle:

$$\Delta E_{bat} = E_{ch} - E_{veh} \tag{1}$$

The energy consumed by the vehicle can be expressed as:

$$E_{veh} = e_{tr} \bullet l + P_{aux} \bullet t \tag{2}$$

where l is the driving distance, t is the driving time, e_{tr} is the average energy consumption of traction drive per distance, and P_{aux} is the power of auxiliaries.

The key element influencing the operation of an electric vehicle is the onboard DC/DC charging converter (charger), supplied from trolleybus OHL (Overhead line) by current collectors, which charges the battery. In the IMC charging system, the main limitation of the charging power is the maximum current capacity of the collectors, which ranges within 500–600 A in currently used solutions and allows charging with the power of 300–500 kW. However, due to thermal limitations during standstill (overeating of the current collector and contact wire), the permissible current taken from the grid drops to approx. 100–200 A, which limits the maximum power and, consequently, the average useful charging power. Taking this into account, the charging energy can be described as:

$$E_{ch} = P_{ch\_m} \bullet t_{ch\_m} \bullet \eta + P_{ch\_s} \bullet t_{ch\_s} \bullet \eta \tag{3}$$

where P_{ch_m} is the charging power on the move, P_{ch_s} is the charging power at stop, t_{ch_m} is the time of movement (speed greater than 0); t_{ch_s} is the stopping time (speed equal to 0), and η is the efficiency of charging.

After denoting the relative running time (the ratio of the time t_{ch_m} to the total travel time t_{ch}) by k, formula (3)can be converted to:

$$E_{ch} = t_{ch} \bullet \eta \bullet (\mathrm{k} \bullet P_{ch_m} + (1-k) \bullet P_{ch\_s}) \tag{4}$$

In the IMC system, charging takes place when driving at vehicle speed v along a charging corridor of length l_{ch}, therefore formula (4) can be expressed as:

$$E_{ch} = (k \bullet P_{ch_m} + (1-k) \bullet P_{ch\_s}) \bullet \eta \bullet \frac{l_{ch}}{v} \quad (5)$$

It can be concluded that the driving/overall time ratio influences the usable charging power, because the charging power is limited when the vehicle is stationary.

An important element influencing the energy consumption of an electric vehicle are auxiliaries - primarily heating. To reflect the influence of temperature, the data on energy consumption for non-traction purposes from the Gdynia trolleybus transport system was used. These data make it possible to determine the energy consumption in electric buses and the impact of external temperature on the charging process of electric buses. Heating, Ventilation and Airconditioning systems (HVAC) are a key factor in the energy consumption of city buses. The data from the Gdynia's transport system allow to assess this impact based on the real operation values (Fig. 2).

2.2. Estimating the impact of road traffic congestion

The main factor influencing the course of charging the batteries of buses in the urban transport system is the relation between the driving and stopping times, as it determines the operation of both stationary and dynamic charging systems. In the case of stationary charging, the time of standstill affects the amount of energy that can be delivered to the vehicle, while for IMC charging, the key factor is the time of ride under OHL. The authors' efforts were to reproduce the traffic conditions (mainly irregular and stochastic movement) in the urban transport system as accurately as possible. For this purpose, the data obtained from the Tristar system The Tri-City: Gdansk, Sopot, Gdynia Intelligent Agglomeration Transport System, designed to automatically manage traffic in the Tri-City area, were used. The Tristar system carries out multiple measurements of vehicle traffic in the Tri-City road network, which allowed the authors to use real-life times of vehicle travel on dynamic charging sections (trolleybus network) and real parking times on the terminus in the analysis. This approach made it possible to study the charging systems taking into consideration traffic congestion, which significantly affected the available charging times.

To illustrate the problem, Fig. 3 presents an example of traffic delay values, shown as the delays of arrival at the end stop, which were taken from the traffic data on two selected lines of the Gdynia transport system. The presented delay histograms are complemented by the approximating exponential function.

In the case of dynamic charging, the impact of congestion on the charging time is different (Fig. 4). The travel time on the OHL section (i.e., the charging time) does not drop below the minimum value resulting from traffic speed. Therefore, it can be said that, unlike stationary OPP charging, charging in motion from the traction OHL makes it possible to achieve a guaranteed minimum charging time. That means that although the cost of building an IMC charging corridor is higher than that of building a single fast charging station, the charging corridor provides greater charging reliability and allows for greater flexibility in planning vehicle traffic.

To reflect the impact of delay variation on the operation of the charging system, the standstill time has been modified in the energy calculations (formulas 4 and 5). The delay value Δt was determined randomly using a probability distribution – Fig. 4, and accordingly used to modify the standstill time, i.e. stationary charging.

2.3. Battery performance and degradation model

In the past, attempts were made to describe battery degradation with different models, from a semiempirical model (SM) [41,42], passing through the Equivalent Circuit Model (ECM) [43,44], to the Physical Based Model (PBM) [41,45] and finally the Data Driven Model (DDM) [46,44,42]. Different approaches offer different capabilities and consider different features; however, they describe the capacity and sometimes the power battery fading in relation to different operating and storing conditions. While the PBM has high accuracy and the potential to estimate internal battery states (e.g. electrolyte concentration or single electrode potential), along with some predictive capabilities concerning non-parameterized operating conditions, this model type requires high computational power to solve a system of partial differential equations and its parameterization is not trivial. ECMs, on the other hand, are easier than PBM to parametrize, they need less computation power, are robust and still offer physically meaningful problem description, even if the representation of internal variables is not possible and sometimes they can be misinterpreted. The Data Driven models, in turn, are black box models in which physical mechanisms are not captured, but they describe mapping relationships between external input and output characteristics.

In this paper, a semiempirical model has been chosen to give indication on the expected performance degradation based on operating conditions. The superposition approach was applied to the two aging mechanisms: cycling aging (battery capacity and power fading

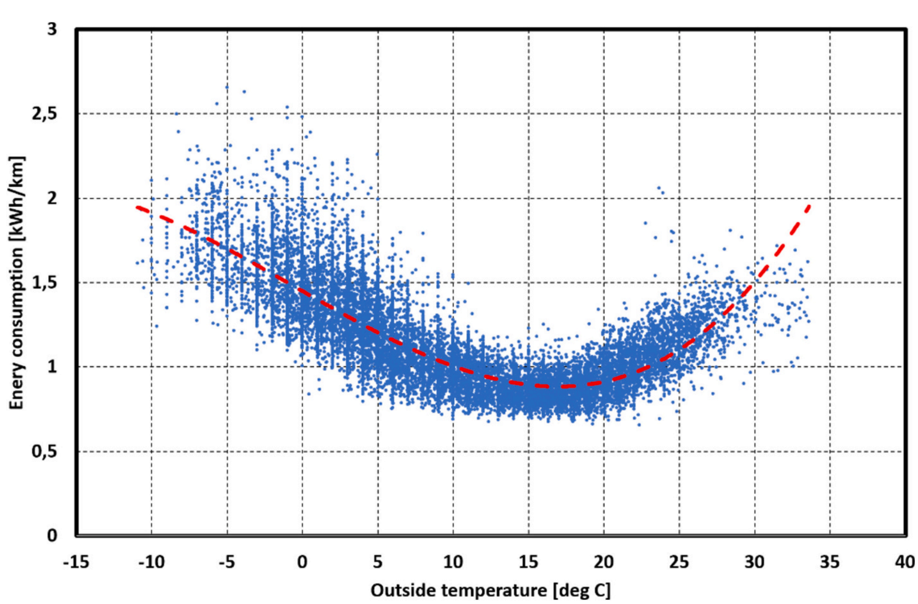

Fig. 2. Energy consumption of 12-m trolleybus as function of outside temperature (source: data logger system from trolleybuses in Gdynia).

