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An innovative decision-making method for choosing a bus fleet based on logistics and sustainability aspects

Vince Kruchina
Institute of Logistics, University of Miskolc, HU-3515 Miskolc-Egyetemváros, Hungary, EU, kruchina.vince@gmail.com (corresponding author)
Peter Tamas
Institute of Logistics, University of Miskolc, HU-3515 Miskolc-Egyetemváros, Hungary, EU, peter.tamas@uni-miskolc.hu
Bela Illes
Institute of Logistics, University of Miskolc, HU-3515 Miskolc-Egyetemváros, Hungary, EU, bela.illes@uni-miskolc.hu

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Abstract: The widespread adoption of electric vehicles (EVs) has played a significant role due to their much smaller carbon footprint compared to their internal combustion engine counterparts. This trend also applies to public transportation in Hungary, where battery electric buses (BEBs) are gradually being incorporated into the fleets of major passenger transport operators. In assessing the total cost of ownership (TCO) of these vehicles, factors such as the expected daily mileage, the current price, capacity, lifecycle, and degradation of the integrated drive train batteries—typically lithium-ion based—play a significant role. This is also considered, if the batteries' second life and reuse can significantly improve the TCO value. Based on the examination of domestic and international literature, it can be established that the selection of the appropriate vehicle fleet exclusively considers the TCO value, which disregards neither the significant benefits arising from the batteries' secondary life cycle, nor considering various quality indicators. This deficiency in fleet selection could result incorrect decisions. In our opinion, the consideration of both logistical and sustainability aspects is indispensable in the decision-making process. To prove this, the paper presents an innovative decision-making method developed by us, which considers the effects of battery degradation related to the secondary life cycle and key quality indicators when selecting the ideal fleet meeting the expected mileage performance. To validate the theoretical background, a case study was also prepared, which is included in the paper. The article also contains considerations related to the topic by Volánbusz Zrt.

1 Introduction

Although buses appeared in road transport much earlier, electric vehicles (EVs) really burst into public transport fleets in the early 2020s. An important element in their uptake has been the fact that their carbon footprint is much smaller comparing to internal combustion engine counterparts, and thus they comply with the legislation and environmental protection requirements resulting from the European Union's climate protection efforts.

Battery electric buses (BEBs) are being progressively integrated into the fleets of major passenger transport operators [1,2], typically leading to mixed fleets [3]. The retention of fossil fuel buses in mixed fleets is primarily related to the driving range of electric vehicles, which determines the types of timetabling that - taking into account the capacity of the batteries and the way they are charged - allow for the safe covering of route distances.

Volánbusz Zrt., which plays a dominant role in suburban and local public transport in addition to domestic intercity bus transport, has been gradually increasing the number of electric buses in its fleet since the early 2000 s [4]. Due to a significant increase in the number of lithium-ion based batteries and their role in the sustainability of the fleet, the rest of this paper will analyse literature on the degradation and second life cycle of electric bus batteries, and then present our research results in this field. Considering this, an innovative decision-making method will be presented that takes into account the positive effects of the second life cycle resulting from battery degradation, and the relevant quality indicators for the selection of the optimal fleet. The results of the calculations based on this decision-making method are presented in the final section of the paper.

2 Thematic literature review

In relation to the objectives stated in this article, a thematic review of literature on batteries for electric buses focused on the following areas:

- types and characteristics of batteries,
- the degradation process in batteries,
- optimal operation and charging of batteries for a long battery life,
- application of reverse logistics in the second life cycle of batteries,
- integration of battery electric buses into mixed fleets.

2.1 Typical types of batteries for battery electric buses (BEB)

As in all areas of life, lithium-ion batteries have also found applications in electric vehicles. As the technology has evolved, competition has started in the following parameters: energy consumption measured in kWh/km; the reduction of overall battery weight; and achievement of the highest energy density.

The acronyms for the three most popular types of lithium-ion technologies are derived from the abbreviations of the minerals used in cell chemistry: LTO (lithium titanium oxide), LFP (lithium iron phosphate) and NMC (nickel manganese cobalt). Figure 1 is based on BMZ Poland's analysis, showing that NMC leads in terms of energy density, but also in unit weight and volume [5].

