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Bartłomiejczyk, Mikołaj; Jarzebowicz, Leszek; Baig, Mirza Khalid; Diab, Ibrahim; Chandra Mouli, Gautham Ram; Bauer, Pavol

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Comparison of battery technologies, size, and charging strategies for inter-city in–motion-charging buses

Mikołaj Bartłomiejczyk [a,*], Leszek Jarzebowicz [a], Mirza Khalid Baig [b], Ibrahim Diab [b], Gautham Ram Chandra Mouli [b], Pavol Bauer [b]

[a] Gdańsk University of Technology, Faculty of Electrical and Control Engineering, ul. G. Narutowicza 11/12, 80-233 Gdansk, Poland
[b] Electrical Sustainable Energy department Technische Universiteit Delft (TU Delft), Delft, the Netherlands

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ABSTRACT

The growth of suburbs is a challenge for public transport, and new tools are needed to electrify suburban and intercity bus lines sustainably. In-motion-charging (IMC) buses combine the advantages of both trolleybuses and electric buses. This paper analyses a case of using IMC buses on a 17-km-long intercity route service between Arnhem and Wageningen in the Netherlands. The analysis covers different traction battery technologies, sizes, and charging strategies to find the economically optimal solution. The study was carried out using a numerical model of an IMC bus, which was validated and tuned based on year-round experimental recordings obtained from Arnhem trolleybuses. The model outputs were next used to analyse the batteries ageing under specific charging-discharging current profiles. The analysis shows that the most long-term cost-effective solution for the considered case consists of using merged IMC and opportunity charging as well as a 90 kWh LTO battery, whose expected lifetime would be more than 14 years.

1. Introduction

In today's world, when environmental concerns are increasingly pressing, seeking ecological alternatives in transport systems becomes essential [1]. The demand for zero tailpipe emission and high energy efficiency leads to replacing internal combustion vehicles with electric ones. Regarding public transport, electrification is widely adopted for intra-city systems, where diesel buses are replaced by electric ones (e-buses) [2]. For intercity connections, however, the demand for a large energy capacity of onboard energy storage and the significant time required for charging make e-buses much less competitive than diesel-propelled buses. Nevertheless, the above-mentioned drawbacks of the e-buses may be substantially reduced when in-motion-charging (IMC) bus is considered.

The IMC bus is a hybrid form of vehicle, filling the gap between trolleybuses and e-buses [3,31]. When compared to the conventional trolleybuses, IMC buses operate in two distinct modes (Diab et al. [4]):

- Trolley mode: when riding along sections equipped with catenary, the IMC bus is powered by energy from the overhead supply and simultaneously charges its battery. The power drawn from the catenary covers the traction drive demand, auxiliary loads and charges the on-board battery.

- battery mode: when riding along sections without catenary network, the IMC bus draws power from the on-board battery. The energy stored in the battery is used to cover both traction and auxiliary loads, like in an e-bus [5].

Due to in-motion charging, the on-board battery can be charged while the vehicle rides along the catenary section. Hence, no out-of-service time due to charging needs to be assured [6]. The requirement for battery capacity is lower since it is charged during parts of each vehicle run. Lower battery capacity makes the vehicle less expensive and heavy [7]. The latter factor increases energy efficiency and acceleration [8].

Due to their limited range, electric buses are not predestined to service long lines. However, the growth of suburbs is a challenge for public transport, and new tools are needed to sustainably electrify suburban and intercity bus lines.

1.1. Research gap: The new domain of IMC buses - Intercity routes.

With the development of electromobility, there is a visible trend to introduce electric buses to service intercity lines as well [9]. It is possible to operate intercity lines with electric buses by using appropriate

* Corresponding author.
E-mail address: mikolaj.bartlomiejczyk@pg.edu.pl (M. Bartłomiejczyk).

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Nomenclature

C-rate	Current-Related Battery Charge/Discharge 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 Ferro Phosphate Battery
LTO	Lithium-Titanium-Oxide Battery
NMC	Lithium-Nickel-Manganese-Cobalt Battery
OHL	Overhead Line (Trolleybus Catenary)
ONC	Overnight Charging
OPP	Opportunity Charging
SM	Semiempirical Model
SOC	State Of Charge
SoH	State Of Health
SoR	State Of Resistance

List of variables:

Variables related to energy calculations:

E_{tot}	Overall Energy Delivered To Battery,
E_{OHL}	Energy Transferred From Catenary To Vehicle During Autonomous (Battery Mode) Ride,
E_{veh_bat}	Energy Demand On Battery Section (Includes Regenerative-Braking Energy),
E_{OHL_day}	Energy Supplied To Battery During The Day Using Dynamic Charging,
E_{bat_day}	Energy Consumed During Autonomous (Battery Mode) Ride,
P_{IMC}	Charging Power Drawn From The Catenary During Ride,
P_{IMC_st}	Charging Power Drawn From The Catenary During Vehicle Stop,
$P_{traction}$	Total Tractive Power,
F_{total}	Total Propelling/Braking Force,
e	Average Energy Consumed By Vehicle Per Distance.

Variables related to vehicle parameters:

a	Vehicle Acceleration,
ρ	Air Density,
C_d	Drag Coefficient
V	Vehicle Velocity,
A	Vehicle Drag Area,
C_d	Rolling Coefficient,
m	Vehicle Mass,
η	Efficiency.

Variables related to movement parameters:

t_{OHL}	Time Of Running Under Catenary,
l_{bat}	Battery-Mode Section Length,
l_{OHL}	Catenary-Mode Section Trip Length,
l_{day}	Total Daily Mileage,
l_{cycle}	Trip Length Of A Running Cycle,
t_{stop}	Dwelling Time,
d	Day Of The Year,
n_{day}	Daily The Number Of Vehicle Trips.

Variables related to the economic analysis:

C_i	Initial Cost,
T	Entire Period Of Analysis (Years),
N	Given Periods For Analysis (Years),
R	Financial Discount Rate,
C_{op} (N)	Operational Costs In A Given Period N,
SV	Residual Value Of Infrastructure And Vehicles After Period T Of Analysis,
H_r	Regenerative Braking Efficiency.

strategic charging and battery swapping (Wang et al. [42]) or using fuel-cell hybrid vehicles (Mongkoldee et al. [38]). However, many European cities operate trolleybus networks, which are the starting point for further expansion of electric transport. IMC technology is currently predestined mainly for electrifying urban Bus Rapid Transit (BRT) lines with high traffic intensity [10]. Still, IMC technology can also be used to electrify intercity lines.

For intercity IMC buses, the battery-operated length of route is significantly greater than that for intracity ones (Diab et al. [4]). Hence, to keep the battery cost and mass at reasonable levels, it may be valid to complement the IMC with other charging methods like opportunity charging (OPC) [11] or over-night charging (ONC) [12] composing a merged charging strategy. Such a case poses a unique operating conditions for the battery. Hence, the selection of battery technology, size and lifetime should be preceded by a comprehensive analysis reflecting the exceptional application. The analysis should not only include the technical aspects but also the battery cost.

So far, IMC lines have been exclusively intercity lines, as detailed in the upcoming section of this paper. However, the case of the Dutch city of Arnhem is ushering in a new use case for IMC buses under intercity routes. Such a service comes with its challenges, as the longer battery-mode route and the relatively larger battery capacity leave no substantial margin for oversizing the battery by following the customary conservative method for reducing battery degradation. This motivates to look deeper into battery technologies, sizes, and charging methods that this paper offers.

1.2. Research Contribution

It is common practice for trolleybuses to oversize their batteries to battle the battery degradation process. However, oversizing is no longer feasible as IMC buses begin to enter the intercity domain and require relatively large battery packs. This paper looks deeper into comparing battery solutions and their trade-offs to find a suitable operation scenario for intercity IMC buses. Furthermore, this paper analyses a case of using the IMC buses in a 17-km-long intercity route service between Arnhem and Wageningen in the Netherlands. To enable the battery-mode operation on a round trip route of 26 km, various stationary charging options that complement the IMC were considered. Moreover, multiple types of traction batteries were analyzed, considering their capacity, mass, and lifetime. The analysis was carried out using a numerical model of the IMC bus, which was validated and tuned based on a year-round experimental recording obtained from Arnhem trolleybuses. The model outputs were next used to analyse the batteries ageing under specific charging-discharging current profiles.

Issues similar to those considered in this paper have been addressed in the literature. For instance, the optimal length of charging corridor for IMC buses is considered in (Diab et al. [4]). The paper introduces an approach to sizing the charging corridor that includes both the stopping and moving times of a typical IMC bus and studies two charging schemes for the IMC bus battery charging. (González-Rodrígue [46]) deals with the problem of optimisation procedures in choosing the optimal motor and batteries. The paper considers three types of vehicles, i.e. e-bus. It uses a multi-objective optimisation optimisation strategy concerning vehicle dynamics, efficiencies, and vehicle behavior in accordance with a list of real-life drive cycles. In turn, [13] introduces a comprehensive mathematical model for optimal charging infrastructure design and battery sizing for e-bus public transport systems in urban setups, including the charger power rating and the number of chargers required to cater for e-buses charging demands. (Manzolli [47]) focuses on optimising the e-bus charging strategy regarding battery degradation. This paper introduces a semi-empirical battery degradation model to evaluate the ageing effect. Also (Al-Saadi [48]) analyses the impact of fast charging on battery degradation under operation profiles from real driving cycles. The analysis includes different battery chemistries, i.e. NMC, LFP and LTO.

According to the authors' knowledge, no publications related to inter-city IMC bus transport would aim to select the optimal capacity and technology of onboard batteries or consider various merged charging strategies. Moreover, even for intra-city transport, there are no papers on combining the IMC with over-night charging (ONC). While trial charging systems consist of IMC and stationary opportunity charging (OPP) at the end terminus [14], no systems merge IMC and ONC. However, this paper proves that such a hybrid IMC + ONC solution may be attractive for cities already having a trolleybus network.

An essential scientific contribution of the article is the fight against the transport exclusion of suburban regions. The development of regional bus lines plays a key role in providing residents with access to education, work, health care and everyday services. The transport exclusion of suburban areas is becoming a significant problem [15]. Convenient bus connections reduce the problem of transport exclusion and make it possible for residents of smaller towns to take advantage of the wide range of educational, cultural and recreational opportunities in larger cities [49]. This is important in the current times of rapid development of agglomerations. The use of IMC technology for the electrification of regional lines proposed in this article may be a tool to combat transport exclusion.

1.3. Paper structure

Section 1 of this paper started with an introduction to the problem and the paper's contributions. Section 2 presents a general survey of the battery technologies and charging methods commonly used in electric bus fleets. Section 3 details the paper's methodology, emphasising battery degradation modeling. Then, in section 4, the hybrid solution for charging is presented, which will be used in the case study of section 5. Ultimately, section 6 summarises the conclusions of the paper.

2. A General survey of battery technologies and charging methods for electric buses

2.1. Stationary charging methods

Stationary charging is used in e-buses but can also be a supplementary method for intercity IMC buses. Stationary charging can be carried out in two forms, which differ in terms of travel range and charging time [11]: opportunity charging system (OPP) and over-night charging system (ONC). The OPP-charged e-bus requires a relatively small battery pack that provides a limited driving range (typically 10–20 km) and its full charge (80–100 %) can be achieved at the end stops within 5–15 min. In contrast, the ONC-charged e-bus must be equipped with a large battery pack to assure a range of up to typically 250 km. The charging is usually much longer than in the case of OPP and takes up to approx. 2–6 h.

Both solutions are not free from disadvantages. A bus's total daily energy consumption, including electric heating in winter and air conditioning in summer, may reach 900 kWh [16]. Hence, it is not possible to implement ONC system for buses with electric heating/cooling. And even in the case of additional oil or gas heating, achieving a satisfactory daily mileage (250–350 km) for electric buses charged ONC riding in unfavourable weather conditions is problematic. In turn, OPP charging requires adequate stopping time to recharge the batteries at the end stops, which significantly limits the flexibility of the transport system. Problems caused by fast battery charging, i.e. limited battery life, high costs of contracted power and associated grid impact, are also a significant inconvenience. Importantly, OPP loading requires precise preparation of timetables, which may limit the flexibility of the transport system [17]. These problems are evident in the case of intercity lines, where delivering a significant amount of traction energy is essential due to the considerable length of the route.