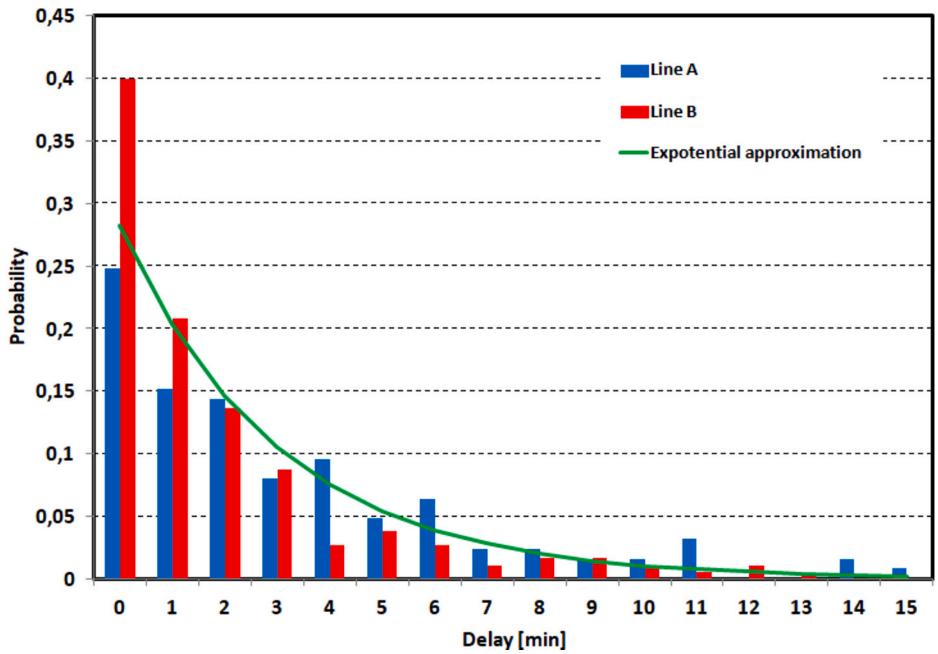

Fig. 3. Histograms of the delay of arrival at the end stop and the approximating exponential function (source: Tristar system, Gdynia).

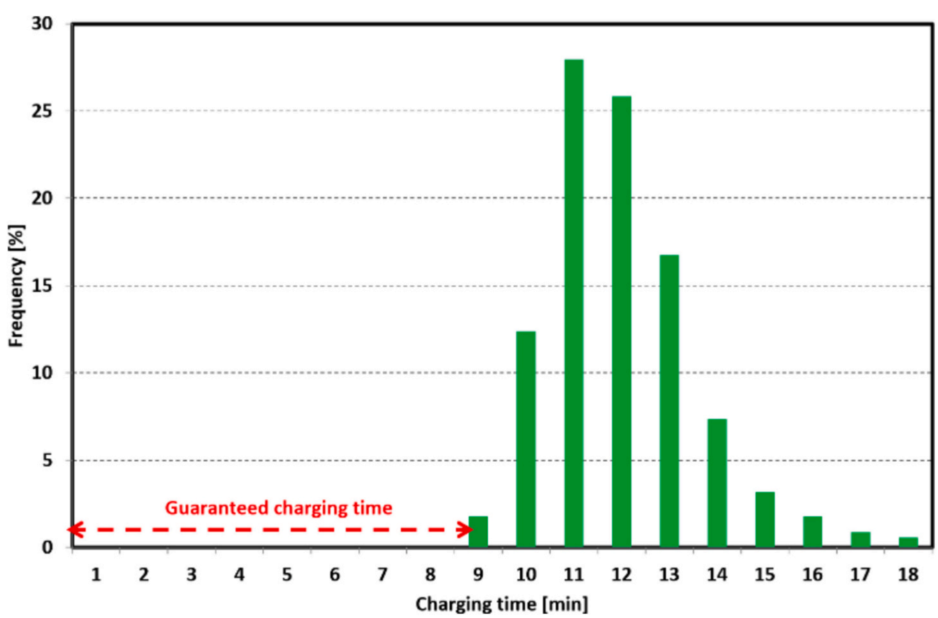

Fig. 4. Histogram of charging times in dynamic mode from trolleybus OHL on a 4-km section (source: Tristar system, Gdynia).

occurring when the battery is charged and discharged) and calendric aging (battery capacity and power fading occurring when the battery is stored, regardless of its use), following the same approach as [42] but complementing the output with the power fading information. In this case, the semiempirical approach, parametrized with test data, was performed on NMC cells at different operating conditions.

To model the battery aging processes, the Open-Sesame Battery model (Open Sesame) was used, which is an open-source battery simulation tool based on a semi-empirical battery model [47]. The simulation framework allows to predict the performance of the battery and estimate its lifetime by quantifying the degradation due to the operation and depending on cell chemistries. The software input at each time instant was the power profile or, alternatively, the SOC (State of Charge) profile, complemented with the information about the environmental temperature at which the battery was operated. The outputs were the evolution of the state of health (SoH) and the state of resistance (SoR) during the operation time, which reflected the capacity and power fading of the battery due to cycling and calendric degradation.

The battery state of health (SoH) describes the ratio between the maximum capacity stored in the battery at a given time and the maximum energy that was able to be stored initially (nominal capacity):

$$SoH = \frac{Q_{max}(t)}{Q_{max}(t=0)} = \frac{Q_{max}(t)}{Q_{nominal}} \tag{6}$$

The state of resistance (SoR) describes the ratio between the internal resistance value of the battery at a given time and the initial value of battery resistance, measured at a given temperature and state of charge.

$$SoR = \frac{R(t, SOC, T)}{R(t = 0, SOC, T)} = \frac{R(t, SOC, T)}{R_{nominal}(SOC, T)} \tag{7}$$

Open-Sesame has been developed in the framework of the IEA Annex 32, a research initiative of the International Energy Agency that aims to evaluate the role of energy storage systems in the future energy scenario by means of open-source models.

The Open-Sesame (Fig. 5) includes three Li-ion cell chemistries, which differ in terms of the cathode material used:

- Nickel Manganese Cobalt (NMC).
- Lithium-titanate batteries (LTO).
- Lithium iron phosphate (LFP).

Each of these cell types has its own library in the simulation, in which individual characteristics of the cells are described in terms of stress factors. Given the modular program structure, it is possible to add further cell technologies or to modify the library of the existing cells, thus adapting the model to current developments in Li-ion technology.

The simulation of battery aging is based on a semi-empirical model where the degradation is described using functions that reproduce the aging measurements from experimental tests and/or literature data as close as possible. To achieve the result, so-called stress factors were used, which describe the influence of a given operating condition, e.g. the current C-rate, on aging. Since the approach adopted in the simulation framework considers a superposition of calendric and cycling aging on total degradation, different stress factors are used to describe these two effects. The total aging is then calculated as the sum of calendric and cycling aging.

The starting point for aging calculations is determining the degradation under standard conditions. This can be obtained based on laboratory tests, or, if no measurements are available for a cell, from the data sheet. In Open-Sesame, the standard degradation determination includes calculation of the following four parameters:

- Reference calendric aging (SoH) in ΔSoH /time [%/sec] - decrease in battery capacity per time
- Reference cycling aging (SoH) in ΔSoH /EFC [%/EFC] - decrease in battery capacity per EFC cycle
- Reference calendric aging (SoR) in ΔSoR /time [%/sec] - decrease in battery internal resistance per time
- Reference cycling aging (SoR) in ΔSoR /EFC [%/EFC] - decrease in battery internal resistance per EFC cycle

where EFC means the Equivalent Full Cycles (number of charging-discharging cycles related to nominal capacitance). These variables represent unit values of aging processes under rated conditions.

Based on the degradation under standard rated conditions and the stress factors reflecting actual working conditions and the simulation time intervals, the calendar aging is calculated for each time step as:

$$\Delta SoH_{cal\ (t=x)} = SF_{SoC}{}^{*}SF_{temp}{}^{*}Ref_{cal}\left(\frac{\Delta SoH}{dt}\right){}^{*}dt \tag{8}$$

where SF_{SoC}, SF_{temp} are the stress factors, i.e. the coefficients that reflect the influence of SOC and temperature, determined from the characteristics, and Ref_{cal} is the Reference calendric aging.

A similar equation applies to the calculation of calendric aging of SoR for each time step.