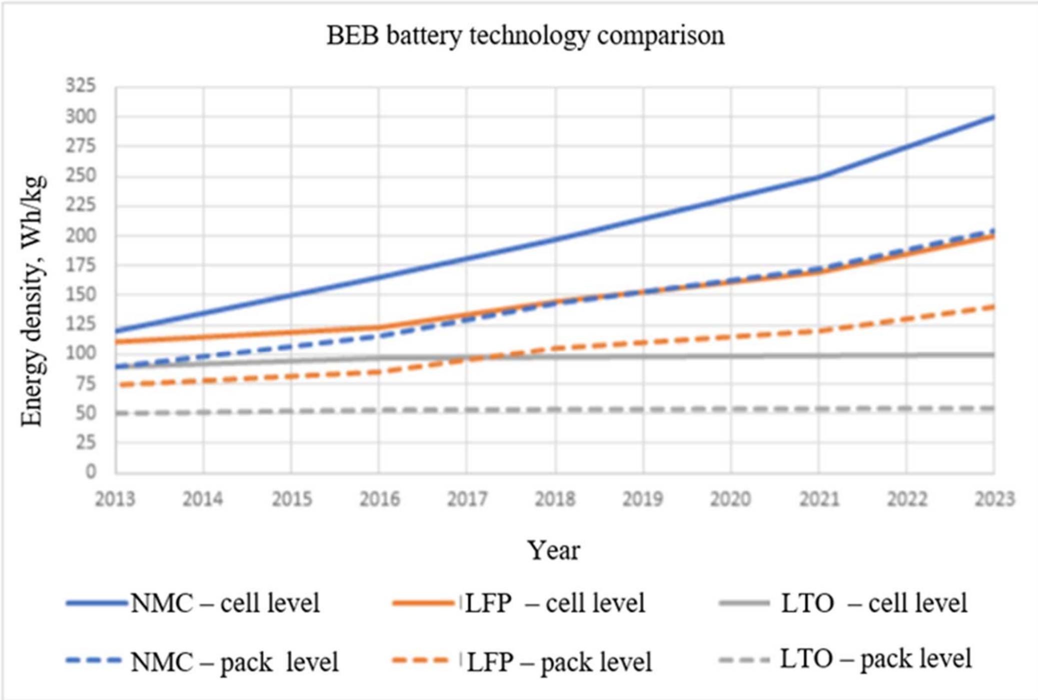

Figure 1 Comparison of the evolution of NMC, LFP and LTO technologies in terms of energy density at the levels of cells and battery packs [5]

2.2 Degradation of batteries

Battery degradation is the result of a number of complex processes, in which cyclic aging and calendar ageing play a combined role, leading to an increase in internal resistance. During cyclic ageing the capacity of the battery decreases, mainly due to an increase in the frequency of charging and discharging cycles. This is due to an increase in the internal solid electrolyte interphase layer, degradation of the electrodes, and cyclic lithium loss. Conversely, calendar ageing - which also leads to loss of capacity - refers to self-discharge reactions influenced by charge state, time and temperature. These phenomena are particularly relevant for electric vehicles, as significant degradation of batteries can increase the total energy consumption of electric vehicles and their greenhouse gas emissions per kilometre on a given driving cycle.

2.3 Optimal operation and charging of batteries for a long battery life

Some studies suggest that battery life can vary between 2,500 and 9,000 charge/discharge cycles [6]. The geographical location of buses can also have an impact on this, as one of the main causes of battery degradation is unfavourable ambient temperature, with lifetime significantly dependent on local temperature - i.e. climatic – conditions. Geography affects not only the lifetime of vehicles, but also their operating costs. Charging costs can vary depending on the time of year and time of day, and the carbon emissions of buses also depend on the energy mix of the power grid in a given country [7]. The lifetime guarantee of batteries is between 5 and 10 years, depending on the manufacturer. The guarantee is defined by manufacturers as a function of chemical composition, operation and charging.

Studies aimed at optimising the operation and charging of battery electric buses estimate battery lifetimes of 8 to 12 years, however, this is closely related to the charging process, and also the development of battery manufacturing technologies can undoubtedly increase the lifetime outlook [8].

But for assessing the long-term return on investment and fleet operational efficiency, a detailed analysis of the effects of degradation is essential. All this is influenced by a number of factors, such as charging rate, temperature, depth of discharge and time/discharge cycle, as well as battery design, manufacturing and operating conditions.

If we want to look at the degradation of a whole battery system and not just one cell, we have to note that the performance of the system is determined by the performance of the individual cells. Ageing of the cells can lead to ageing of the system, but the performance of the battery system is greatly affected by inconsistencies and disparities between cells [9].