2.2. IMC charging

In-motion charging (IMC), also known as dynamic charging, is a concept developed to address challenges faced by battery electric buses and trolleybuses [36]. It is based on the idea of charging vehicles in motion, which is considered an alternative to classic stationary charging of vehicles [18]. In the case of IMC systems, the trolleybus traction network is the power source for charging [19]. For trolleybuses fitted with a traction battery, the IMC allows them to run outside the catenary-covered area (Diab et al. [4,20]). This results in a significant reduction in the length of the electrified corridor.

Overall, there is much potential for in-motion charging technology to increase the viability of electric buses for intra-urban and inter-urban transportation. It combines the benefits of both e-buses and trolleybuses. It reduces the requirement for catenary section length, making it a more practical choice for cities looking to switch to sustainable public transportation. Using the IMC eliminates the need for a separate charging infrastructure for regular electric buses [21]. Moreover, thanks to IMC technology, it is possible to reduce the battery capacity, which translates into a reduction in the vehicle's weight and, consequently, energy consumption [39]. Selecting the right battery has a key impact on the energy balance of the transport system [22]. Importantly, IMC technology significantly reduces the financial outlays associated with batteries, extending the battery life up to 15 years (Bartłomiejczyk & Caliandro [50]). The increase in charging power of the IMC system also allows for a significant reduction in the charging corridor required to charge the batteries to the level of 20–30 % (Bartłomiejczyk et. al. [32]), which translates into a significant reduction of costs when compared to classic trolleybuses.

Over the past few years, several IMC bus pilot projects have been implemented in Europe. These projects aim to explore the feasibility of battery-electric trolley buses and the benefits they can achieve through in-motion charging technologies. An example of such a project is the "trolley:2.0 initiative supported by Electric Mobility Europe" (EMEurope 2023) [35], which included several pilot systems (Table 1).

A comparison of the battery mode distance for the pilot lines is shown in Fig. 1. As it may be concluded, most initial pilot projects have primarily focused on short routes, employing small batteries to accommodate the limited distances required for battery mode operation. Consequently, these initiatives operated with minimal depth of discharge (DoD) levels. However, the Arnhem case presents a distinctive contrast within this landscape. Spanning a battery mode operation that covers 26 km, this project demands a considerably larger battery capacity.

2.3. Trolleybus network as a range extender for electric buses

Electrification of bus lines, especially intercity ones, poses many problems. It is required to use traction batteries of enough capacity to cover the service route and ensure long enough stop times at the final stops to enable charging. However, many cities have trolleybus networks that can be used for IMC, which turns electric public transportation into a flexible electromobility platform based on "hybrid trolleybuses" with batteries [33,36,43]. Charging trolleybuses in motion can be seen as a trade-off between capital costs and battery capacity and is recommended for cities already operating this system [24]. In such a

Table. 1
Pilot IMC systems in Europe.

City	Description	Battery size	Charging power	Battery technology
Gdynia, Poland	Gepard project, operation of 32 line with dedicated Trolley 2.0 vehicles manufactured by Solaris/Medcom	87 kWh	150 kW	LTO
Solingen, Germany	Since 2018, Solingen's operation of line 695 by articulated Trollino 18 trolleybuses equipped with IMC500 technology and catenary cover only 25 %. They are known as BOBs (battery overhead wire buses)	60 kWh	200 kW	LTO
Esslingen, Germany	Operation of articulated Trollino 18 trolleybuses on route 113	60 kWh	200 kW	LTO
Freiburg, Switzerland	Operation of HESS Swiss Trolley Plus trolleybuses on route 1 with catenary covering 30 % of total route length	66 kWh	350 kW	LTO
Odessa, Ukraine	Operation of converted IMC Skoda 21 Tr trolleybuses	60 kW	60 kW	LFP
Praha, Czech Republic	*Re*-opening of the trolleybus transport after 50 years, operation of articulated SOR/Cegelec trolleybuses on route 58	106 kWh	150 kW	NMC
Praha, Czech Republic	Double articulated Skoda/Trollino 24 trolleybuses on route 59	75 kWh	150 kW	LTO
Arnhem, The Netherlands	Operation of Solaris Medcom 18 trolleybuses on route 352	90 kWh	100 kW	LTO

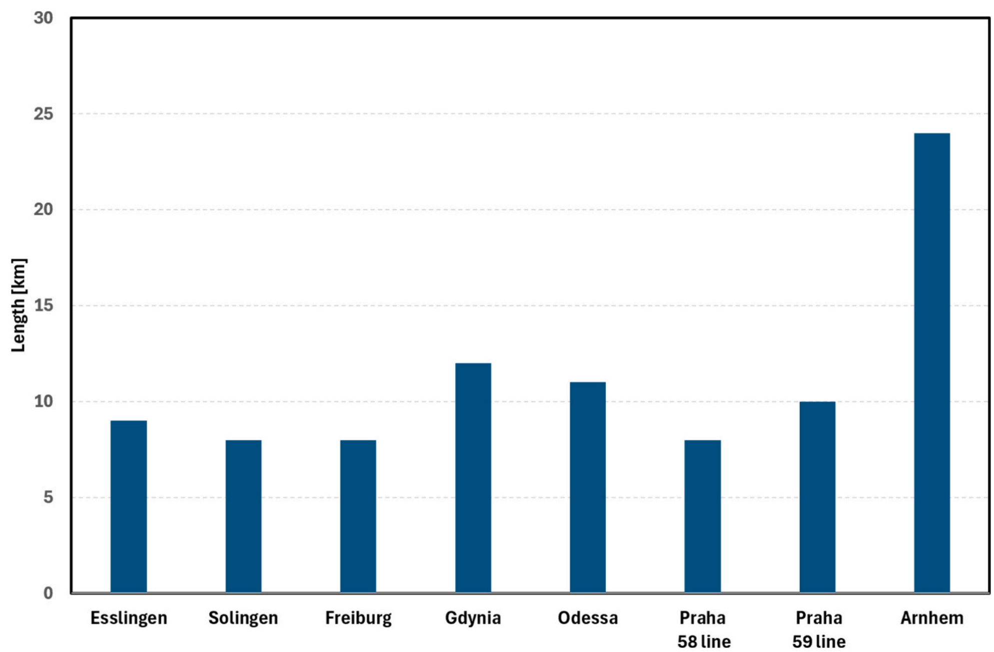

Fig. 1. Comparison of IMC pilot projects: the longest battery-powered driving section of the route.

case, the trolleybus catenary can be considered as a range extender for the e-bus. Moreover, the IMC can be combined with OPP at the final stop or ONC in the depot. The idea of such a merged charging system is shown in Fig. 2.

In the case of operating bus lines with IMC vehicles, the ratio of driving time powered by the traction network to the total driving time and energy consumption in the battery section are crucial (Diab et al. [4]). An important factor that increases the attractiveness of such a solution is the traffic characteristics of intercity lines. In the case of the route layout as in Fig. 2 (traction network in the city centre, battery section outside the city centre), the average driving speed in the centre is usually low, which extends the driving time with power on the section covered with the catenary. This increases the amount of energy supplied during charging. In turn, the battery driving section is located in suburban areas, with smooth traffic and lower energy consumption. This allows for an increase in the driving distance when running on the battery. Hence, in the case of intercity line, the IMC-based system can perform even better than for urban ones.

2.4. Types of traction batteries

The battery is an essential cost factor of an e-bus [37]. Moreover, due to its limited service life, in most cases, it needs to be replaced during the entire life of the vehicle [25]. Table 2 shows the fundamental battery indicators for considered charging systems, including the cost.

Particularly in the case of over-night charging, the most popular type of e-buses, the costs of purchasing and replacing batteries can constitute a significant part of the total vehicle expenditure. In such a case, the supplementation of ONC with IMC allows for:

- limiting the required battery capacity,
- reducing the necessary charging power and limiting the stationary charging time required from OPP.

2.5. Battery degradation process

The battery lifetime is limited to its degradation process, which consists of two elements ([27,23,28,29,41]):

- cyclic ageing,

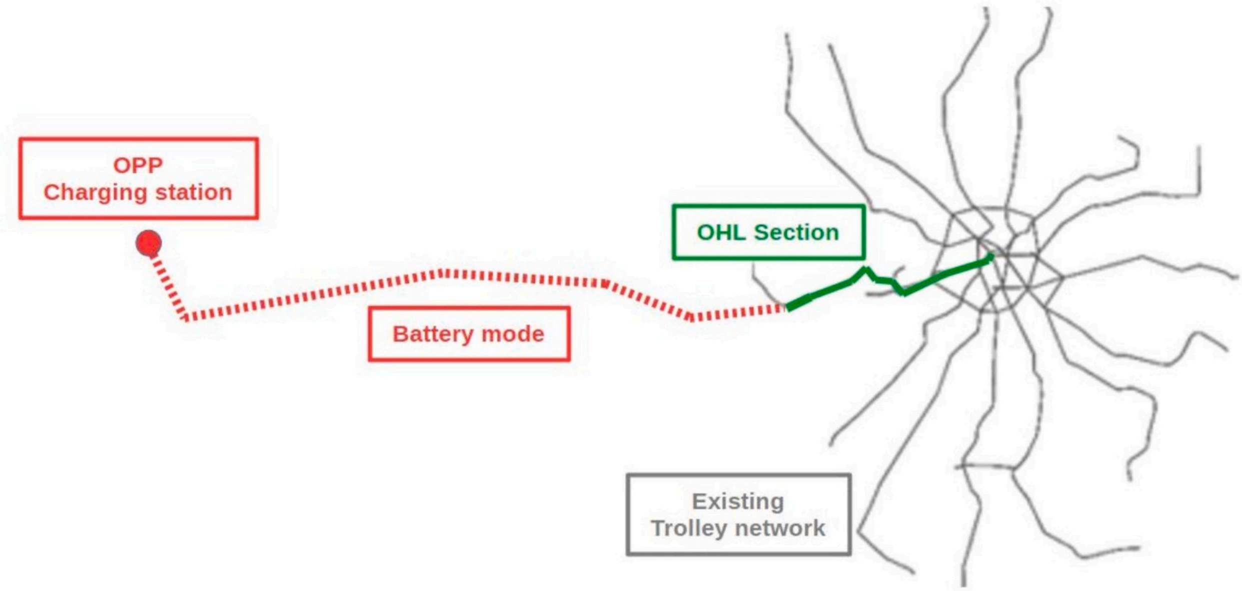

Fig. 2. The idea of a merged charging system for the Arnhem-Wageningen intercity line.

Table. 2
Batteries in electric buses [26].

Charging system	Chemistry	Capacity	Cost	Lifetime
ONC	NMC	400–800 kWh	200–400 kEUR	5–8 years
OPP	NMC	100–300 kWh	50–150 kEUR	5–8 years
OPP	LTO	50–150 kWh	150–300 kEUR	8–15 years

- calendar ageing.

Calendar ageing results mainly from the degradation of the battery during the flow of ions between the anode and the cathode and changes in the volume of the anode and cathode during the charging and discharging process. Calendar ageing is related to chemical processes primarily driven by forming the solid electrolyte interface.