For the calculation of cycling aging, the temporal resolution is not relevant and the cycling aging is calculated for each cycle using the rain flow algorithm:

$$\Delta SoH_{cyc\ (cyc=x)} = SF_{DOD}{}^{*}SF_{SOC}{}^{*}SF_{C-rate}{}^{*}SF_{temp}{}^{*}Ref_{cyc}\left(\frac{\Delta SoH}{FEC}\right){}^{*}FEC_{(cyc=x)} \tag{9}$$

where SF_{DOD}, SF_{SoC}, $SF_{C\text{-}rate}$ SF_{temp} are the relevant stress factors, i.e. the coefficients that reflect the influence of, respectively, DOD (Depth of discharge), SoC, C-rate (relative cell current), and temperature, determined on the basis of characteristics, while Ref_{cyc} is the Reference

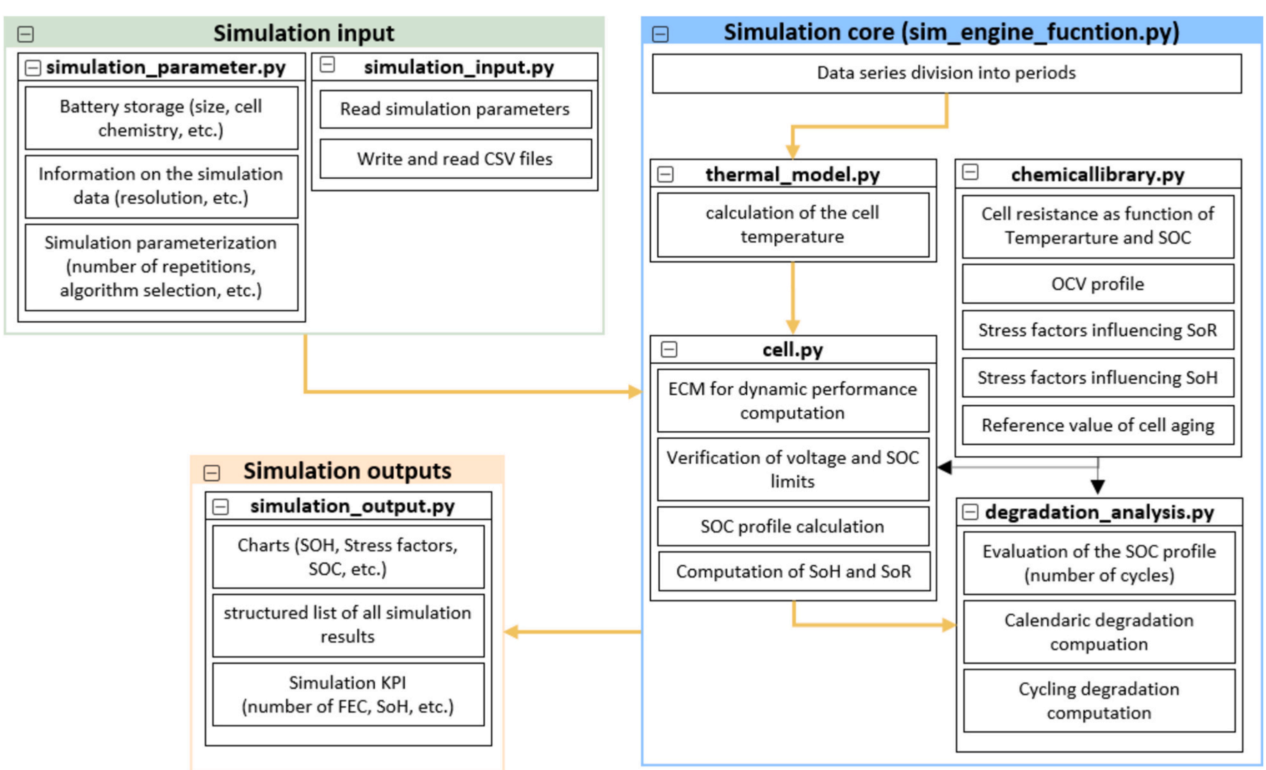

Fig. 5. Software architecture flowsheet.

cycling aging.

The cycling capacity fading equation applies analogously to the calculation of the cycling aging of the SoR. The calendric aging calculation, which is carried out for each time step, is subsequently summed up with the results of the cycling aging. The total degradation caused by a cycle is assigned to the last time step of the cycle in Open-Sesame. The course of the SoH and SoR is thus given a staircase shape.

3. Trolleybus overhead catenary as a charging corridor

From the point of view of the dynamic charging process, the amount of energy supplied to the vehicle per unit length of the charging corridor is of key importance. It determines the effectiveness of vehicle charging and the amount of necessary infrastructure (trolleybus traction network). The key element is therefore the power of the on board charging converter. This is because in an IMC system, the charging converter is part of the vehicle and therefore substantially contributes to its cost and weight. Increasing the battery charging power allows for faster charging, but it also means less effective use of the full power of the charger. An increase in the converter power increases the charging rate, but is associated with an increase in the converter cost. Consequently, it is crucial to take into account traffic conditions that affect the actual charging power. For that reason the dependence of charging processes on real traffic conditions was investigated using Tristar data from battery trolleybuses serving the trolleybus line 32 in Gdynia. Due to the lack of a BRT system in Gdynia, a fragment of the route was selected that corresponds to the conditions of BRT traffic (smooth traffic, separate bus lanes).

For the purposes of the presented analysis, three network sections were selected:

1) city center traffic section: *Węzeł Franciszki Cegielskiej - Plac Kaszubski*, length of 2 km, average speed of 14 km/h;
2) city center traffic section with terminus: *Węzeł Franciszki Cegielskiej - Plac Kaszubski*, length of 2 km, average speed of 14 km/h when in motion, and 5–15 min of waiting at terminus)
3) traffic section outside city center: *Energetyków - Obłuże Centrum* where the traffic meets BRT conditions (length of 1.5 km, average speed of 28 km/h).

Fig. 6 shows the relationship between the maximum charging power and the degree of its use for the above three traffic conditions, calculated based on traffic data from line 32.

Fig. 7 shows the dependence of the amount of energy that the batteries can be charged with for a distance of 1 km as a function of the rated charging power. Fig. 8 presents the duration of stationary 600 kW charging which corresponds to IMC with a 3-km charging corridor as a function of average speed. This relationship determines the minimum degree of route coverage with the overhead trolleybus catenary in the IMC system, as shown in Fig. 9.

The size of the infrastructure needed for the operation of electrified BRT systems was demonstrated using the data from the operated mass transit bus systems. The operating speed is the parameter which is decisive in determining the required minimum degree of coverage with the catenary in the IMC system. Fig. 10 shows the data from worldwide BRT corridors [17,18] and their corresponding minimal cover rates of trolleybus catenary in cases of IMC implementation.

On lines with smooth traffic and few stops, such as the Bus Rapid Transit system, the running time (when the vehicle velocity is greater than 0) accounts for 75–85 % of the total time. In this case, stoppages are only a small fraction and therefore the useful available power of the charger is high. Consequently, in case of high rated power of charger this power is used to a significant extent. The situation is different for the city center traffic, which is characteristic for a high impact of congestion and many stops (the running time is 60–70 %). It becomes even more complicated when the stopping time at the terminus is taken into account, especially where the overhead catenary is located at the end stop and, additionally, there are long equalizing stops. In this case, the use of the charger's rated power can be limited, which reduces the charging rate in relation to the maximal charging parameters. This is an argument against using a high-power converter in such conditions. Therefore, it can be concluded that under standard conditions, a battery charging power of 150–200 kW is sufficient. Only in the cases of BRT systems with very smooth traffic, increasing this power to 300–350 kW should be considered.

Depending on traffic conditions and charging power, a one-kilometer section of the overhead contact line allows for delivering from 5 to 15 kWh of energy to the vehicle (Fig. 7). A standard traction substation is capable of powering a 3–4 km long section of the traction network. Such a section can therefore be treated as one section of a linear charger in the

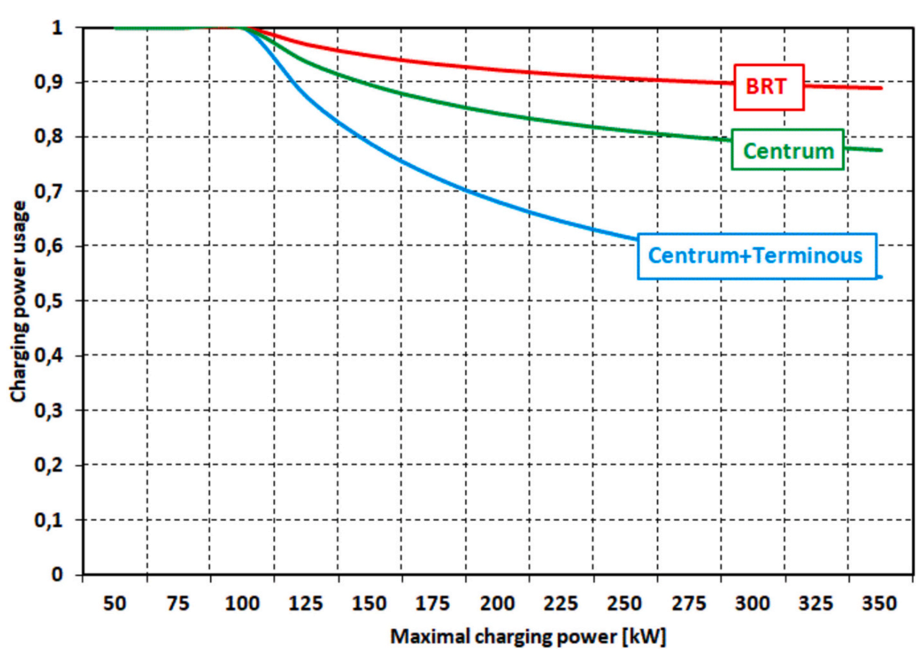

Fig. 6. Use of rated power of the charger.