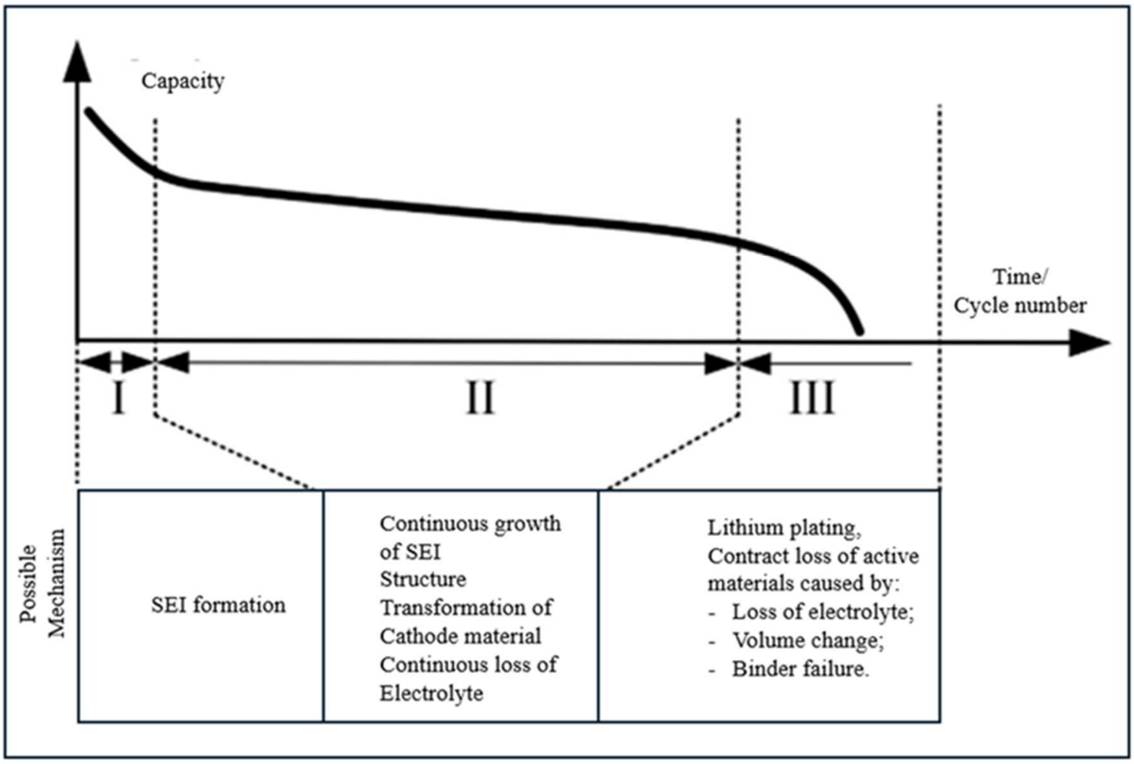

Figure 2 Mechanism of degradation [9]

The non-linear ageing of batteries can be divided into three stages:

- Stage I: solid electrolyte interface formation; sudden, rapid degradation.
- Stage II: further solid electrolyte interface formation, structural change in cathode material, electrolyte loss; linear stage.
- Stage III: lithium plating, continuous loss of material; sudden, rapid degradation.

Generally speaking, most batteries currently used in electric vehicles exhibit the characteristics of non-linear ageing, which can basically be divided into the three phases shown in Figure 2. In the first stage, the battery capacity decreases rapidly during the first few charging cycles. In the second stage, the battery performance decreases continuously due to the different reactions taking place inside the battery. In the third stage, a rapid decrease in capacity and increase in resistance occurs towards the end of the battery’s life. This may be due to a rapid loss of lithium-ion supply and/or a loss of active material due to loss of electrolyte, failure of the binder and volume changes.

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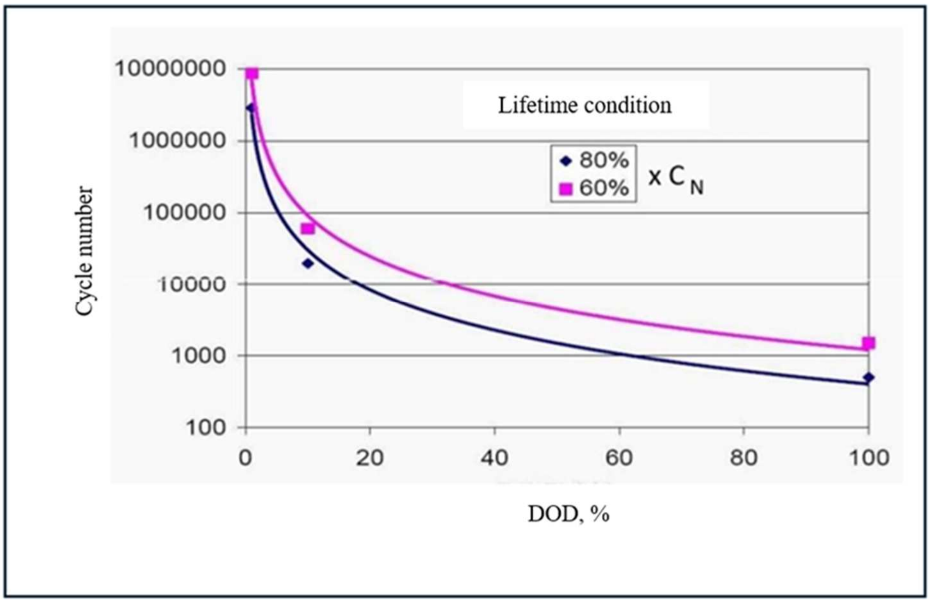

Figure 3 Effect of charging on battery degradation [10]

The state of charge (SOC) of a battery has a significant impact on battery life. The SOC value indicates the amount of available capacity stored in the battery. It is important to note that the SOC and the voltage of the battery are interdependent values. The battery voltage can be derived from the battery SOC and current. In general, a higher SOC results in higher terminal voltage, which means lower anode potential and higher cathode potential. This can accelerate the ageing process of the battery. A lower SOC, on the other hand, means higher anode potential and lower cathode potential, which is generally beneficial for battery life. If the SOC is too low, however, corrosion of the copper current collector of the anode and decomposition of the active material structure of the cathode can negatively affect battery life.