Cyclic ageing can be described as a function of time, as a battery capacity loss per year. However, cyclic ageing can be expressed as a function of equivalent full cycles (EFC), which means the number of charging-discharging cycles related to the nominal capacity E_{capacity} [V]:

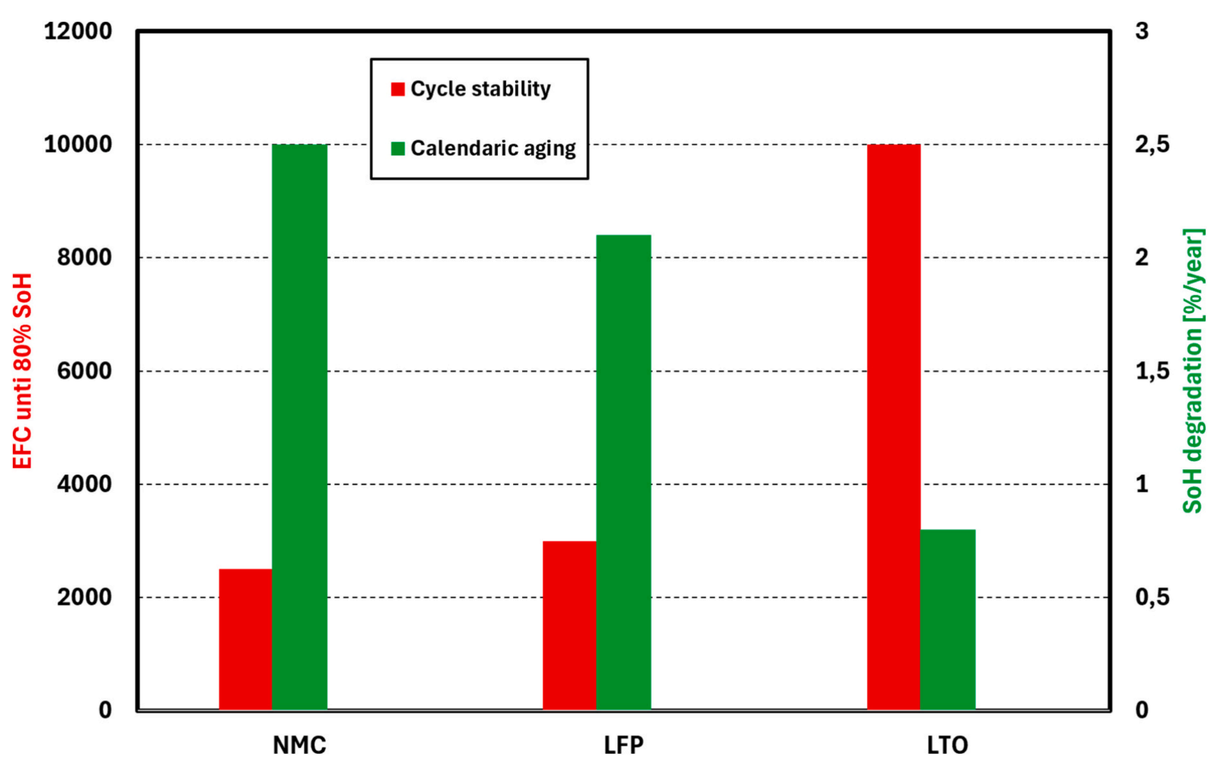

Fig. 3. Comparison of cell chemistries in regard to calendar ageing and cycle stability (Beyeler [34]).

$$EFC = \frac{E_{tot}}{E_{capacity}} \quad (1)$$

where:

E_{tot} – overall energy delivered to the battery.

A comparison of battery ageing rates is shown in Fig. 3. Fig. 4 shows the rate of capacity fade for different battery technologies. The values presented are for reference purposes to illustrate degradation processes. The parameters of individual cell manufacturers may differ significantly. However, slower ageing processes in LTO cells and a much slower capacity loss are visible. The impact of both time and charging cycles is much smaller for them.

An influential parameter for the cyclic battery degradation process is the C-rate (Lyu et al. [23]) defined as the ratio between battery current (in Ampers) and the battery capacity (in Amp-hours). In general, as the C-rate increases, the stress on the cells also increases; thus, the degradation is faster. The greater the current in the cell is, the greater the increase in temperature and pressure compared to the diffusion resistance of migrating ions through the different layers. For this reason, low C-rate is desirable. The influence of C-rate on the rate of degradation processes is particularly visible for NMC and LFP batteries, for this reason the maximum long-term charging current is limited to 1C for these technologies. In such a case, the charging power may be the main factor that impacts the sizing of the battery. In regard to the energy demand, it would be possible to use a battery with a smaller capacity, but it would not be able to recharge sufficiently fast. In the case of LTO, charging with a current higher than 1C (even 10C) is possible, but this shortens the battery life.

When analyzing battery life for a given e-bus line, the key element is the number of equivalent full cycles (EFC). A traction battery with a smaller or larger capacity can be designed for the same traffic conditions. An increase in battery capacity for the same load profile reduces EFC and, consequently, increases the battery lifetime. Also, reducing the EFC is possible by reducing the energy flowing through the battery, e.g. by covering part of the route with supply from trolleybus catenary.

Using the above-described properties, the following cases can be determined for the selection and operation of batteries for individual charging systems in intercity bus lines operation:

- a very high battery capacity of 600–800 kWh is required when ONC is used due to the long driving distance. Due to the large capacity of the battery, cycling ageing is not as dominant as for OPP or IMC (battery is cycled only once per day). However, the large required battery capacity significantly increases the price of the vehicle and the subsequent cost of replacing the battery. Moreover, due to the need to reduce energy consumption, it is necessary to use additional combustion heating (fuel oil, gas) of vehicles, which makes operation more difficult and reduces ecological benefits. The larger battery makes the vehicle heavier, thereby increasing its energy consumption and limiting the space and weight available for passengers;
- in the case of OPP, a significant reduction in capacity is possible when compared to ONC. However, the battery capacity and ageing are determined by cyclical consumption and high charging current. Battery is cycled several times in a day, depending on the battery size and charging frequency and the number of trips, which significantly increases cyclic ageing process;
- The use of the IMC allows for the limitation of charging power, which decreases the requirement for the battery capacity in regard to the C-rate limit. Moreover, charging the battery in motion, similarly to the OPP system, reduces the length of the battery mode driving distance,

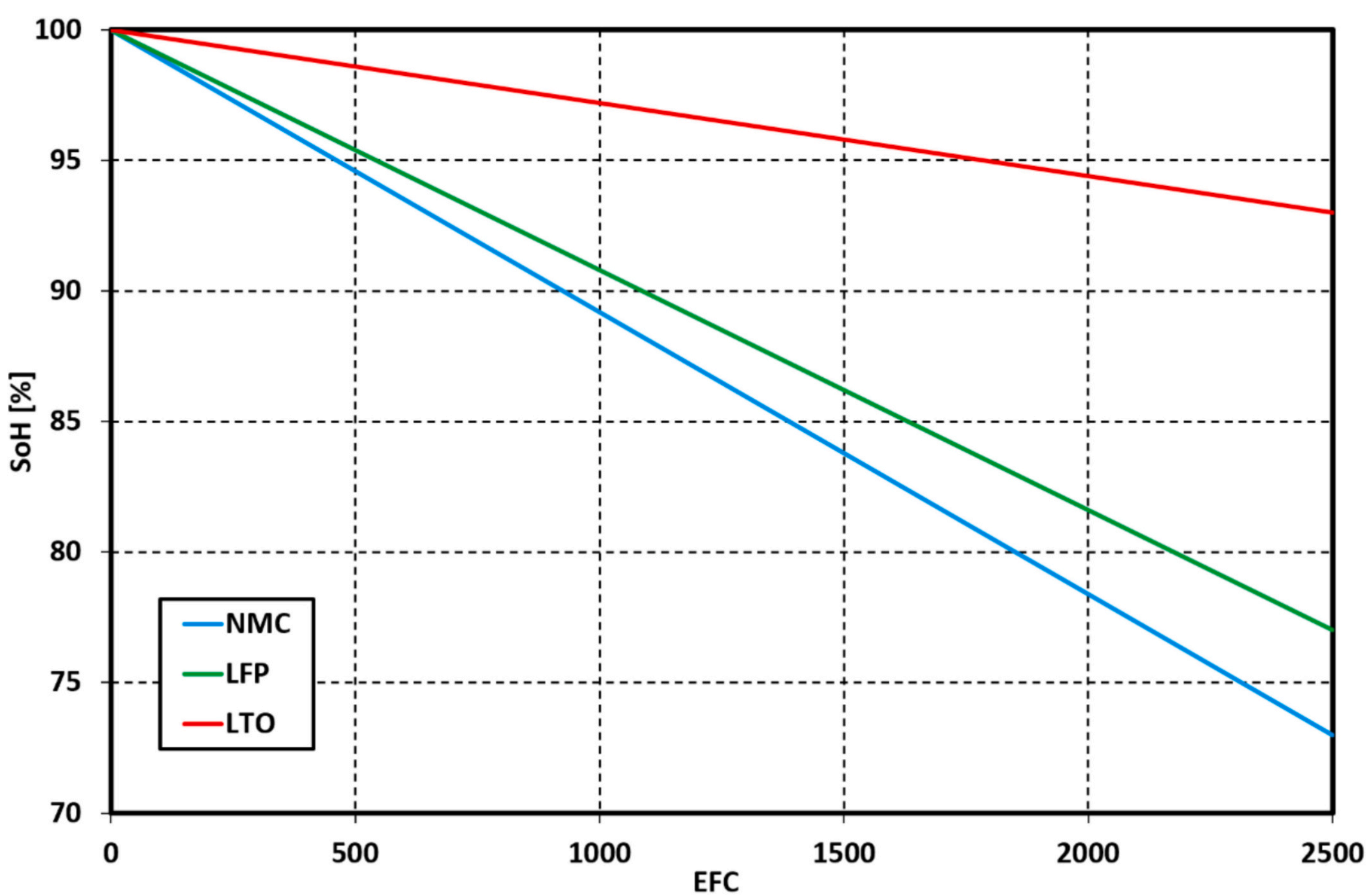

Fig. 4. Cycle stability of particular battery cell chemistries (Beyeler [34]).

which also allows for limiting the battery capacity and increases battery lifetime.

2.6. Battery degradation modeling

Battery degradation modeling can be categorized into three types:

- Physics-based models (PBMs): Effective modeling of battery systems requires accurate representation of the underlying material properties and reaction mechanisms taking place inside the battery. Electrochemical or physics-based models have been found to be the most effective in achieving this, as they provide a detailed understanding of the system behavior. However, these models are complex, and their implementation in power systems is challenging due to the presence of nonlinear differential equations and numerous unknown variables (Lyu et al. [23]).
- Electrical circuit models (ECMs): To overcome challenges of physics-based models, electrical circuit models have been developed. They employ electrical components, such as capacitors, resistors, and voltage sources, to represent the battery current-voltage (I-V) characteristics. Compared to the electrochemical models, ECMs have simpler structures and fewer unknown variables, making them more suitable for battery-powered system control models (Yong et al. [45]). Various ECMs have been developed for different types of batteries, as demonstrated in studies by Hu et al. [44] and Low et al. [30]. However, there are few models available for lithium-titanate-oxide (LTO) batteries.
- Empirical and semi-empirical models (EMs) provide an alternative approach to modeling battery systems. Instead of relying on electrochemical or physics-based models, EMs use analytical formulas obtained by fitting the relationship between various stress factors and the available data through curve-fitting techniques. EMs are widely used in various battery-related studies, such as battery management systems, optimization models, and system-level design issues due to their versatility and ease of use (Lyu et al. [23]).

Out of the three types of models presented above, EMs require minimal input data and can be developed through simple mathematical relationships. EMs also provide a more practical approach to modeling, making them easier to integrate into system-level models. They are useful for studying the effect of different stress factors on battery performance, such as temperature, cycling rates, and state of charge. These models investigate both calendar and cyclic ageing and merge them both to formulate a comprehensive empirical model. Empirical models are constructed based on experimental results, which are then fitted to mathematical equations in order to establish a model. Therefore, it is important to carefully consider the range of conditions within which the experiments were conducted and to fit the mathematical curves. Calendar ageing is depends on the battery cell SOC and temperature. Periodic assessments of their remaining capacity are then conducted. Cycle ageing is dependent upon factors including the depth of discharge (DoD), average SOC, as well as the charging and discharging C-rates. It is quantified by evaluating cell (Ah) throughput. Cycle ageing is evaluated by subjecting the battery to repetitive charge-discharge cycles at specific DoD and C-rate settings. Subsequent measurements of the remaining battery capacity after a defined number of cycles allow for the determination of the rate of ageing. The development of empirical models relies on utilizing experimental data encompassing varying stress factor ranges. The present analysis will use these pre-existing models from the literature to investigate the ageing effects within the context of IMC operational conditions.