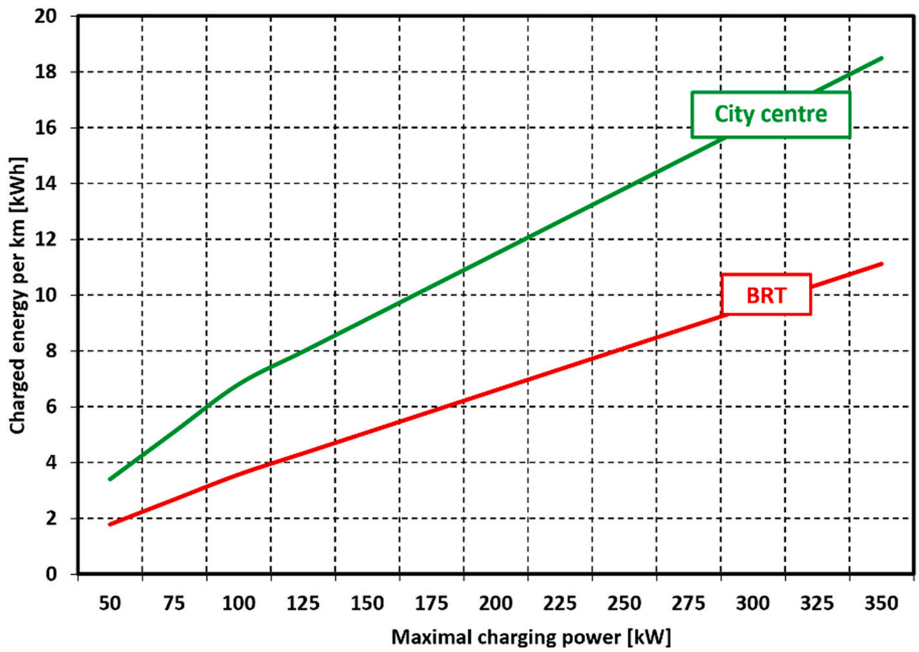

Fig. 7. IMC energy delivered to the vehicle as function of DC / DC charging converter.

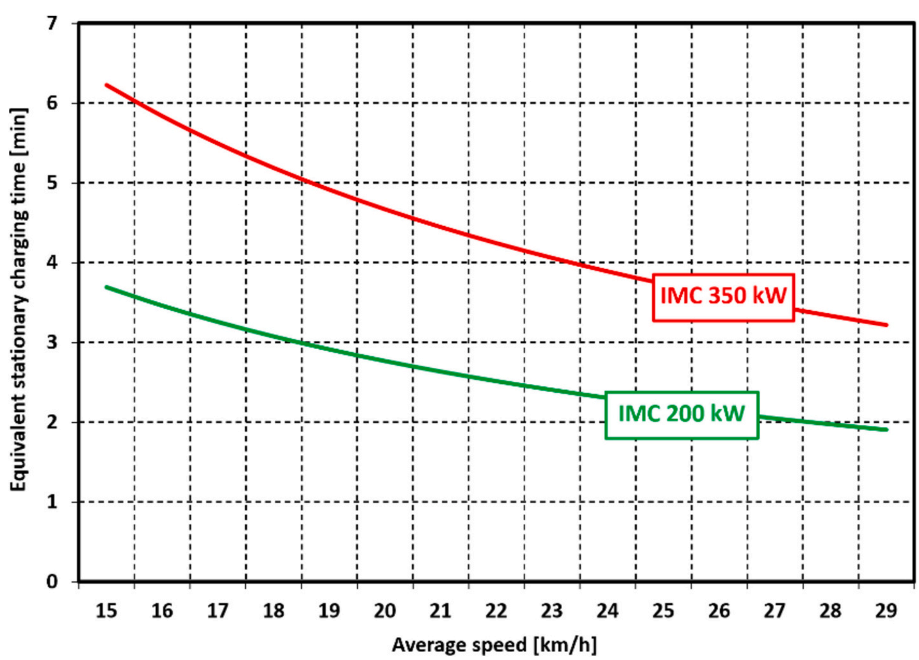

Fig. 8. Duration of stationary 600 kW charging which corresponds to IMC with 3-km charging corridor as function of average speed.

IMC system which allows for the delivery of 20–60 kWh of electricity. Assuming the energy consumption of an articulated vehicle at the level of 2.3 kWh/km, this allows for the operation of a transportation line with a length of 10–25 km. That means that the IMC charging corridor with the length of 3 km can replace 3–6 min of fast stationary OPP charging (Fig. 8). Generally, it can be stated that the coverage of the route with the traction network to the extent of 30 % is sufficient in most cases for the operation of the IMC system (Fig. 9–10).

4. Traffic delays

In order to quantitatively assess the impact of road traffic congestion on the charging process, the impact of traffic disturbances, including ambient temperature changes, on the traction battery charging process has been analyzed.

For the presented analysis, a line with the following parameters was adopted:

- 10-km length,
- one 600 kW fast charging station,
- articulated electric buses with traction batteries LTO 150 kWh.

The calculations were performed assuming the scheduled charging time at the final stop at the level of 5 min, 7 min, and 10 min. The scheduled stopping time at terminus was adjusted to the data on traffic delays obtained from the Tristar system (Fig. 3).

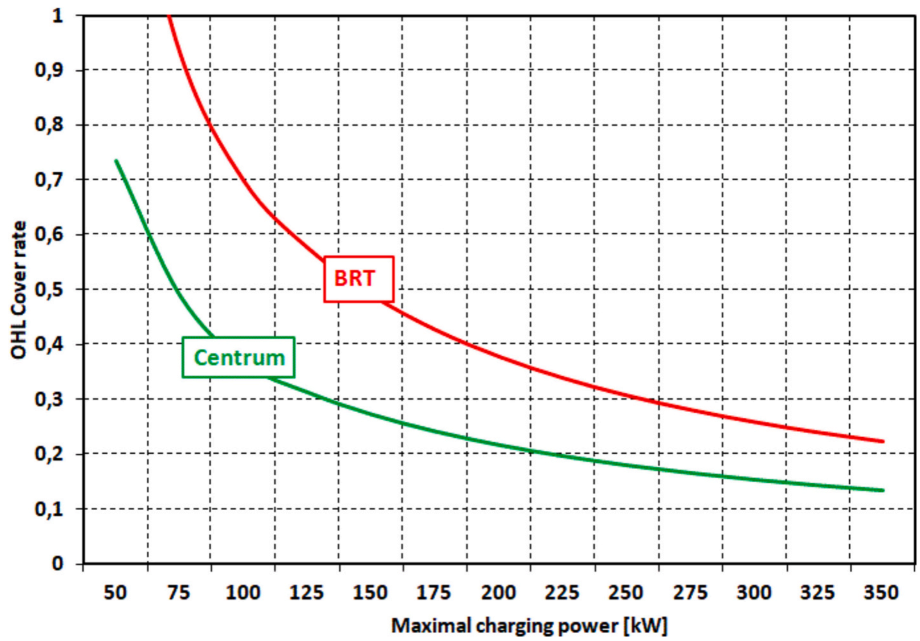

Fig. 9. OHL cover rate of IMC route as function of maximal charging power (articulated vehicles).