DOD (depth of discharge) also has a complex effect on battery life. According to professional opinion, there is an optimum DOD for battery life, but this DOD is generally too small to meet driving range requirements.

In scientific publications there has been analysis of several other aspects of the degradation of lithium-ion batteries typically used in electric buses. Chen et al. (2015) established a prediction model by analysing discharge characteristics, [11] while Tseng et al. (2015) [12] carried out an in-depth investigation into the effect on battery condition of voltage and internal resistance variation. O'Kane et al. (2022) were the first to publish a model linking two degradation mechanisms [13].

Degradation measurements make it clear that the life cycle of batteries is shorter than the designed service life of electric buses, so that when a battery is no longer suitable for its original function but still has significant value, environmental and economic considerations support the need to address its second life.

2.4 Application of reverse logistics in the second life cycle of batteries

The process known in the literature as reverse logistics [14] can play a significant role in creating a second life for batteries. The reverse logistics network design of Hao et al. (2021) for electric vehicle batteries focused on recall risks [15]. Yükseltürk et al. (2021) discussed the design of a reverse logistics centre for end-of-life electric vehicle batteries based on fleet size prediction [16]. Azadnia et al. (2021) analysed the barriers to the application of reverse logistics using the TISMA-MICMAC approach [17].

Harris at al, (2018) developed a novel framework to assist decision-makers in assessing the uncertainty of the life cycle impacts of alternative bus technologies, [18] while Jefferies at al. (2018) presented a comprehensive TCO evaluation method for electric bus systems based on discrete-event simulation including bus scheduling and charging infrastructure optimisation [19].

2.5 Findings from a review of the literature

Published material on the degradation of electric bus batteries has been associated with a number of sub-disciplines. The results acquired can be used in a more holistic operational model, in which an accurate knowledge of battery degradation allows for planning the second life of batteries in order to optimise the whole life cycle cost of a fleet. A key element in the second life cycle planning of batteries is precise knowledge of the degradation and charging characteristics of the batteries in a fleet, which can be achieved by having actual measurement results from the operator. A degradation study carried out by the company and its results are presented below

3 Degradation measurements for Volánbusz Zrt.

As a public transport bus operator, Volánbusz Zrt. has developed a concept for the development of electric vehicles as a strategic alternative, and has set itself the objective of significantly rejuvenating and upgrading its bus fleet. In line with this vehicle development, the company is already operating 102 purely electric buses.

Among the main driving forces behind the development of electromobility are the need to improve technology and service levels, to improve energy efficiency and reduce emissions. A further aim is to produce electricity as a fuel for the company itself, thereby reducing its use of fossil fuels and increasing its energy security and independence.

Alongside exploration of the development of its own energy generation capacity, the company has launched a research project in cooperation with market players and universities. The project's purpose is to investigate how, based on the principle of circular operation, batteries from electric buses can further serve the company's operations and interests by being used as storage in the infrastructure for secondary use. The benefits of this re-use are manifold. The purchase costs of batteries used in buses are substantial. Based on experience from manufacturers and users, in principle batteries should be replaced every 10 years, due to capacity loss. By using functioning batteries as storage units beyond this manufacturer's warranty period, the company can keep them in service for a number of additional years, thus preserving their usability for the company and improving return on investment. In the previous chapter we saw that if batteries are used optimally for 15 years, there is still potential for other uses, which will facilitate use of the circular economy model. The degradation measurements on batteries carried out by Volánbusz Zrt. led to the following results.