3. Methodology

As indicated in the previous section, selection of charging methods, battery type and capacity, and analysis of the battery degradation process are complex and application specific. Therefore, the analysis for the Arnhem-Wageningen e-bus line was carried out using comprehensive models and methods discussed in this section. The described equations have been implemented as MATLAB and Python codes.

3.1. E-bus model

The e-bus model takes into account the different forces influencing the dynamics of the vehicle. When combined with the velocity data, these forces yield the essential power requirements for traction. The formulation of the bus model is based on parameters from the HAN bus model (Omar et al. [40]). However, it must be acknowledged that certain parameters, namely η (drivetrain efficiency) and η_r (regenerative braking efficiency), had to be assumed due to their absence in explicit documentation. Due to the predominantly flat terrain in the Netherlands, gravitational forces are not taken into account when calculating the total tractive forces. However, there is no limitation with using the presented system and model in mountainous terrain. Hilly terrain will affect energy consumption, but the impact of the terrain is minor in the case of electric vehicles compared to combustion vehicles due to regenerative braking. So in mountainous terrain, the autonomous driving range will decrease slightly.

The drag force is given by:

$$F_{drag} = 0.5 \bullet \rho \bullet C_d \bullet V^2 \bullet A \tag{2}$$

ρ – air density.
C_d – drag coefficient.
V – velocity.
A – vehicle drag area.
The rolling resistance force is given by:

$$F_{roll} = C_r \bullet g \bullet m \bullet \cos\theta \tag{3}$$

C_r – rolling coefficient.
m – vehicle mass.
θ – road gradient.
The gradient force is given by:

$$F_{grad} = m \bullet g \bullet \sin\theta \tag{4}$$

Force due to acceleration a is given by:

$$F_{acc} = a \bullet m \tag{5}$$

Total force F_{total} is given by:

$$F_{total} = F_{drag} + F_{roll} + F_{acc} + F_{grad} \tag{6}$$

All the above forces together constitute total forces acting on the body. The total tractive power $P_{traction}$ is given by (for the flat terrain):

$$P_{traction} = \frac{\left(F_{drag} + F_{roll} + F_{acc}\right) \bullet v}{\eta} \tag{7}$$

During regenerative braking, a notable part of the kinematic energy can be stored for later use. For this driving phase, the power can be computed as:

$$P_{regen} = \left(F_{drag} + F_{roll} + F_{acc}\right) \bullet v \bullet \eta_r \tag{8}$$

The widely accepted regenerative braking efficiency of $\eta_r = 0.7$ was adopted.

Eqs. 6 and 7 represent the total electric power associated to traction. However, to comprehensively model the power consumption of the IMC bus system, it is imperative to consider the auxiliary power requirements. This additional power is mainly related to interior heating or air conditioning and it may be comparable in magnitude to the power. In order to include the auxiliary power in the total energy consumption, a comprehensive data-gathering effort was undertaken for all trolleybuses running in Arnhem, for which auxiliary power data was available. Since all these trolleybuses operate in the same geographical location as considered IMC bus route, they are exposed to similar ambient temperatures. To obtain useful auxiliary power patterns, the data for all trolleybuses were plotted in the form of average auxiliary power per day, as illustrated in Fig. 5. A clear similarity in the daily patterns of auxiliary power among different buses emerged. The minor deviations in auxiliary power, represented by spikes on days close to each other, were primarily attributed to variations in bus schedules.

To streamline the analysis, the quadratic-function approximation for the average auxiliary power of all buses was calculated. This approximation, shown in Fig. 5, is given by:

$$P_{auxilary} = 0.35 \bullet d^2 - 135.91 \bullet d + 21642.69 \quad (9)$$

where d is the day of the year.

Another perspective to consider the energy consumption is by examining the energy consumption per kilometer, as shown in Fig. 6. The energy consumption pattern per kilometer mirrors that of the total energy consumption, as the total distance traveled per day remains consistent. During winter, the energy consumption per kilometer can be as high as 2.3 kWh/km, while during spring, it may decrease to approx. 1.5 kWh/km.

By considering the auxiliary power variations throughout a year, the total power consumption of the intercity IMC bus was successfully developed. This approach accounts for the dynamic nature of energy demands and presents a comprehensive understanding of the electric bus systems energy consumption extended durations.

3.2. Battery capacity calculations

In the IMC system, the energy supplied to the vehicle on-board battery during movement along the catenary section must cover the demand of the vehicle for the battery mode section. The battery also gets charged due to regenerative braking, both in catenary and battery modes. The power used for driving the vehicle under the catenary is not considered as this power is immediately used for propulsion. The relation between energies is given by:

$$E_{OHL} \bullet \eta = E_{veh\_bat} \quad (10)$$

where E_{OHL} – energy transferred from the catenary to the vehicle during battery charging, E_{veh_bat} –energy demand on battery section (includes recuperation), η – efficiency.

Assuming t_{OHL} as the time of running on the catenary section, P_{IMC} – the charging power drawn from the catenary, e – average consumption of energy by the vehicle per unit distance, l_{bat} – the length of battery mode section, the formula (9) can be rewritten as:

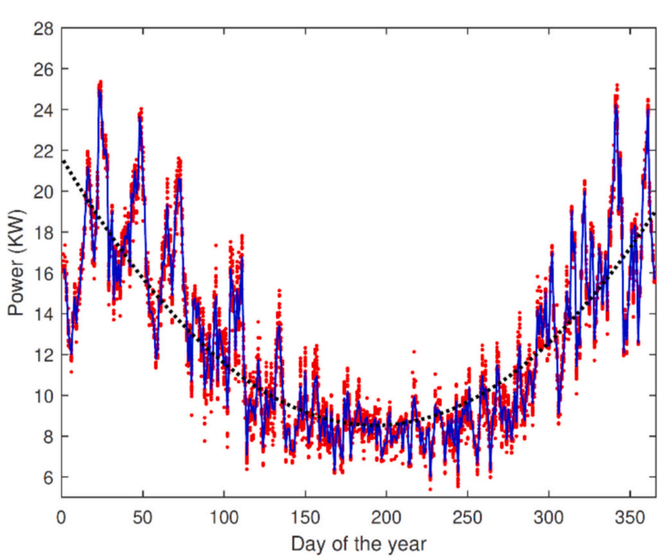

Fig. 5. Average auxiliary power variation for an exemplary trolleybus throughout a year.

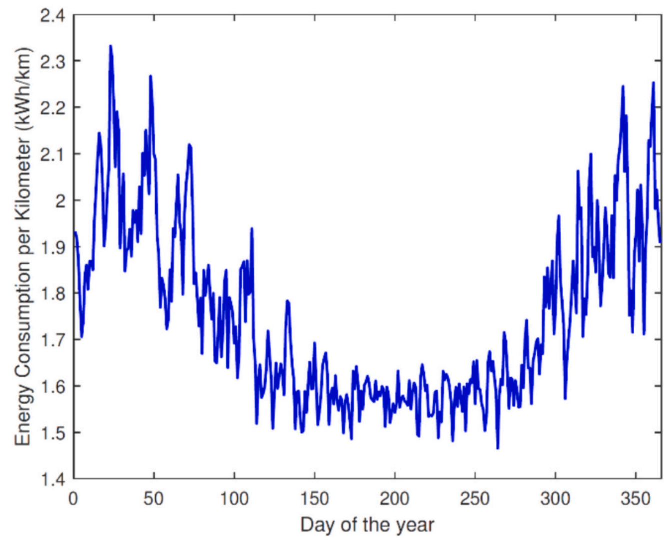

Fig. 6. Average energy consumption per km of a single vehicle on line 352.

$$P_{IMC} \bullet t_{OHL} \bullet \eta = l_{bat} \bullet e \quad (11)$$

Taking into consideration average speed v of the vehicle we can define charged energy in function of the catenary section length l_{OHL}:

$$E_{OHL} = P_{IMC} \bullet \frac{l_{OHL}}{v} \eta \quad (12)$$

From the point of view of the energy balance for the entire day, it is possible to define the difference between the energy E_{OHL_day} supplied to the battery during the day using dynamic charging and the energy E_{bat_day} consumed during battery mode driving. If the energy supplied during charging is not sufficient to cover the energy consumption, then additional energy E_{disch_day} must be supplied to the vehicle

$$E_{disch\_day} = E_{bat\_day} - E_{OHL\_day} \quad (13)$$

An important value is the number of vehicle trips n_{day} on a given line in one direction, equal to the ratio of the total daily mileage l_{day} to the length l_{cycle} of one trip:

$$n_{day} = \frac{l_{day}}{l_{cycle}} \quad (14)$$

Taking into account the length of the traction network section l_{OHL} and battery mode operation l_{bat}, (13) can be re-formulated as follows:

$$n_{day} = \frac{l_{day}}{l_{OHL} + l_{bat}} \quad (15)$$

Additionally, taking into account stationary charging with the power P_{IMC_st} during the stop time t_{stop}, the above relationships can be transformed to:

$$E_{disch\_day} = n_{day} \bullet e \bullet l_{BAT} - n_{day} \bullet P_{IMC} \bullet \frac{l_{OHL}}{v} \eta - 0.5 \bullet n_{day} \bullet P_{IMC\_st} \bullet t_{stop} \quad (16)$$

and:

$$E_{disch\_day} = \frac{l_{day}}{l_{OHL} + l_{BAT}} \bullet \left(e \bullet l_{BAT} - P_{IMC} \bullet \frac{l_{OHL}}{v} \eta - 0.5 \bullet P_{IMC\_st} \bullet t_{stop} \right) \quad (17)$$

where n_{day} coefficient is referred to one direction trip and one stationary charging event refers to two single trips. This fact is illustrated by the constant 0.5 in eqs. 15 and 16.

4. General features and performance of hybrid charging system

The hybrid system may combine: dynamic IMC charging, stationary OPP charging and stationary ONC charging. It is possible to use all the three technologies or only two of them. This determines the required capacity of the on-board battery .

The impact of individual parameters of the IMC system on the required battery capacity was illustrated using the example of a line partially covered with the trolleybus contact line. A case study was adopted in which there is a section of the traction network of a length of 4.3 km and the possibility of extending the vehicle route based on battery power is analyzed. A constant daily total milage of the vehicle is assumed at the level of 400 km and energy consumption at the level of 2.2 kWh/km. In addition, the following options have been included:

- the charging power of OPP station is 90 kW.
- ONC charging.

The analysis results were performed as a function of:

- additional stationary OPP charging time.
- IMC charging power.

The simulation results also present the battery capacity required for the hybrid IMC-ONC system. The minimal required battery size for the given battery mode in function of battery driving mode section is shown in Fig. 7.

The required battery capacity in the vehicle depends on the relationship between the line parameters, OPP stationary charging and additional ONC night charging. Depending on the charging power, battery driving distance and additional stationary OPP charging time, the following parts of the battery capacity characteristic in Fig. 7 can be distinguished:

1. linear, corresponding to the situation when the energy consumed while driving in battery mode is balanced in each cycle by the energy supplied during IMC charging. In this case, we are dealing with IMC charging, which, depending on the relationship between the length of the traction network section and the total length of the route, may take the form of:
   1.1. pure IMC charging (time “0 min” in Fig. 7),
   1.2. a combination of IMC and OPP if the charging time under the catenary is insufficient (charging time greater than 0 in Fig. 7).
2. non-linear (above the line in the graph), corresponding to the case when energy consumption while driving in battery mode is greater than the energy supplied during IMC charging. In this case, the battery charging from IMC and OPP is insufficient to meet energy demands and battery discharge increases with each driving cycle. This requires introducing additional night charging at the depot, hence it is a combination of IMC, OPP and ONC. The required battery capacity depends on the distance of autonomous driving and any additional stop time. However, a smaller battery capacity is sufficient when compared to regular ONC charging.