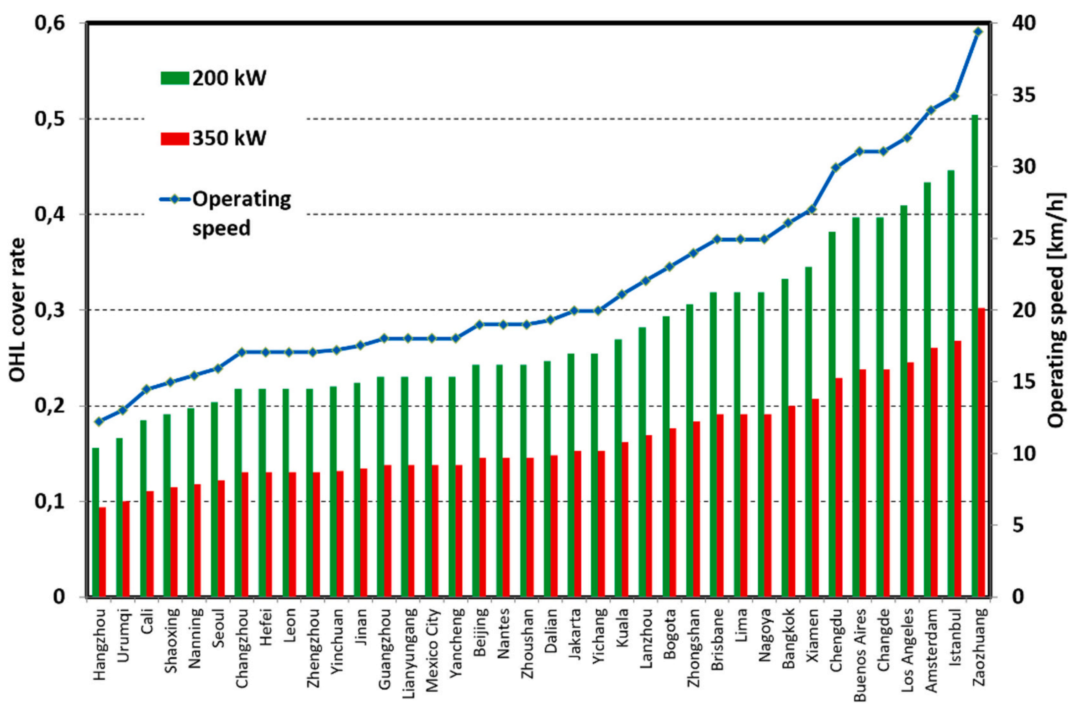

Fig. 10. BRT corridors and their corresponding minimal cover rates of trolleybus catenary in cases of IMC implementation.

Traffic delays shorten the time available for charging the batteries, which results in the inability to fully charge them. Fig. 11 shows the calculated frequency of situations in which the battery charge level during the vehicle movement fell below the acceptable threshold for its operation. Such a situation requires using a reserve vehicle to operate a given line. Due to the fact that the main factor influencing the energy consumption is the ambient temperature, the calculations were carried out as a function of the external temperature.

To avoid the need for using additional spare vehicles, the reliability of the charging process should be increased, which can be done by increasing the capacity of the traction battery. Therefore, based on the characteristics of traffic delays (Fig. 3), the operation of the battery system was modeled at various average delay values and the minimum permissible battery capacity. Their goal was to estimate the required battery parameters that guarantee the reliable operation of the bus line in the event of traffic disturbances as a function of traffic congestion. The calculations were made for the energy worst case situation – outside temperature value assumed at —10C deg. The obtained results are presented in Fig. 12.

The use of IMC dynamic charging from the trolleybus traction network allows to soften the relationship between the charging time and road traffic conditions (Fig. 13). To show the effect of using the IMC

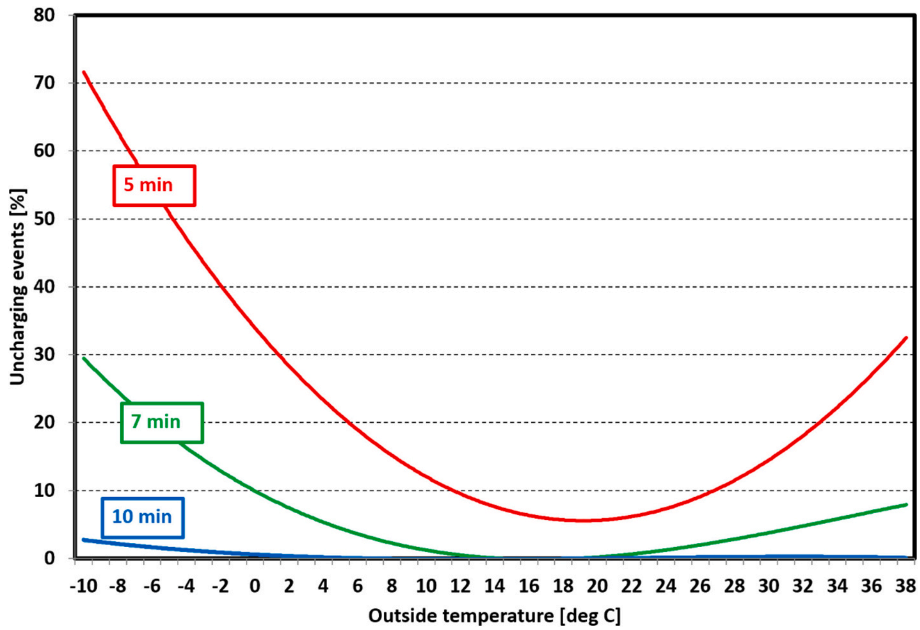

Fig. 11. Undercharging events as function of outside temperature for the scheduled stopping times of 5, 7 and 10 min, 150 kWh batteries, and 600 kW charging considering traffic delays.

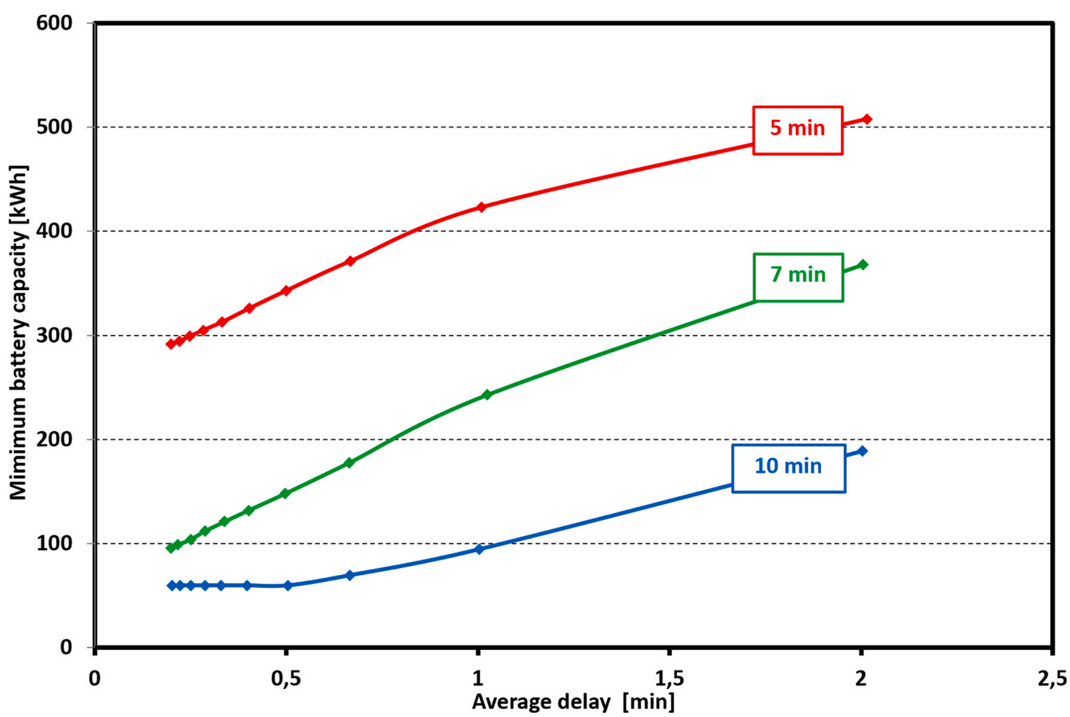

Fig. 12. Minimal required capacity of traction battery charged with 600 kW fast charging at final stop as function of average delay for stopping times equal to 5, 7 and 10 min.

technology, a simulation was performed for a charging system with trolleybus network section. Assuming analogous assumptions as in the previous case (a 10-km long line served by articulated vehicles), the analysis of the impact of traffic delay on maximum battery discharge (minimal capacity) was performed for three selected charging systems:

- OPP stationary charging,
- IMC dynamic charging (overhead contact line of 3 km in length),
- combination of OPP and IMC charging (overhead contact line of 2 km in length).