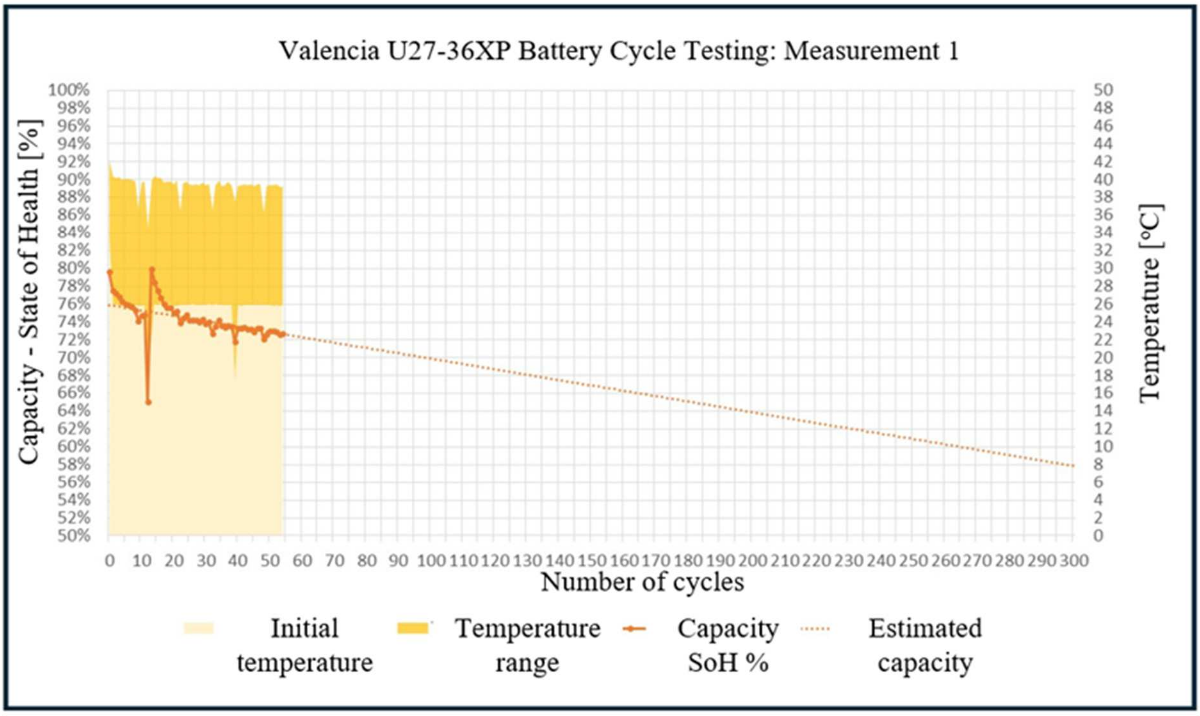

Figure 4 Valencia U27-36XP battery cyclic test: Measurement 1

Figure 4 summarises Valencia U27-36XP used battery test results from Volánbusz Zrt. The X-axis represents the total number of cycles. The cycles were performed with a 0.5C charge rate and a 1.0C discharge rate. On the left, the Y-axis shows the remaining capacity of the battery relative to its original capacity, i.e. the percentage of capacity remaining, with measurement points represented by orange dots. The broken orange line shows a linear extrapolation of the data, i.e. an estimate of the further capacity loss that can be expected for the same rates of charge and discharge. (The capacity loss of batteries under the same conditions can be said to be linear.)

In our experience, this linearity is true up to about 60% of remaining capacity, after which the capacity loss becomes progressively more severe (battery ageing), and then at a certain level collapses completely. So in general vigilance is advisable when capacity drops below 60%.

Figure 5 summarises the battery measurements of the battery test in a refrigerated medium. The axis descriptors and diagram elements are the same as in Figure 4, but the measured values are different.

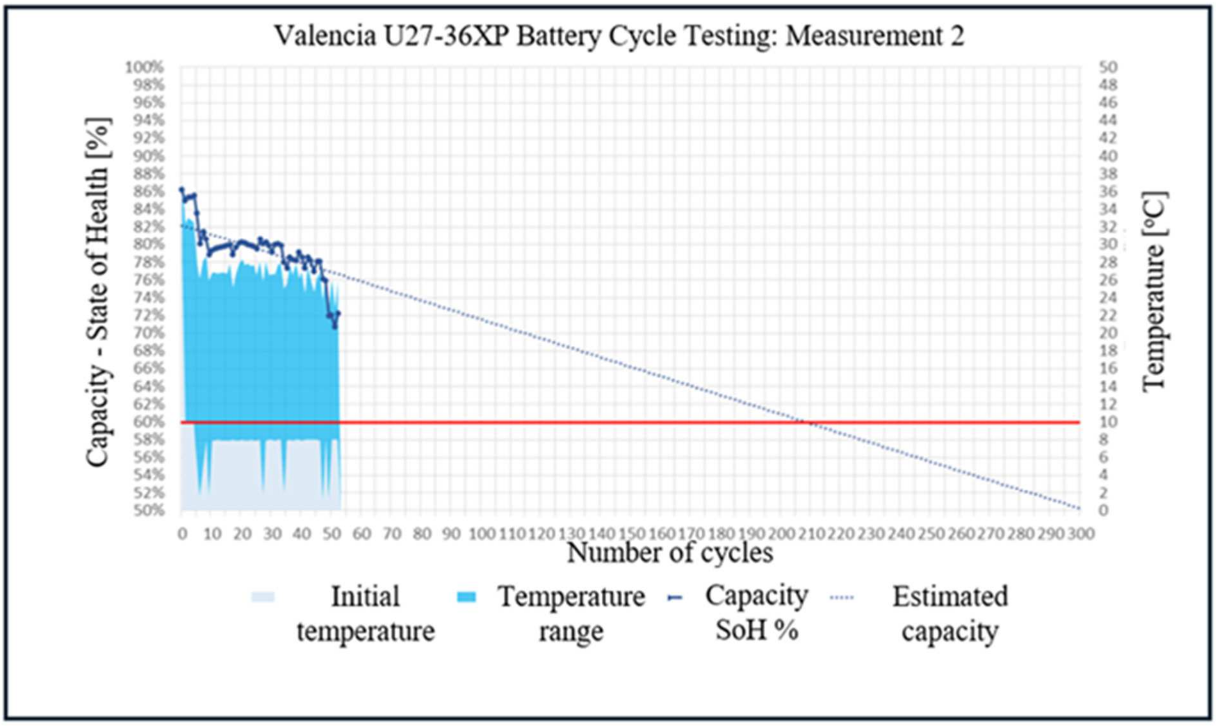

Figure 5 Valencia U27-36XP battery cyclic test: Measurement 2

The measurements clearly demonstrated the need to measure degradation under specific operating conditions for the use of batteries in vehicles and for second life cycle planning

4 An innovative decision-making method for bus fleet selection taking battery degradation into consideration

The selection of the right fleet for the operating company requires the consideration of a number of decision criteria and the application of a normalisation-based decision-making method which takes all relevant aspects into account. This chapter will describe the system variants that can be considered and the criteria and decision-making method for selecting the appropriate fleet.