From the point of view of the technology of batteries used in vehicles, the following variants can be distinguished:

- o when IMC is merged with OPP, and the stationary charging time is sufficient to charge the battery, then batteries with a capacity of 50–100 kWh may be used. This gives a wide range of technology choices. NMC, LFC or very long-life LTO cells can be used. However, this requires the construction of charging stations and ensuring adequate stopping time;
- o if the stationary charging time is too short, or there is no possibility of stationary charging at all, and the traction network section is too short to charge the batteries, then the batteries must be additionally charged in the depot (ONC charging), which requires an increase in the battery capacity. When merging IMC with ONC, a larger battery capacity is required (200–300 kWh), but still much smaller than the standard capacity in the ONC system (600–800 kWh). This in turn decreases the cost of battery and vehicle mass. Due to the significant capacity, it is necessary to use NMC or LFP technology in such a case.

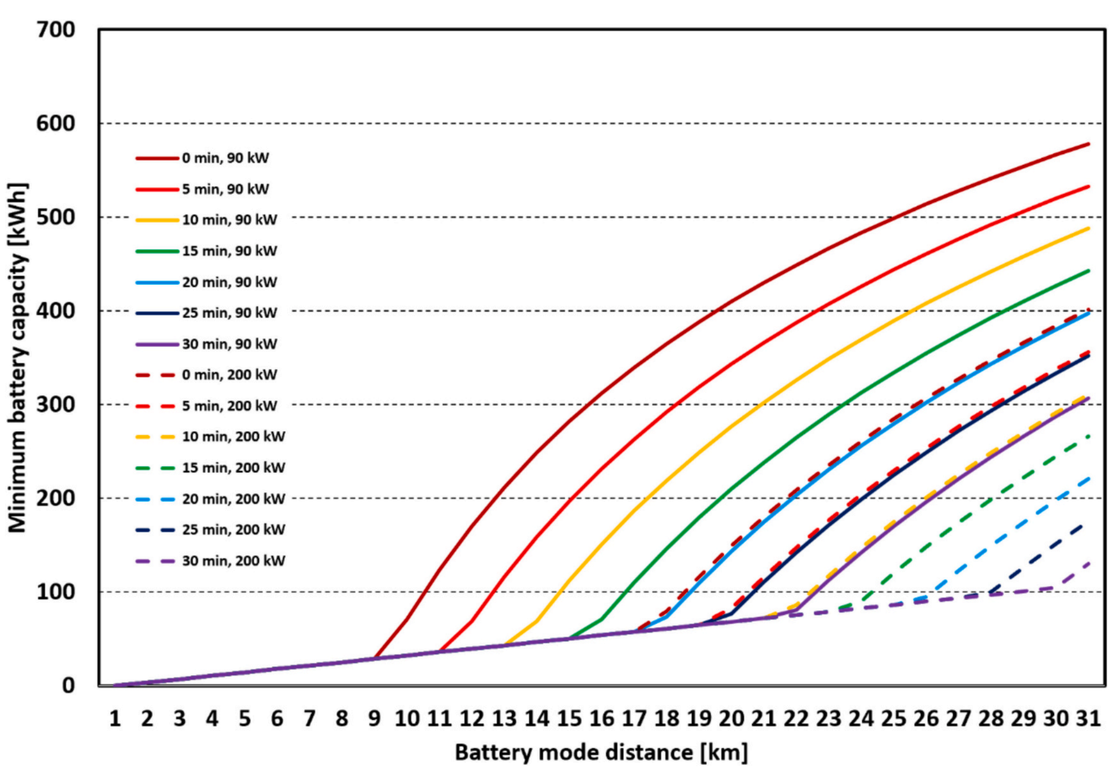

Fig. 7. Minimum battery size for different OPP-IMC-ONC combinations for various OPP charging times and the IMC charging power. The graph legend provides the values of the power and additional charging time on the final terminus.

5. Case study of Arnhem - Wageningen IMC bus intercity line

5.1. E-bus line properties

This section describes the analysis of the Arnhem – Wageningen line serviced by IMC buses. The line covers approximately 35 km for a complete roundtrip (Fig. 8), the dynamic-charging corridor has a length of 4.3 km. The main parameters of the route are shown in Table 3.

The IMC mode of operation extends from "Arnhem Centraal" to "Oosterbeek, Gementeehuis" station. Afterwards, the e-bus switches into the battery mode and covers the part from "Gementeehuis" station to "Wageningen" station. The corresponding distances associated with these specific routes are outlined in Table 3. It is worth noting that the catenary provides coverage for approximately 25 % of the total route distance.

5.2. Velocity profile

The e-bus numerical model, described in Section 2.1, requires reference velocity waveforms. For the IMC mode sections, where trolleybuses run, the data from their on-board recorders were used to prepare the reference velocity profile. As for the battery mode section such experimental data were not available, the velocity profile was prepared artificially, by taking into account stops, speed limits and vehicle dynamics. The merged reference velocity profile is presented in Fig. 9, together with the resulting power waveform.

By synthesizing the velocity profile for the bus along the entire route, the bus model became capable of effectively simulating the tractive power required during journeys that extend beyond the confines of the catenary network. This foundational step was necessary for comprehensively evaluating the energy demands of the IMC bus system under investigation.

5.3. Merged charging scenarios

For the case study analysis, the following charging technologies were initially adopted:

- IMC with a power of 200 kW (IMC 200),
- IMC with a power of 90 kW (IMC 90),
- ONC (ONC),
- OPP with a power of 300 kW (OPP).

The variant of line operation using dynamic charging and line operation based on electric buses with stationary charging were compared. Fig. 10 shows the battery load profile for several variants:

- On the OHL section, depending on the driving mode, the batteries are charged (IMC 90 and 200) or discharged by the vehicle's current.

- At the Wageningen bus stop, depending on the driving mode, the batteries are charged (IMC OPP or OPP) or discharged by vehicle's auxiliary current (IMC or ONC).

Table. 3
Trolley-mode and battery-mode distances at the route of line 352.

Segment		Mode	Distance (km)
1	Arnhem centraal to Oosterbeek, Gemeentehuis	IMC	4.3
2	Oosterbeek, Gemeentehuis to Wageningen bus station	Battery	13.0
	Arnhem centraal to Wageningen bus station		17.3

The picture doesn't show the charging power for ONC electric buses. Fig. 11 shows the minimal IMC charging power for the case of charging vehicles only in motion from the catenary. Calculations were performed for particular months of the year.

On this basis and the analysis performed in the previous chapter, the following conclusions can be drawn regarding the conditions for the electrification of the line Arnhem - Wageningen:

- fully charging from IMC, including the necessary reserve, is possible with charging power at least 200 kW
- in case of IMC 90 kW it is not possible to fully charge under trolleybus catenary for both summer and winter: combination with OPP or ONC charging is required
- when using OPP, IMC or merged IMC-OPP, it is possible to use NMC or LTO battery technology. The implementation of the ONC variant or a combination of IMC and ONC is only possible using NMC batteries.

Due to above-mentioned reasons, the following electrification variants were finally adopted (see also Table 4):

- IMC (200 kW) and LTO or NMC batteries,
- merged IMC (90 kW) + OPP (300 kW) and LTO or NMC batteries,
- merged IMC (90 kW) + ONC and NMC batteries,
- OPP (300 kW) and NMC or LTO batteries,
- ONC and NMC batteries.

Due to thermal limitations (heating of current collectors) during standstill, the charging power from the overhead contact line in the IMC system is limited to 90 kW for the merged IMC OPP charging.

5.4. Battery ageing

In this study, the Open-Sesame empirical battery ageing model was used to analyse the battery ageing. Within Open-Sesame, an array of lithium-ion battery chemistries, namely LFP, NMC, and LTO, are incorporated. Each cell within this simulation framework is characterized by a distinct chemical library, containing specific traits and attributes. Stress factors play a pivotal role in characterizing the impact of

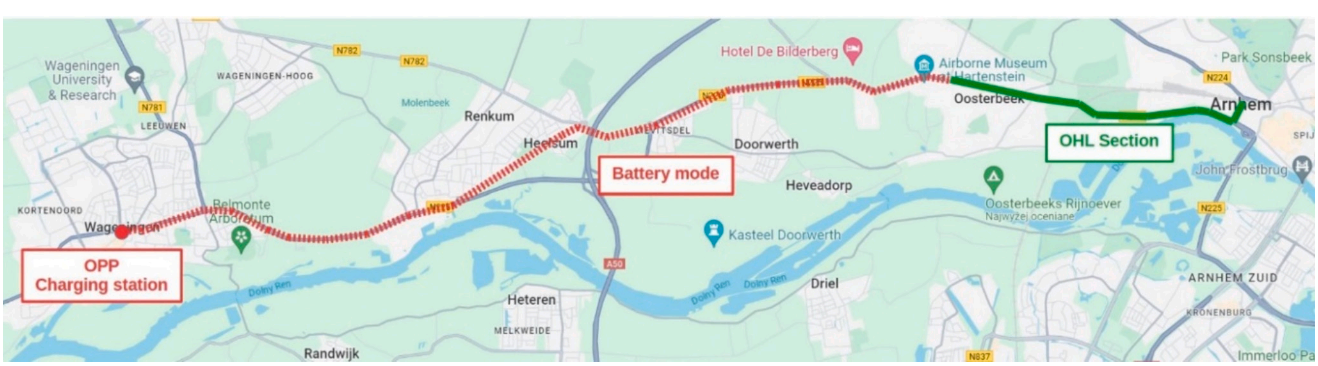

Fig. 8. The scheme of Arnhem - Wageningen IMC bus intercity line.

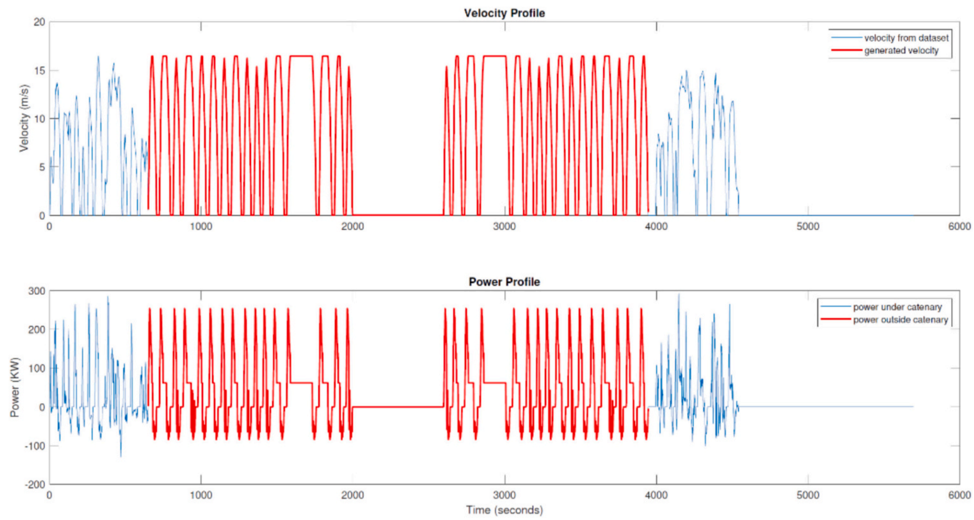

Fig. 9. Velocity profile and traction power waveforms for one round trip (blue IMC mode section, red – battery mode section). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

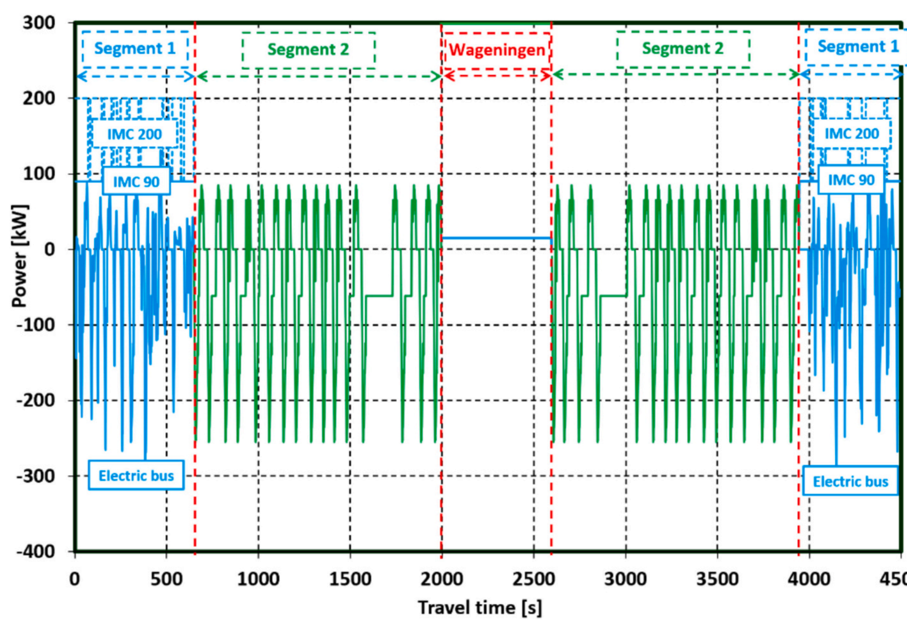

Fig. 10. Battery load profile for bus line 352 for a round trip from "Arnhem Centraal" to "Wageningen" bus station – battery current depending on the variant (positive power means charging).

influential variables, such as the current, C-rate, and average SOC on the ageing process of a battery. These stress factors describe the contributions of both calendar and cyclic ageing phenomena. The foundational step in the ageing calculation process is degradation under standardized conditions. These degradation metrics were obtained through rigorous laboratory tests used in the creation of the tool, which act as a baseline scenario [34].