Fig. 13 shows the results obtained for these three systems. It is clearly visible that the use of IMC dynamic charging reduces the impact of road traffic congestion on the degree of discharge of traction batteries and allows for the reduction of their capacity. The batteries can be reduced even several times: in a stationary charging system, in case of strong traffic disruptions, batteries with a capacity of 150 kWh are required while the IMC system allows to reduce their capacity to 60 kWh.

5. Battery degradation analysis

The analysis of the impact of the applied charging method on battery

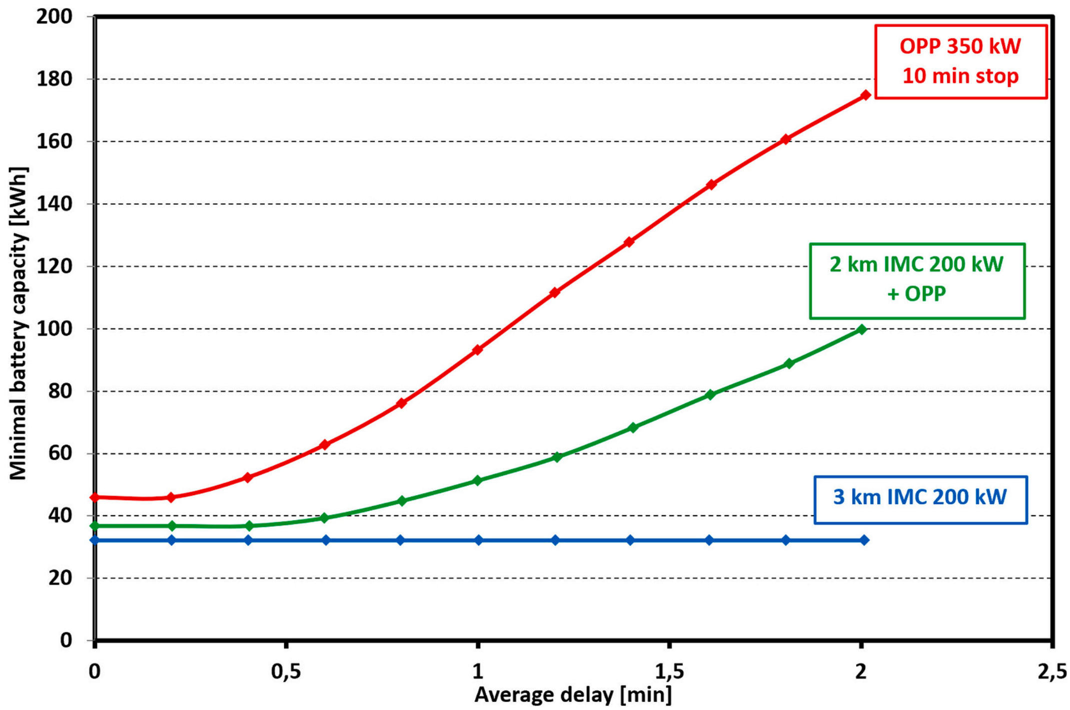

Fig. 13. Minimal required capacity of traction battery charged with different charging systems: OPP, combination of OPP and IMC, and IMC only.

degradation was carried out for the bus line 194 in Gdynia. The operation of traction batteries was analyzed for:

- IMC charging:

1) 350 kW charging with 75 kWh batteries and centrally located section of the OHL charging corridor (*Energetyków – Stare Obłuże*),
2) 350 kW charging with 75 kWh batteries and the OHL charging corridor located at beginning of the route (*Plac Kaszubski – Węzeł Ofiar Grudnia),*
3) 200 kW charging with 75 kWh batteries and the OHL charging corridor located at beginning of the route (*Plac Kaszubski – Energetyków),*

- OPP charging:

4) 600 kW charging with 600 kWh LTO batteries.
5) 400 kW charging with 400 kWh NMC batteries.

The selection of variants for the analysis was dictated by commonly

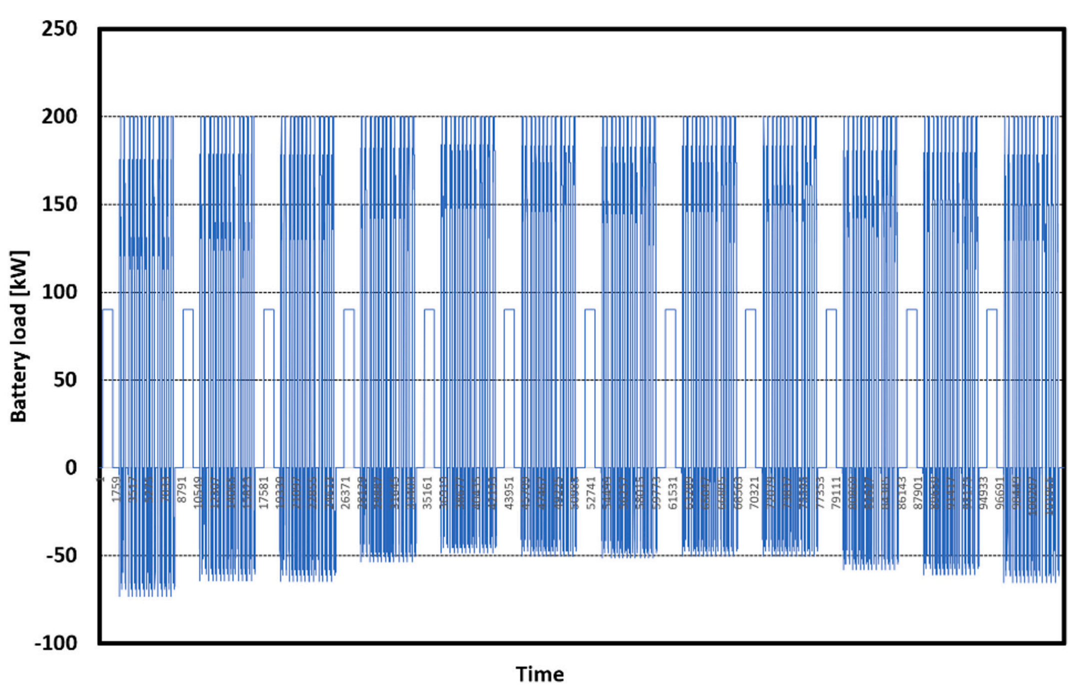

Fig. 14. Sample Open SESAME input data: load of traction battery.

used technical solutions.

As the first step, the traction battery load profile was determined based on the timetables and data on energy consumption. In order to take into account annual changes in electricity consumption, a profile containing 12 days was adopted for the calculations, with each day corresponding to the average energy consumption in one month. The time resolution of the battery load profile was 10 s. These data were used for simulation calculations in OPEN-SESAME (Fig. 14).

Then, the lifetime of the battery in each variant was determined. The SoH of 80 % was assumed as the threshold of battery usability. Two selected results of simulation – SoH as a function of time – are presented in Figs. 15 and 16 for 400 kWh NMC batteries and 150 kWh LTO batteries, respectively. What is noteworthy in these figures is the greater impact of calendric aging processes in the case of NMC batteries in relation to LTO batteries (yellow lines in Figs. 15 and 16).

Table 1 presents the summary of the obtained calculation results in the form of battery lifetimes for individual variants. The length of the traction network section was selected such as to allow the battery to be fully charged during the vehicle's operating cycle. In the case of using batteries made in NMC (high energy) technology, the main factor limiting the battery life is calendric aging. For this reason, it is very difficult to extend the battery life beyond 10 years with this technology. However, this is possible for f LTO batteries, which are characterized by significant cyclicity and slow calendric aging, as a result of which their lifetime can reach even 20 years. However, in the case of fast charging, the lifetime of LTO batteries is also reduced by a high value of the charging current (high C-rate). This feature is presented in Fig. 17 which shows the impact of battery capacity and charging system type on the lifetime of LTO and LFP batteries (as a promising alternative for LTO technology). Increasing the capacity of the battery leads to a decrease in its discharge, which further results in an increase of its service lifetime. It can be said that only in the case of IMC charging with a power of 200 kW and LTO technology, the battery lifetime can reach 15 years, which means that there is no need to replace them during the entire life of the vehicle. In all other cases, it will be necessary to replace them after 7–10 years of vehicle operation. In the case of LFP battery technology, it becomes reasonable to use a battery with capacity of 150 kWh and a charging power of 200 kW. Its lifespan will equal approximately 7.5 years, which means that they will need replacement during the lifetime of the vehicle. Increasing the charging power significantly accelerates the aging processes, therefore in the case of LFP technology it is not possible to use charging powers above 200 kW.