4.1 Description of the system variants that can be tested

The decision-making method developed can be applied to all companies involved in public transport bus services, regardless of the type of fleet being assessed and the way in which batteries are managed and used. The examination possibilities are contained in Figure 6. During the examination, the optimal selection of a fleet consisting of a given vehicle type - suitable for achieving the expected daily mileage performance - is carried out. If the study includes an electric fleet, then only the first, and first and second life cycle impacts of batteries can be considered. In the first life cycle of batteries, the possibility to operate vehicles and sell spare capacity to the electricity supplier can also be examined. If the capacity of batteries falls below a predefined limit and they are longer capable of performing the required tasks, i.e.,daily mileage, secondary use becomes necessary. The latter may involve the following: sale of the battery on the market, for example for storage; as a captive reserve, for instance, storage of energy generated by captive solar or wind power, storage of peak-period electricity in order to power vehicles during peak periods, etc.; or a combination of these.

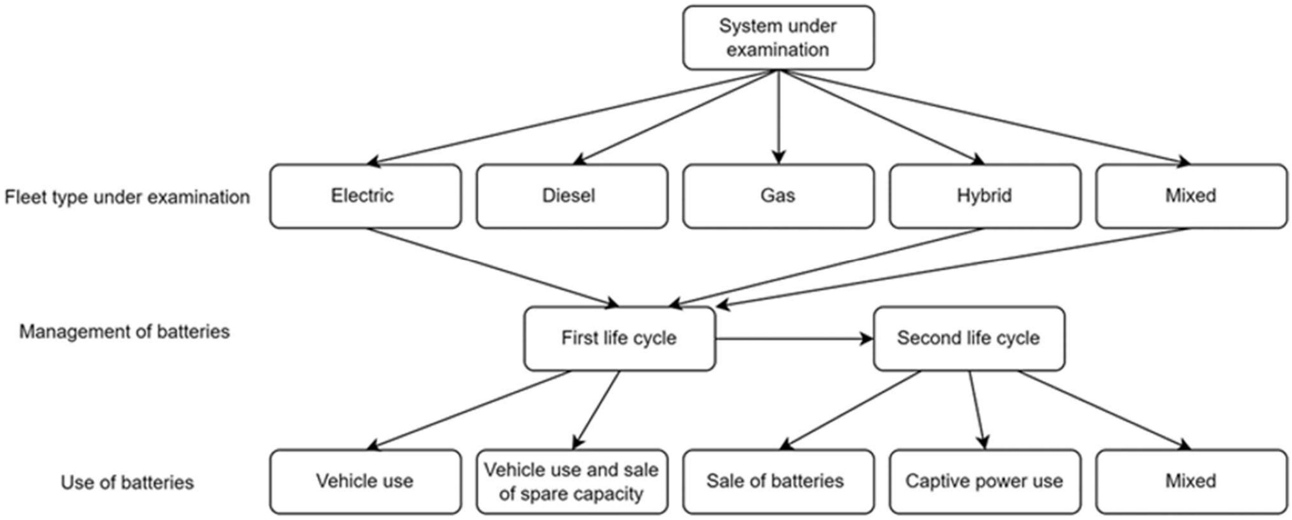

Figure 6 Description of testable system variants

4.2 Description of the decision-making method

The decision-making method is used to determine the type of fleet to be operated under predefined conditions, in the following steps:

1. Determining requirements for fleet utilization

In this section the requirements to be met in the operation of the fleet are specified, the most important of which are the following:

- average ambient temperature and fluctuations in it,
- the expected average speed of vehicles,
- expected mileage,
- available resources,
- environmental requirements,
- infrastructure available and capable of being developed for operation.

2. Determining the number of vehicles to be purchased

Determination of the number of vehicles needed to cover the forecast mileage and to provide an adequate level of service.

3. Determining the types of vehicles to be tested

In this step, the types of fleet that meet the requirements in Step 1 are selected. In essence, the analysis will select the variant most suitable for the company's needs.

4. Determining the decision criteria

A fundamental problem with many assessment methods is that they only make cost-based comparisons, without taking into account other factors such as quality and subjective considerations. When applying the decision-making method we have developed, the following aspects may need to be considered:

- Total Cost of Ownership (TCO),
- Carbon footprint indicator,
- Customer satisfaction factor.