This initial degradation assessment serves as a cornerstone for comprehending the ageing dynamics of the battery over its operational lifespan. Open-Sesame employs a comprehensive set of six stress factors influencing the state of health (SoH) - current battery capacity relative to the initial capacity:

- SoC (state of charge),
- Average SoC,
- DoD (depth of discharge),
- C-rate,
- Temperature – for cycling ageing,
- Temperature – for calendar ageing.

The calculation is based on a composed set of factors, including the degradation under standard conditions, the dynamic influence of stress factors, and the temporal resolution inherent to the simulation. Conversely, temporal resolution plays a negligible role in calculating cyclic ageing. Cyclic ageing depends on each distinct cycle that is identified within the simulation. The determination of a cycle's progression, relative to a full cycle, hinges upon the DoD experienced during that cycle. The cycle counting algorithm employed is the rain flow counting method. This method facilitates the identification and quantification of subcycles, subsequently enabling the calculation of average charge and discharge rates (C-rates) as well as DoD values based on these subcycles. This approach ensures an accurate assessment of the

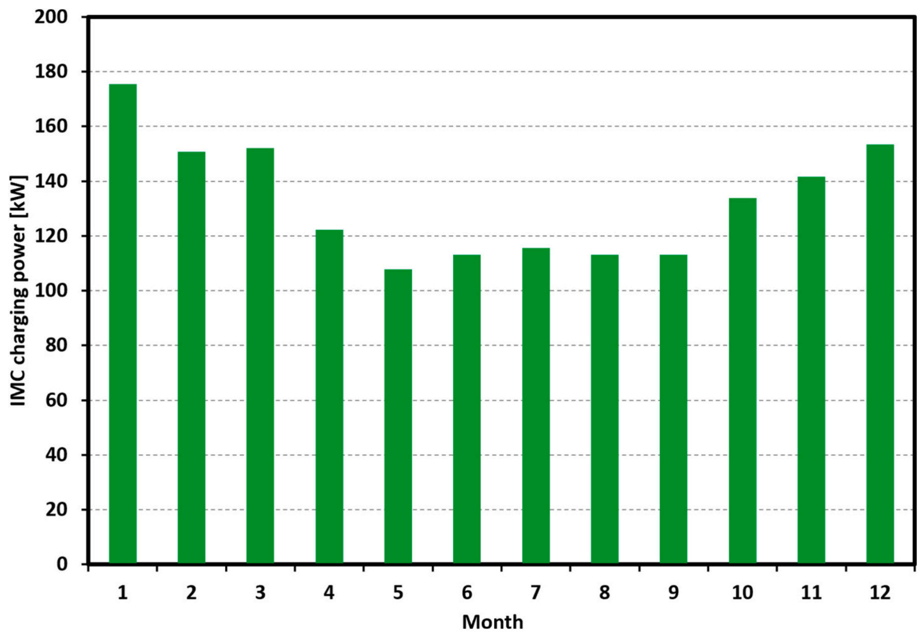

Fig. 11. Minimal IMC charging power required to fully charge the battery in the absence of additional charging for several months.

Table. 4
Variants of charging strategies.

Variant	Battery technology	IMC charging power in motion	IMC charging power while stopping	OPP charging power
IMC, LTO	LTO	200 kW	90 kW	0
IMC + OPP, LTO	LTO	90 kW	90 kW	90 kW
IMC, NMC	NMC	200 kW	90 kW	0
IMC + OPP, NMC	NMC	90 kW	90 kW	90 kW
IMC + ONC, NMC	NMC	90 kW	90 kW	0
ONC, NMC	NMC	0	0	0
OPP, NMC	NMC	0	0	300 kW
OPP, LTO	LTO	0	0	300 kW

'battery's operational dynamics. The degradation analysis unfolds in a sequence of steps. Initially, calendrical ageing is calculated at every time step, encompassing the full span of the simulation. Subsequently, these calendrical ageing values are integrated with the outcomes of cyclic ageing calculations.

Battery lifetime calculations were made for different capacities and different charging systems. The traction battery load profile was determined based on the results discussed in the preceding subsections. 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 of the year. The lifetime threshold was set at 70 % of initial battery capacity. Results of the analysis are shown in Fig. 12. It is clearly visible that LTO generally provides a much longer lifetime than NMC. Moreover, limiting the charging power increases the battery life (in the case of LTO technology, charging IMC OPP 90 kW causes slower battery wear than IMC 200 kW and significantly slower than OPP 300 kW). Due to the high charging power and type of battery technology, the fastest degradation occurs in the 300 kW OPP system. It should also be noted that the battery ageing in the hybrid IMC OPP system with NMC batteries is relatively slow.

5.5. Cost analysis

In each case included in Fig. 12, increasing the battery capacity reduces the depth of discharge (DOD), which increases its lifetime. On the other hand, higher battery capacity means higher purchase and replacement costs. For this reason, a life-cycle cost (LCC) analysis was carried out in which the criterion is discounted costs (infrastructure, batteries and vehicle):

$$LCC = C_i + \sum_{n=1}^{n=T} \frac{C_{op}(n)}{(1+r)^n} - \frac{SV}{(1+r)^T} \tag{17}$$

where:

C_i – initial costs,
T – entire period of analysis (years),
n – given time periods (years),
r – 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.

A linear depreciation of vehicles and infrastructure was assumed. For the calculation of costs, each year the cost of the battery was assumed as the ratio of the battery purchase to its operating time. The results of LCC calculations are shown in Fig. 13, where the optimal capacity of traction batteries for each variant can be found.

Based on the results presented in Fig. 13, optimal solutions for each technology were selected and presented in Table 5. Fig. 14 shows a comparison of battery costs for individual solutions. Assumed 15-year analysis period.

From the point of view of the total life costs of the vehicle, the best solution is to use the LTO battery. In particular, with a low charging power (90 kW), corresponding to a 1C battery current, achieving a battery life of close to 15 years is possible. This means that there is no need to replace the battery during the entire life of the vehicle. In this respect, the optimal solution is to use IMC charging with a relatively limited charging power (90 kW). The use of NMC batteries is associated with higher costs due to their faster degradation. However, suppose it is not possible to fully charge the battery while driving and standing (e.g. it is not possible to build OPP charging station). In that case, it is necessary to use additional night charging, which prevents the use of LTO

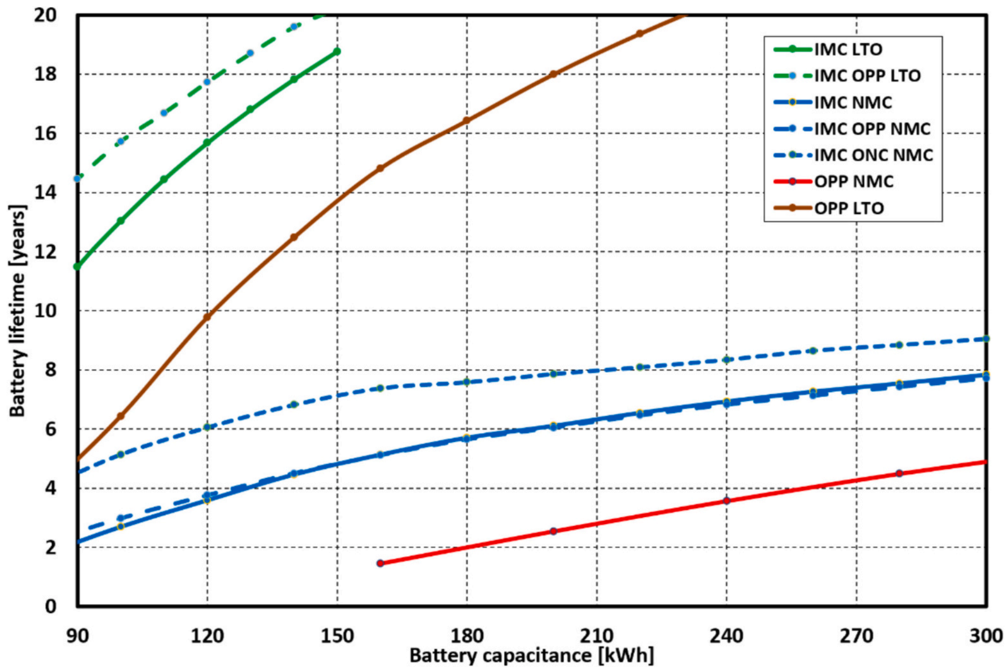

Fig. 12. Battery lifetime as a function of charging system and battery capacity.