The location of the charging corridor in the entire route also plays a role in the operation of the IMC system. Placing the catenary section in the central part of the line (variant 1, Table 1) allows to reduce the level of battery discharge and slightly extend its life. On the other hand, if the charging corridor is located at the beginning of the route (variant 2), then it is possible to shorten its length (21 % in present case), because it is possible to additionally charge the battery while stopping at the final loop. However, the depth of discharge of the battery increases and its service life decreases slightly.

Fig. 18 shows the total battery cost for 20 vehicles operating on the route and the cost of building the trolleybus traction network. In the case of an IMC system with charging power of 200 kW, these costs are the lowest. If the charging power is increased to 350 kW, the lifetime of the batteries is reduced, and it becomes necessary to replace them. However, due to small battery capacity, the total costs are relatively low. The battery costs increase significantly for stationary charging, when it becomes necessary to use higher capacity batteries. It should be noted that the outlays for the construction of the traction network, although significant, may turn out to be lower than the total outlays related to the batteries and their replacement.

6. Results and discussion

Taking into account road traffic conditions, in order to achieve the reliable operation of stationary charged electric buses in urban traffic, it is necessary to use batteries with a capacity of at least 200 kWh. In such a situation, it is necessary to use batteries made with NMC technology. However, due to aging processes, their service life is limited to 5–10 years, which means that they have to be replaced during the lifetime of the vehicle. The battery lifetime can be increased using LTO batteries. However, in practical applications, their capacity is limited to 150 kWh due to high cost and weight. This low capacity makes it sensitive to traffic disturbances, as a shortened stopping time at the final stop may be insufficient to recharge the battery. A way to improve the reliability of stationary charging is to increase the charging power. However, this is limited by many factors, e.g. charging power that determines the minimum battery capacity.

Charging buses from the trolleybus traction network allows to reduce battery capacity by significant increasing of charging reliability. IMC minimizes the impact of traffic disturbances on the charging process,

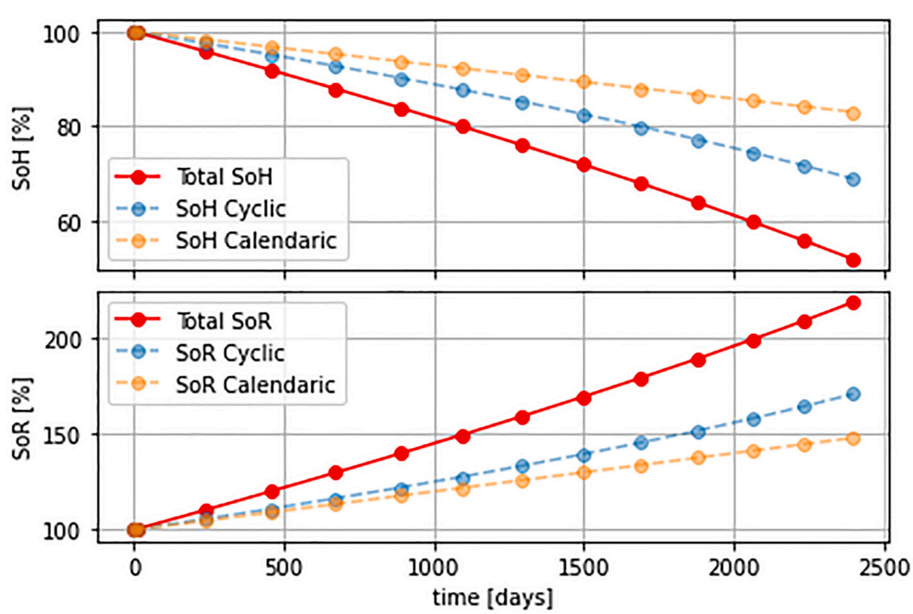

Fig. 15. Open SESAME degradation analysis of OPP charged electric bus with 400 kWh NMC batteries.

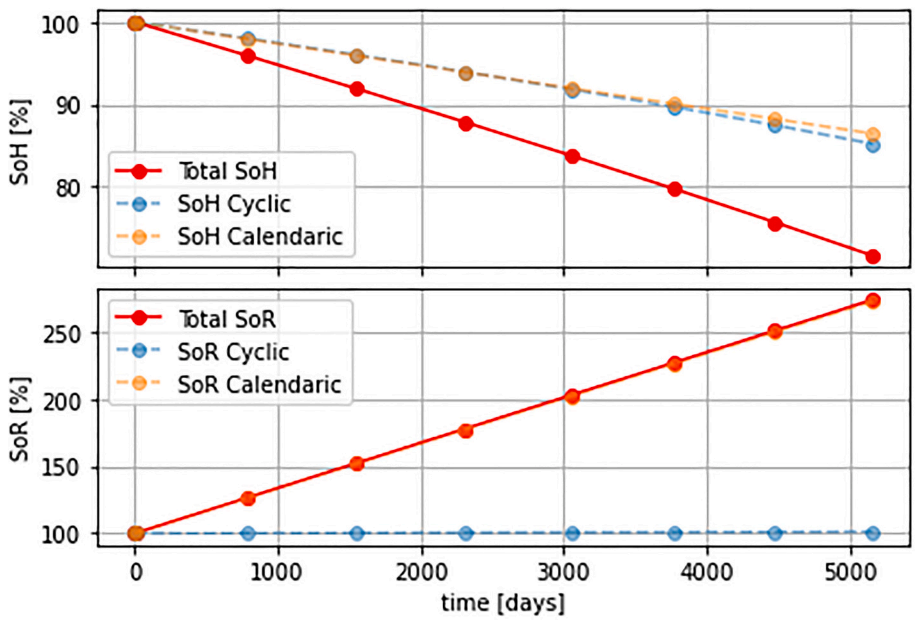

Fig. 16. Open SESAME degradation analysis of OPP charged electric bus with 150 kWh LTO batteries.

Table 1
Comparison of variants of trolley catenary operation.

Input parameters							Calculation results	
Variant	Charging	Battery technology	Battery Capacity	Charging section	Length of OHL	Route cover by OHL	Max. discharge energy**	Battery lifetime
1	IMC 350 kW	LTO	75 kWh	Energetyków – Stare Obłuże (central section)	3,0 km	30 %	25 kWh	10,5 years
2	IMC 350 kW	LTO	75 kWh	Plac Kaszubski – Węzeł Ofiar Grudnia (initial side section)	2,1 km	21 %	44 kWh	9,9 years
3	IMC 200 kW	LTO	75 kWh	Plac Kaszubski – Energetyków (initial side section)	3,8 km	38 %	28 kWh	15,4 years
4	IMC 200 kW	LFP	150 kWh	Plac Kaszubski – Energetyków (initial side section)	3,8 km	38 %	28 kWh	7,1 years
5	OPP 600 kW	LTO	150 kWh	Charging station at Plac Kaszubski	–	–	51 kWh	9,4 years
6	OPP 400 kW	NMC	400 kWh	Charging station at Plac Kaszubski	–	–	60 kWh	6,7 years

** maximum depth of battery discharge during the scheduled vehicle traffic.

which leads to the reduction of battery capacity and does not require very high charging power. All this allows for more freedom in choosing the appropriate battery technology, e.g., LTO batteries, and makes it possible to extend the battery lifetime up to the vehicle lifetime. Taking into account the total cost of the batteries (purchase and replacement), the cost of building a trolleybus traction network may turn out to be lower than the total cost of the batteries.

In the case of the IMC system with a charging power of 200 kW, the use of an LFP battery is also justified. Although they are slightly more expensive in terms of total costs than LTO, their larger capacity and growing popularity make them an attractive alternative.

7. Conclusions

The presented analysis demonstrates the benefits of the IMC dynamic charging system. In particular, this article offers the following contributions:

1) technical parameters of the IMC charging corridor,
2) the analysis of the impact of road traffic congestion on the reliability of the electric bus charging system,
3) the effect of battery charging method selection on the aging process.