5. Normalisation of objective function values

6. Selection of the type of fleet to be purchased

4.2.1 Total Cost of Ownership

This is the sum of the capital expenditure (CAPEX) used to acquire the vehicle, and its associated operating expenses (OPEX). The model does not take inflation and depreciation into account, as these two factors impact equally on the economic rates of return for both electric buses and diesel buses. The definitions in the literature do not take into account the potential second life cycle of batteries, which in business practice is increasingly becoming a cost-reducing factor. Accordingly, the TCO for the fleet type under consideration should be defined as follows.

Capital expenditure for the period under examination (1):

$$C_i^{CAP} = C_i^{AM_v} + C_i^{AM_I} - R_i^{II} - R_i^{O} \qquad (1)$$

in which:

- $C_i^{AM_v}$: the present value of the amortised cost of vehicles in fleet type *i*,
- $C_i^{AM_I}$: the present value of the amortised cost of the infrastructure for fleet type *i*,
- R_i^{II}: present value of the additional revenue from the second life cycle of the batteries of the vehicles in fleet type *i*,
- R_i^{O}: present value of the revenue from the sale of vehicles in fleet type *i* and related infrastructure.

Operating expenses for the period under examination (2):

$$C_i^{OP} = C_i^{OP_M} + C_i^{OP_F} + C_i^{OP_S} + C_i^{OP_O} \quad (2)$$

in which:

- $C_i^{OP_M}$: the present value of the maintenance costs for fleet type *i*,
- $C_i^{OP_F}$: the present value of the fuel costs for fleet type *i*,
- $C_i^{OP_S}$: the present value of the wage costs associated with fleet type *i*,
- $C_i^{OP_M}$: the present value of other costs (road tolls, parking fees, etc.) associated with fleet type *i*.

Total life cycle cost for the period under consideration (3):

$$C_i^{TCO} = C_i^{CAP} + C_i^{OP} \quad (3)$$

4.2.2 Carbon footprint indicator

This indicator expresses the amount of carbon dioxide equivalent greenhouse gases associated with the production and subsequent operation of a fleet associated with a given vehicle type over the period under examination. This is an important indicator from a sustainability point of view, and is denoted as CF_i for fleet type *i*.

4.2.3 Customer satisfaction factor

This is a subjective indicator that expresses the expected customer satisfaction for a given fleet type, for example, amenities provided, reliability of vehicle type. The indicator is defined on the basis of a survey of service users, and is denoted by CS_i for fleet type *i*. For this indicator, values range from 1 to 10 (10 being the best rating).

4.2.4 Normalisation of objective function values

In this step, the values of the decision criteria relevant to the decision are determined and then normalized. During normalisation, the defined values are transformed so that they fall between 0 and 1, allowing them to be included in the objective function.

Full life cycle cost normalisation (4), (5):

$$C^{TCO(max)} = \max_i \{C_i^{TCO}\} \quad (4)$$
$$\alpha_i^1 = C_i^{TCO} / C^{TCO(max)} \quad (5)$$

Normalization of carbon footprint indicator (6), (7):

$$CF^{(max)} = \max_i \{CF_i\} \quad (6)$$
$$\alpha_i^2 = CF_i / CF^{(max)} \quad (7)$$

Customer satisfaction factor normalization (8), (9):

$$CS^{(max)} = \max_i \{CS_i\} \quad (8)$$
$$\alpha_i^3 = 1 - CS_i / CS^{(max)} \quad (9)$$

4.2.5 Selection of the types of fleet to be purchased

In this step, the experts from the company under consideration need to determine the weighting of each of the assessment criteria in order of importance (the sum of these should be 1, as shown in the following). Following this, the weighted sum of the components of the normalised objective function is formed, whereby the fleet type with the minimum value is the most appropriate choice for the company's criteria.

Determination of the weights of the objective function components (10), (11):

$$0 \leq \partial_h \leq 1 \quad (10)$$
$$\sum_{h=1}^{3} \partial_h = 1 \quad (11)$$

Determination of objective function (12):

$$F = \min_{\gamma} \sum_{h=1}^{3} \partial_h \cdot \alpha_\gamma^h \quad (12)$$

4.3 *Application of the decision-making method*

The system under examination relates to the operation of a mixed fleet of electric and diesel buses in Hungary's largest public transport bus company. The aim of the study is to select the fleet that best fits the company's criteria for the future under the given circumstances. Based on a preliminary assessment, the company's requirements are met by two types of fleet: one diesel and one electric.

For the purposes of the decision-making method described in the previous section, only the whole life cycle cost was considered, assuming that, based on this indicator alone, the electric bus is the better choice (the carbon footprint for the electric bus is clearly better, and in terms of customer satisfaction there is no significant difference between the options). For reasons of company confidentiality, a large amount of factual data cannot be published, but the following general conclusions can be drawn:

- the cost of batteries accounts for almost 50% of the price of the electric buses to be purchased, but this is expected to decrease in the future,
- the expected daily mileage performance for the vehicles is 300 km, for which a capacity of about 300-320 kW is necessary. Thus, in the case of a 400 kW battery, a maximum degradation of 25% is acceptable.
- empirical measurements show that the average consumption of electric buses is 1 kWh/km,
- the second life cycle of batteries after degradation is a significant factor in reducing costs/increasing revenue,
- degradation measurements show that batteries are being phased out of vehicles after 6–8 years due to capacity loss, while the significant remaining capacity can be used in the second life cycle,

- maintenance costs for electric buses are about half those of diesel buses.