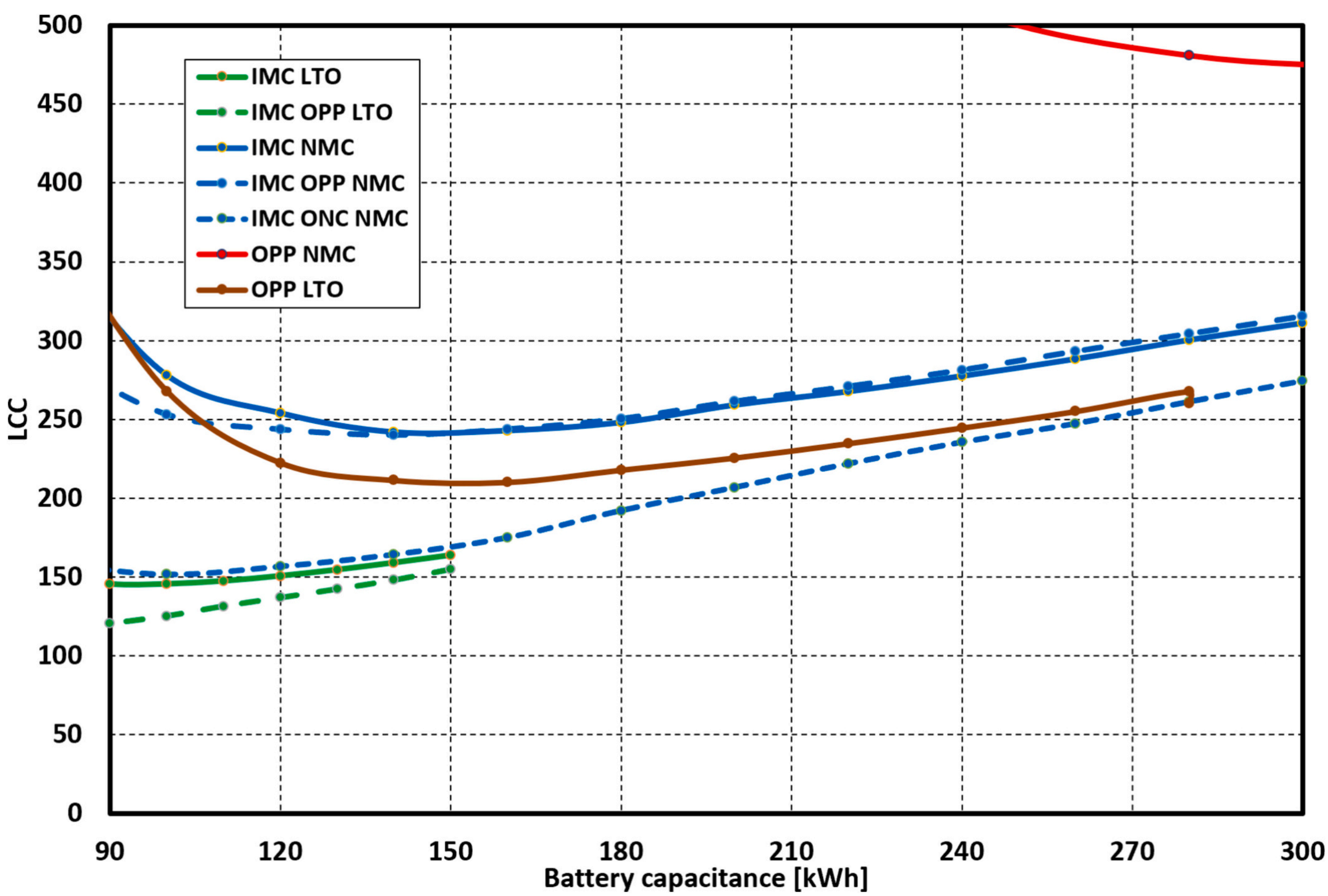

Fig. 13. Battery total life-cycle cost (LCC) in year scale as a function of charging system and battery capacity, (NMC battery price 600 €/kWh, LTO battery price 1300,€/kWh, discount rate 3 %, annual decrease in battery prices 3 % [26]).

Table. 5
Comparison of several analyzed scenarios.

Variant	Optimal battery capacity	Battery lifetime	Number of exchanges
IMC, LTO	110 kWh	14.5 years	0
IMC + OPP, LTO	90 kWh	14.5 years	0
IMC, NMC	150 kWh	5 years	2
IMC + OPP, NMC	150 kWh	5 years	2
IMC + ONC, NMC	250 kWh	8.5 years	1
ONC, NMC*	800 kWh	8.5 years	1
OPP, NMC	300 kWh	5 years	2
OPP, LTO	150 kWh	14 years	0

* not shown on Fig. 13.

batteries. In this case, NMC batteries are necessary. This is associated with an increase in battery costs, resulting from faster battery degradation and the required lower capacity. However, in this case, the advantage of using IMC charging is visible, even in combination with overnight charging, because it reduces the required battery capacity and, consequently, their purchase and replacement costs, especially concerning pure ONC charging. In the case of buses charged only in a stationary way (OPP), the main factor determining the size of the battery is the high charging power. This increases the costs associated with batteries in relation to IMC charging.

6. Conclusion

The analysis of various charging systems and battery technologies for e-buses, with a particular focus on in-motion charging, provides a comprehensive view of opportunities to optimize efficiency, reduce environmental impact, and minimize operational costs. This is an important step towards building more sustainable transportation systems that can contribute to improving quality of life and environmental protection.

In-motion-charging buses, being a hybrid form of vehicle between trolleybuses and e-buses, appear to be an interesting and cost-effective solution for intercity routes. Traditionally, trolleybuses have relied on overhead wire networks for continuous operation, limiting their utility to urban environments. However, with advancements in the batteries technology, trolleybuses can now operate independently from overhead wires for extended distances. This breakthrough eliminates the need for extensive infrastructure investment in intercity regions, where installing overhead wires would be impractical and cost-prohibitive. This hybrid approach maximizes the advantages of both catenary and battery-powered vehicles, offering reduced emissions and noise pollution in urban centers while maintaining flexibility and range for long-distance travel.

The main contribution of the article is the proposal to use IMC charging in the service of intercity lines, which is an attractive solution, especially for cities already operating a trolleybus network. This issue is of great importance in the context of the development of agglomerations and the migration of residents to suburban areas.

The conducted research allows to list the following key findings:

1) The combination of different charging methods allows for increasing the scope of application of IMC charging from the trolleybus network,
2) It is beneficial to reduce battery charging power, which has a positive effect on service life. This is possible, among other things, by using additional charging on the final stops,
3) in case of interurban lines, a combination of IMC charging with overnight charging and using high energy batteries (NMC or LFP) can be a beneficial solution. This is particularly attractive in the context of the growing popularity of LFP batteries,
4) IMC dynamic charging can be an attractive sustainable tool for the electrification of intercity bus lines: IMC allows to connect growing demand for zero-emission transportation of suburbs areas with better usage of existing city infrastructure.

For the considered case of Arnhem-Wageningen intercity line, the LTO batteries clearly overperformed NMC costs accumulated during vehicle service life. The most cost-effective option is to set LTO batteries using the merged IMC + OPP charging strategy. However, the battery cost for sole IMC charging is not substantially higher, and may appear also as an attractive option, especially if the OPP charging station needs to be constructed exclusively to service the considered line. The most cost effective solution that does not use IMC is OPP, LTO, whose cost is

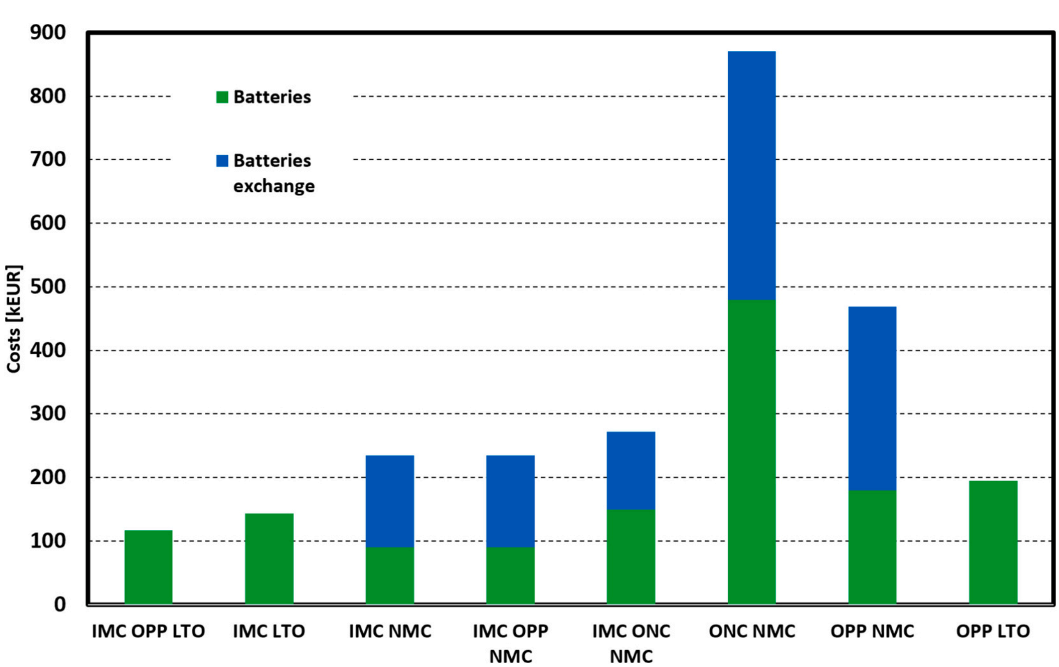

Fig. 14. Battery cost structure.

approximately 1,7 times higher than IMC + OPP, LTO. This confirms that the use of trolleybus catenary, even if the charging corridor constitutes only a quarter of the total route length, substantially reduces operational costs.

Future works should look into the applicability of these conclusions to routes that differ from the Arnhem-Wageningen route, especially in the road gradient and number of bus stops, both of which affect the energy consumption and battery degradation. Furthermore, the price of battery technologies should be continuously re-assessed as battery markets are very dynamic. A generalizable version of this paper that takes battery price as a variable is highly welcomed.

CRediT authorship contribution statement

Mikołaj Bartłomiejczyk: Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Funding acquisition. **Leszek Jarzebowicz:** Writing – review & editing, Supervision, Software, Investigation. **Mirza Khalid Baig:** Visualization, Validation, Software, Resources, Methodology, Investigation, Data curation, Conceptualization. **Ibrahim Diab:** Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gautham Ram Chandra Mouli:** Writing – review & editing. **Pavol Bauer:** Supervision, 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.

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Data availability

Data will be made available on request.