It needs to be emphasized that the reduction of financial outlays related to the batteries in the IMC system is achieved by:

- the possibility of reducing the battery capacity as a result of high charging reliability, which reduces the need to increase the battery backup capacity,
- extending the battery lifetime by delaying their aging processes due to the use of lower charging power,
- decreasing the battery powered driving distance.

The conducted research allows to list the following key findings:

1) 20–40 % coverage of the traction network is sufficient to operate a bus line with battery trolleybuses. It means that the IMC charging corridor of 3–4 km in length is able to allow the operation of 10–15 km eBRT line.
2) Due to the time required for charging and the impact of road traffic congestion, to ensure reliable stationary charging of electric buses, additional vehicles need to be used or the traction battery oversized.

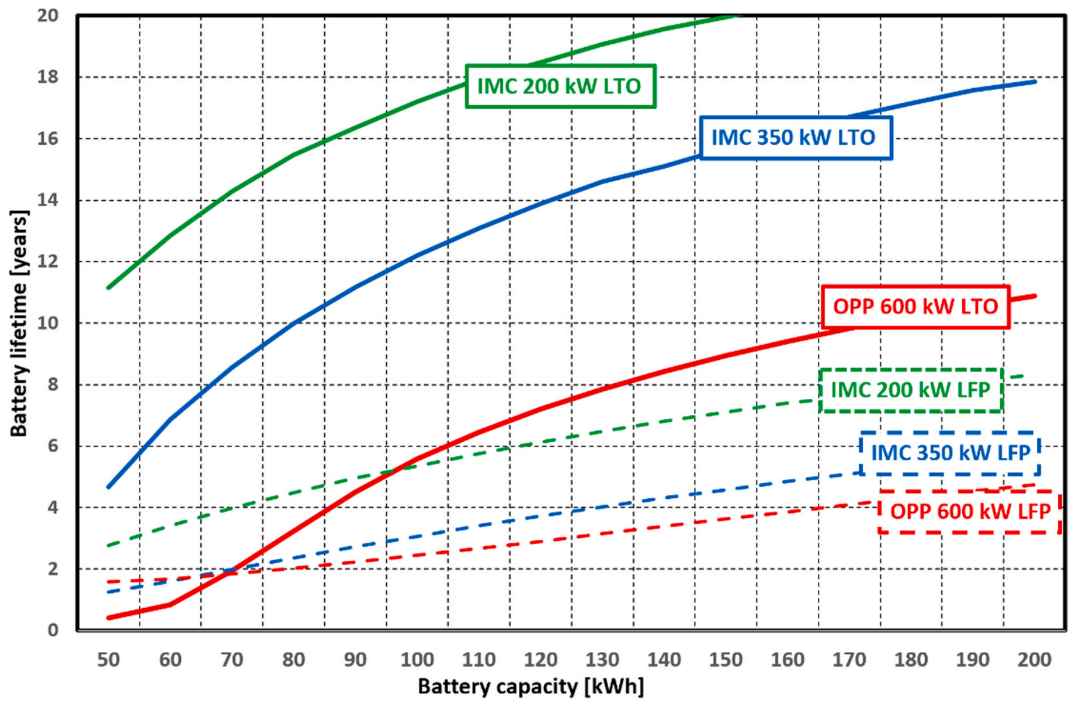

Fig. 17. Battery lifetime as function of charging system type and battery capacity (OHL section located at beginning of the route).

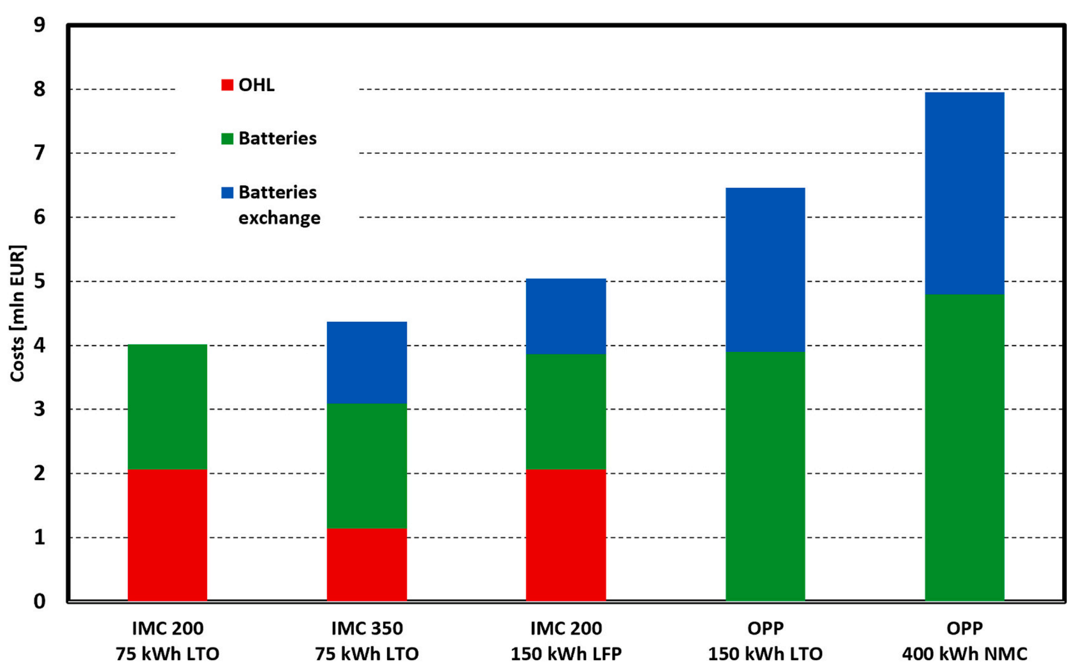

Fig. 18. Costs of batteries and infrastructure structure for 20 vehicles in operation (trolleybus OHL building cost: 800000 €/km, infrastructure depreciation period 30 years, residual value after 15 years assumed, NMC and LFP battery price 600 €/kWh, LTO battery price 1300,€/kWh, discount rate 3 %, annual decrease in battery prices 3 %, [48]).

3) A traction battery with a capacity of less than 100 kWh is sufficient to operate a bus line in the IMC system. If the LTO technology is used and appropriate selection of operating parameters done, this allows the battery to be operated without a need for replacement during the entire lifetime of the vehicle.
4) According to technical requirements for IMC systems, from the point of view of battery lifetime as well as currently available power electronic converter technologies, the optimal charging power in the IMC system is 150–200 kW. Using LTO traction batteries with a capacity of 70–85 kWh makes it possible to extend the battery life to 15 years. This means that there is no need to replace them throughout the lifetime of the vehicle. However, for BRT systems with smooth motion at high speed, the benefits of high charging power are much more apparent. Reducing the length of the necessary overhead contact line can be significant, with financial benefits.
5) In the case of IMC 200 technology with charging power of 150–200 kW, it also makes sense to use LFP batteries. Their lifespan is much shorter, but taking into account their greater availability, growing

importance and lower price, it may be justified to use the LFP batteries with a capacity of 150 kWh with a charging power of 200 kW.

If a trolleybus traction network already exists, it is possible to use it to charge battery trolleybuses in the IMC system, which is an argument for using it in cities with the a trolleybus network. However, the power supply system may require modifications: due to much higher current consumption of IMC trolleybuses, it may be necessary to build additional traction substations or power supply cables (feeders). It may also be necessary to modify elements of the existing overhead traction network, in particular replacing section insulators with those enabling running with current consumption.

Batteries are a significant part of the cost of electric bus purchase. If we also take into account the cost of replacing them, these two costs may turn out to be a decisive factor from the point of view of the life cycle costing (LCC). Moreover, along with the development of electromobility, the demand for batteries will increase, which may be associated with further problems, e.g. related to limited availability of raw materials. Therefore, it is important to design a transport system taking into account the minimization of the need for batteries. Future research directions should be focused on optimization of on-board charging converters in terms of the use of modern semiconductor element technologies, which will reduce their price and dimensions.

CRediT authorship contribution statement

Mikołaj Bartłomiejczyk: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Priscilla Caliandro:** Software, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

Financial support of these studies from Gdansk University of Technology by the DEC-07/2021/IDUB/II.1/AMERICIUM grant under the IDUB Americium - 'Excellence Initiative - Research University and DEC-03/2023/IDUB/IV.2/EUROPIUM grant under the IDUB Europium - 'Excellence Initiative - Research University' program is gratefully acknowledged.

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