The TCO value for the second life cycle of batteries has been determined for the two fleet types, and is shown in Figure 7.

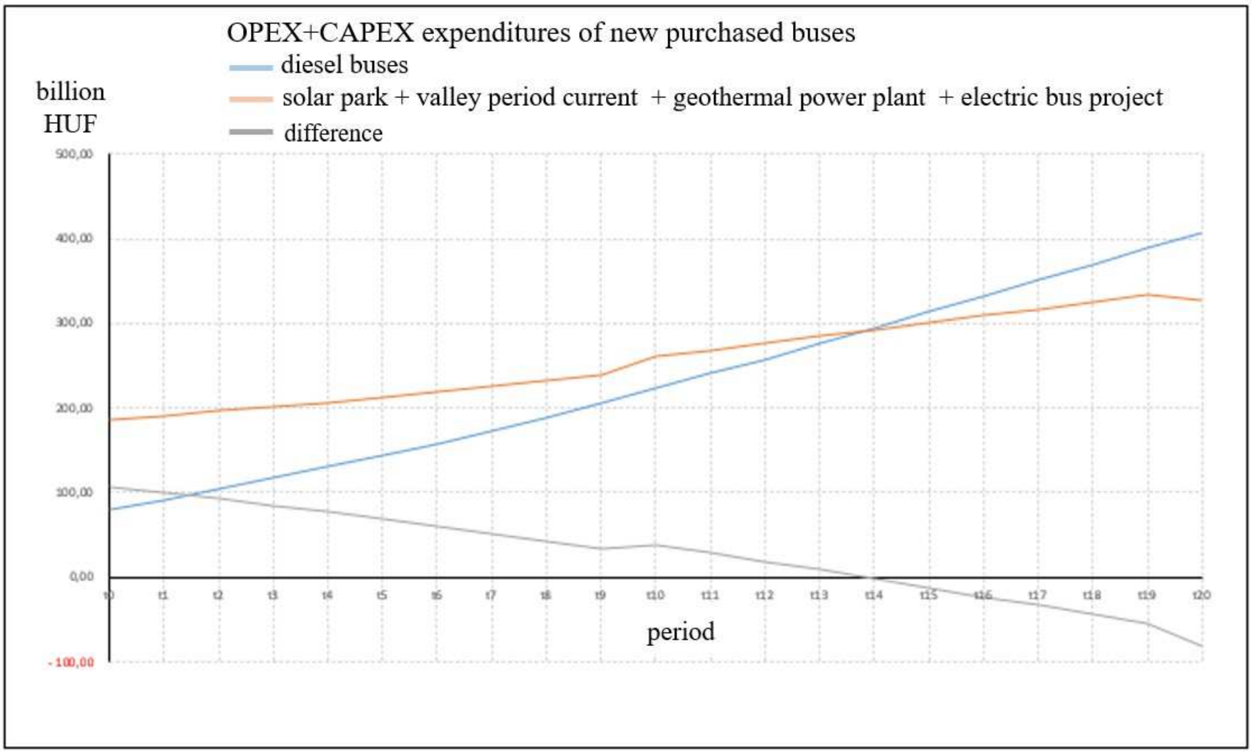

Figure 7 TCO comparison of electric and diesel buses (source Volánbusz Zrt.)

It can be seen, that for the fleet types studied, the use of electric buses is more advantageous for the company after 12.4 years. Of course, the fact, that the carbon footprint of electric buses is preferable to their diesel counterparts and that there is no significant difference in terms of customer satisfaction, adds weight to the decision.

5 Conclusion

The proliferation of electric vehicles in transportation can be considered a lasting and irreversible trend, reinforced by legislation and environmental expectations formed in the wake of the European Union's climate protection efforts. The bus fleet of Volánbusz Zrt., operating in Hungary, is already considered a so-called mixed fleet. The proportion of electric buses used in scheduled services, currently at 0.9%, is expected to reach 50% by 2032. The operation of electric buses increasingly emphasizes the importance of batteries' capacity, lifespan, and aging process (degradation). Therefore, Volánbusz Zrt. is already focusing on implementing a recycling strategy that significantly affects sustainable operation, including the planning of the second life cycle of lithium-ion batteries. As a result of a detailed literature analysis in the paper, we determined that the ideal fleet selection process lacks several relevant components, leading to erroneous decision-making. Among these factors are the consideration of batteries' secondary life cycle, sustainability, and logistics. A general and innovative decision-making method have been developed that addresses these deficiencies in selecting the appropriate fleet type. The method's correctness was verified through a case study using data from Volánbusz Zrt. In the next phase of our research, it is planned to develop innovative operational models related to the secondary life cycle of batteries.

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