References

[1] European Environment Agency. Greenhouse gas emissions from transport in Europe. www.eea.europa.eu, Nov. 2021. URL: https://www.eea.europa.eu/ims/greenhouse-gas-emissions-fromtransport.
[2] P. Li, M. Jiang, Y. Zhang, Y. Zhang, Cooperative optimization of bus service and charging schedules for a fast-charging battery electric bus network, IEEE Trans. Intell. Transp. Syst. 24 (5) (2023) 5362–5375, https://doi.org/10.1109/TITS.2023.3243105.
[3] Bartłomiejczyk M., ""Practical application of in motion charging: Trolleybuses service on bus lines"," in 2017 18th International Scientific Conference on Electric Power Engineering (EPE). IEEE, 2017, pp. 1–6. https://doi.org/10.1109/EPE.2017.7967239.
[4] Diab I., Mouli G. R. C., Bauer P., "Toward a Better Estimation of the Charging Corridor Length of In-Motion-Charging Trolleybuses," 2022 IEEE Transportation Electrification Conference & Expo (ITEC), Anaheim, CA, USA, 2022, pp. 557–562, doi:https://doi.org/10.1109/ITEC53557.2022.9814021.
[5] Bergk Fabian, et al., Potential of in-motion charging buses for the electrification of urban bus line, Journal of Earth Sciences and Geotechnical Engineering 6 (2016) 1792–9660.
[6] K. Gkiotsalitis, Bus holding of electric buses with scheduled charging times, IEEE Trans. Intell. Transp. Syst. 22 (11) (2021) 6760–6771, https://doi.org/10.1109/TITS.2020.2994538.
[7] Moroz D. G., Zhukov A. I., Makurina V. M., Akopov P. V. and Kudryshov M. A., "Methodology for Determining the Minimum Capacity of Traction Batteries of Electric Buses Based on the Operational Characteristics of Routes Using Artificial Intelligence Tools," 2023 Systems of Signals Generating and Processing in the field of on board communications, Moscow, Russian Federation, 2023, pp. 1–6, doi:https://doi.org/10.1109/IEEECONF56737.2023.10092121.
[8] 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, Erich Schmidt Verlag, (ISSN 0340-4536).
[9] García-Afonso Óscar, ""Impact of powertrain electrification on the overall CO2 emissions of intercity public bus transport: Tenerife Island test case"", Journal of Cleaner Production, Volume 412, 137365, ISSN 0959-6526 (2023), https://doi.org/10.1016/j.jclepro.2023.137365. (https://www.sciencedirect.com/science/article/pii/S0959652623015238).
[10] A.E. Díez, M. Restrepo, A planning method for partially grid-connected bus rapid transit systems operating with in-motion charging batteries, Energies 14, Page 2550, 14(9) (2021) 2550, https://doi.org/10.3390/EN14092550.
[11] M. Bartłomiejczyk, L. Jarzebowicz, R. Hrbáč, Application of traction supply system for charging electric cars, Energies 15 (2022) 1448, https://doi.org/10.3390/en15041448.
[12] A. Ali, A.F. Ayad, M. Asfoor, Optimal charge scheduling and on-board control of an urban electrified BRT fleet considering synthetic representative driving cycles, Sci. Rep. 14 (2024) 5543, https://doi.org/10.1038/s41598-024-55725-y.
[13] A. Kumari, Z. H. Rather and P. V. Dahiwale, "Optimal Design of Charging Infrastructure and Battery Sizing for Electric Bus based Public Transportation System," 2023 IEEE 20th India council international conference (INDICON), Hyderabad, India, 2023, pp. 1234–1239, doi:https://doi.org/10.1109/INDICON59947.2023.10440896.
[14] Bartłomiejczyk M., Połom M., Jarzębowicz L., Jakimovska K., “Economic benefits of dynamic charging of electric buses” , 2021, TTS 2021 Conference 3rd International Scientific Conference "TRANSPORT FOR TODAY'S SOCIETY", DOI 10.20544/TTS2021.1.1.21.p38.
[15] A. Charnavalau, E.J. Szymańska, G. Czapski, The impact of transport exclusion on the local development of Biała County, Sustainability 14 (2022) 5674, https://doi.org/10.3390/su14095674.
[16] M. Bartłomiejczyk, M. Połom, ""Dynamic Charging of Electric Buses as a Way to Reduce Investment Risks of Urban Transport System Electrification, in: TRANSBALTICA XI: TRANSPORTATION SCIENCE AND TECHNOLOGY, Vilnius, LITHUANIA, MAY 02-03, 2019, 2019, pp. 297–308, https://doi.org/10.1007/978–3–030-38666-5_32.
[17] L.E. Teoh, H.L. Khoo, S.Y. Goh, L.M. Chong, scenario-based electric bus operation: a case study of Putrajaya, Malaysia, international journal of transportation, Sci. Technol. 7 (1) (2018) 10–25. ISSN 2046-0430,, https://doi.org/10.1016/j.ijtst.2017.09.002.
[18] Y. Shanmugam, et al., A systematic review of dynamic wireless charging system for electric transportation, IEEE Access 10 (2022) 133617–133642, https://doi.org/10.1109/ACCESS.2022.3227217.
[19] M. Połom, Technology development and spatial diffusion of auxiliary power sources in trolleybuses in European countries, Energies 14, Page 3040, 14(11) (2021) 3040, https://doi.org/10.3390/EN14113040.
[20] I. Diab, R. Eggermont, G.R.C. Mouli, P. Bauer, An adaptive battery charging method for the electrification of diesel or CNG buses as in-motion-charging trolleybuses, IEEE Transactions on Transportation Electrification 9 (3) (2023) 4531–4540.
[21] Tomar, A. S., Veenhuizen, B., Buning, L., & Pyman, B., “Estimation of the Size of the Battery for Hybrid Electric Trolley Busses Using Backward Quasi-Static Modelling”. Proceedings 2018, Vol. 2, Page 1499, 2(23), 1499. doi:https://doi.org/10.3390/PROCEEDINGS2231499.
[22] Kendra, M., Pribula, D., Skrúcaný, T., Blažeková, O., & Stoilova, S.: “Battery-Assisted Trolleybuses: Effect of Battery Energy Utilization Ratio on Overall Traction Energy Consumption”, 2024 Sustainability (Switzerland), 16(24), 11303. doi:https://doi.org/10.3390/SU162411303.
[23] Lyu C., Zhao Y., Han Y., Guo Q. and Zhao X., "An Electrochemical Thermal Coupling Model for High C-rate Conditions in Lithium-ion Batteries," 2020 15th IEEE conference on industrial electronics and applications (ICIEA), Kristiansand, Norway, 2020, pp. 1733–1737, doi:https://doi.org/10.1109/ICIEA48937.2020.9248162.
[24] M. Wołek, M. Wolański, M. Bartłomiejczyk, O. Wyszomirski, K. Grzelec, Hebel, K.. „Ensuring sustainable development of urban public transport: A case study of the trolleybus system in Gdynia and Sopot (Poland), J. Clean. Prod. 279 (2021) 123807, https://doi.org/10.1016/J.JCLEPRO.2020.123807.
[25] Panta Utsav, Gairola Pranav, N. Nezamuddin, Modelling benefit-to-cost ratio for initial phase electrification using battery electric bus, Transp. Policy 145 (2024) 137–149. ISSN 0967-070X,, https://doi.org/10.1016/j.tranpol.2023.10.016.
[26] Verkehrsverbund Luzern Infrras, E-Bus-Strategie Schlussbericht. https://www.vvl.ch/application/files/7516/1910/0474/20190404_Bericht_E-Bus-Strategie-VVL_final.pdf, 2019.
[27] Li T., Zhang W., Huang G., He H., Xie Y., Zhu T., Liu G., ""Real-world data-driven charging strategies for incorporating health awareness in electric buses"", Journal of Energy Storage"," Volume 92, 2024, 112064, ISSN 2352-152X, doi:https://doi.org/10.1016/j.est.2024.112064.
[28] A. Ndiaye, R. German, A. Bouscayrol, M. Gaetani-Liseo, P. Venet, E. Castex, Impact of the user charging practice on the battery ageing in an electric vehicle, IEEE Trans. Veh. Technol. 73 (4) (2024) 4578–4588, https://doi.org/10.1109/TVT.2024.3356116.
[29] Zhao, C. Li X. and Yao Y., "Quality Analysis of Battery Degradation Models with Real Battery Ageing Experiment Data," 2023 IEEE Texas power and energy conference (TPEC), College Station, TX, USA, 2023, pp. 1–5, doi:https://doi.org/10.1109/TPEC56611.2023.10078599.
[30] W.Y. Low, et al., Electrical model to predict current–voltage behaviours of lithium ferro phosphate batteries using a transient response correction method, J. Power

Sources 221 (2013) 201–209, https://doi.org/10.1016/j.jpowsour.2012.07.140. (Visited on 06/15/2022).
[31] Bartłomiejczyk M., Mirchevski S., Jarzebowicz L., Karwowski K., "How to choose drive's rated power in electrified urban transport?," 2017 19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe), Warsaw, Poland, 2017, pp. P.1-P.10, doi:10.23919/EPE17ECCEEurope.2017.8098948.
[32] M. Bartłomiejczyk, M. Połom, Possibilities for developing Electromobility by using autonomously powered trolleybuses based on the example of Gdynia, Energies 14 (2021) 2971, https://doi.org/10.3390/en14102971.
[33] M. Bartłomiejczyk, L. Jarzebowicz, S. Mirchevski and M. Połom, "Advancing Urban Transit: Gepard and CAR projects - Innovations in Trolleybus Technology," 2024 Zooming innovation in consumer technologies conference (ZINC), Novi Sad, Serbia, 2024, pp. 31–35, doi:https://doi.org/10.1109/ZINC61849.2024.10579108.
[34] Beyeler Marco, Alterungsoptimierte Batteriebewirtschaftung Mithilfe von Open Source Simulation, Master Thesis,, Fahchhochschule Bern, 2022.
[35] In-Motion-Charging for emission-free public transport Interim report on the Electric Mobility Europe (EMEurope) project trolley:2.0 two years after project start. 2020. URL: https : / / www . electricmobilityeurope.eu/wp-content/uploads/2020/09/Trolley-2-0-Zwischenberichtenglish- final.pdf (visited on 01/12/2023).
[36] Iliopoulou Christina, Tassopoulos Ioannis X., Kepaptsoglou Konstantinos, ""Multi-objective planning of electric bus systems in cities with trolleybus infrastructure networks"", Sustainable Cities and Society, Volume 103, 105227, ISSN 2210-6707 (2024), https://doi.org/10.1016/j.scs.2024.105227.
[37] X. Lu, J. Li, S. Yuan, H. Jin, C. Wu, Z. Xu, Toward real-time pricing and allocation for surplus resources in electric bus charging stations, IEEE Trans. Intell. Transp. Syst. 25 (2) (2024) 2101–2115, https://doi.org/10.1109/TITS.2023.3314648.
[38] Mongkoldee Kritsada, Sukjit Ekarong, Kulworawanichpong Thanatchai, optimal on-board energy buffer design for fuel-cell hybrid intercity vehicles, journal of energy storage, Volume 46 (2022) 103820. ISSN 2352-152X, https://doi.org/10.1016/j.est.2021.103820.
[39] U. Spaeth, A. Popp, H. Fechtner, Schmuelling, B.: "Dynamic Vehicle Mass Estimation of Articulated Battery Trolleybuses for Integration in a Smart Trolley Grid", IEEE transportation electrification conference and expo, ITEC 2024 (2024), https://doi.org/10.1109/ITEC60657.2024.10598991.
[40] Omar Abhishek Singh et al. ""Viability of traction battery for battery-hybrid trolleybus"". In: EVS32 Symposium (2019), pp. 1–12. https://www.sustainable-bus.com/news/volvo-8900-electric-launch-bus/ (01.07.2024).
[41] Ufert M., Bäker B. Battery ""Ageing as Part of the System Design of Battery Electric Urban Bus Fleets"". Science & Technique. 2020;19(1):12–19. doi:10.21122/2227-1031-2020-19-1-12-19.
[42] Wang Zhichao, Guo Zhaomiao, Liu Kai, Lin Zhenhong, Li Shunxi, "multi-stage layout strategies of intercity charging and swapping infrastructure for electric logistics vehicles: random, radical, or conservative"? Transp. Policy 153 (2024) 12–23. ISSN 0967-070X,, https://doi.org/10.1016/j.tranpol.2024.05.009.
[43] Wołek, M., Hebel, K.. "Strategic Planning of the Development of Trolleybus Transportation Within the Cities of Poland", Advances in intelligent systems and computing, AISC 1091 (2020) 141–152, https://doi.org/10.1007/978-3-030-35543-2_12.
[44] Hu Xiaosong et al. ""A comparative study of equivalent circuit models for Li-ion batteries"". In: J. Power Sources 198 (Jan. 2012), pp. 359–367. DOI:10 . 1016 / j . jpowsour . 2011 . 10 . 013. URL: https://www.sciencedirect.com/science/article/pii/S0378775311019628 (visited on 10/16/2019).
[45] Yong Tian, et al., Comparison study on two model-based adaptive algorithms for SOC estimation of Lithium-ion batteries in electric vehicles, Energies 7 (2014) 8446–8464, https://doi.org/10.3390/en7128446. (Visited on 12/30/2019).
[46] P. S. González-Rodríguez, J. D. J. Lozoya-Santos, H. G. Gonzalez-Hernandez, J. S. De La Trinidad-Rendon, L. C. Félix-Herrán and J. C. Tudón-Martinez, "Multi-objective optimization methodology to select electric motor and battery pack using real drive-cycles," 2024 International symposium on Electromobility (ISEM), Guadalajara, Mexico, 2024, pp. 1–7, doi:https://doi.org/10.1109/ISEM62699.2024.10786778.
[47] J. Augusto Manzolli, J. Pedro Trovão, C. Henggeler Antunes, "Optimisation of an Electric Bus Charging Strategy Considering a Semi-Empirical Battery Degradation Model and Weather Conditions," 2022 11th International Conference on Control, Automation and Information Sciences (ICCAIS), Hanoi, Vietnam, 2022, pp. 298–303, https://doi.org/10.1109/ICCAIS56082.2022.9990180.
[48] M. Al-Saadi, J. Olmos, A. Saez-de-Ibarra, J. Van Mierlo, M. Berecibar, Fast charging impact on the Lithium-ion batteries' lifetime and cost-effective battery sizing in heavy-duty electric vehicles applications, Energies 15 (2022) 1278, https://doi.org/10.3390/en15041278.
[49] Matthew Bruno, Machiel Kouwenberg, Niels van Oort, "Addressing transport related social exclusion through transportation policy: A novel evaluation method applied to the Amsterdam Transport Region", Transportation Research Interdisciplinary Perspectives, Volume 26, 101177, ISSN 2590-1982 (2024), https://doi.org/10.1016/j.trip.2024.101177.
[50] M. Bartłomiejczyk, P. Caliandro, Electrifying the bus network with trolleybus: Analyzing the in motion charging technology, Appl. Energy 377 (2025) 124585.