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Battery Ageing as Part of the System Design of Battery Electric Urban Bus Fleets

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Abstract. The lifetime of traction battery systems is an essential feature of the economy of battery electric urban bus fleets. This paper presents a model for the analysis and prediction of the lifetime of urban electric bus batteries. The parameterization of the model is based on laboratory measurements. The empirical ageing model is an integral part of a three-stage battery model, which in turn is an important component of the methodology for the overall system design, evaluation and optimisation of battery electric urban bus fleets. In an equidistant closed simulation loop, the electrical and thermal loads of the traction battery are determined, which are then used in the ageing model to calculate the SOH (state of health) of the battery. The closed simulation loop also considers the effects of a constantly changing SOH on the driving dynamics of the vehicles. The model for lifetime analysis and prognosis is presented in the paper, placed in the context of the overall system design and demonstrated by means of a practice-oriented example. The results show that the optimal system design depends, among other things, on whether an ageing simulation was used. Taking battery aging into account, system costs in the example presented can be reduced by up to 17 %.

Keywords: electric buses, battery modelling, battery aging, charging infrastructure, optimisation

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Старение аккумуляторов как часть системы проектирования парков городских аккумуляторных электрических автобусов

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Реферат. Срок службы систем тяговых аккумуляторов играет существенную роль в вопросе экономии для парка электрических городских автобусов. В статье представлена модель для анализа и прогнозирования срока службы аккумуляторных батарей электрических городских автобусов. Параметризация модели основана на лабораторных измерениях. Эмпирическая модель старения – неотъемлемая часть трехступенчатой модели аккумуляторов, которая, в свою очередь, является важным компонентом методологии для общего проектирования системы, оценки и оптимизации парка аккумуляторных электрических городских автобусов. В эквидистантном замкнутом контуре моделирования определяются электрические и тепловые нагрузки тягового аккумулятора, используемые в модели старения для расчета SOH (состояния работоспособности) аккумулятора. Замкнутый цикл моделирования также учитывает влияние постоянно меняющегося SOH на динамику вождения транспортных средств. Предлагаемая модель используется в контексте общего проектирования системы; показан пример практического применения. Согласно результатам исследования, оптимальное проектирование системы зависит, помимо прочего, от того, используется или нет моделирование процесса старения. Принимая во внимание старение аккумулятора, системные затраты в рассматриваемом примере могут быть уменьшены до 17 %.

Ключевые слова: электрические автобусы, моделирование аккумулятора, старение аккумулятора, инфраструктура процесса зарядки, оптимизация

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Introduction

Driven by the ongoing discussion about clean air in German cities, many municipal transport companies are pushing ahead with the conversion of their bus fleets from diesel buses to electric buses. In many cities, this is an elementary step in the pack-age of measures to reduce emissions and comply with legal limits.

In recent years, various pilot projects have been launched and completed in various calls for proposals (e. g. Berlin, Hamburg, Dresden) [1]. In Dresden, for example, a 12 m electric bus with a conductive high power charging system was extensively tested as part of the "Electric Bus Line 79" project [2]. The aim of all of these projects was to test the different systems available on the market with regard to readiness for use and to gain initial experience in handling electric buses and their use in regular passenger service. An overview of the pilot projects in Germany is given in [1]. In many of these projects mainly vehicles were put into operation, which are then used on specially selected routes – often with low daily mile-age in order to avoid the range problem. Only in a few projects was the number of vehicles procured sufficient to operate an entire line with electric buses.

In the coming years, the next step towards switching bus fleets to electric mobility is to be taken. Many public transport companies are planning to procure a larger number of vehicles with which entire lines can then be operated completely with electric buses. In order to maximise public awareness, there is often a desire to choose so-called volume lines. These are lines that have a high passenger volume and often a high daily mileage and require a corresponding range.

The vehicles currently available on the market have very different ranges. The manufacturer's specifications range: from approx. 150 km for a 12 m vehicle [3] to over 300 km for an 18 m vehicle [4]. However, depending on the choice of line, this range may be too short to ensure safe operation under all circumstances. In such cases, charging the energy storage device during operation is required in order to be able to perform the daily driving performance. This charging can be carried out in different ways. The main degrees of freedom are the location, duration and power of the charging.

Switching from diesel buses to electric buses does not only mean simply replacing the vehicles, but is to be understood as a way of designing the system. Today, this design is often based on empirical values. For example, specific mean values (in kW·h/km) are used to estimate the required energy content of the traction battery for a certain distance. For charging, known combinations of charging location and charging power are then used, which are often known from the pilot projects. However, in many cases such a system design has a rather heuristic character and often only a few design scenarios are compared with each other. This procedure is shown exemplarily in [5, 6]. An optimal design, for example with regard to the required investment and operating costs, cannot be determined thereby.

This paper presents a methodology which automatically calculates and evaluates a multitude of technically possible configurations for a given route under given boundary conditions. The core of the methodology is a detailed, multi-stage battery model, since the traction battery is currently the most expensive single component of an electric vehicle [7] and its consideration therefore has a particularly high priority in system design.

Probably the most important differences between electric buses and diesel buses in daily operation are the limited range and the much more complex charging process (charging energy storage vs. refuelling in conventional diesel buses). Analogous to the refuelling process, charging the vehicles in the depot during the night break is the state of the art. The required charging infrastructure confronts transport companies with great challenges, especially if a large number of vehicles are to be charged simultaneously in the depot. However, the charging process in the depot and the required hardware will not be examined in detail in this paper.

The focus of the methodology presented here is on the choice of a suitable energy storage device as well as a possibly necessary charging infrastructure along the route being considered. The following questions are to be answered:

- What is the power requirement of a vehicle to cover the considered distance?
- What is the required energy content of the traction battery?

- How many charging points are required along the line and where are they positioned?
- What charging power must be installed at the charging points?
- Is the stop time planned according to the timetable at the charging points sufficient?
- How does the intended operation affect the lifetime of the traction battery?

Simulation framework

The developed framework was especially designed to answer these questions. The aim is to carry out a system simulation with subsequent parameter variation within the framework. Thus, a large number of technical configurations can be calculated for a specific system and be evaluated in a post-process. The following variation parameters are defined for this purpose:

- energy content of the traction battery;
- number and position of charging points in the network;
- power to be installed at the charging points.

The route to be investigated is first examined with regard to the possible charging point locations. All locations that could be used as potential charging points are marked. Criteria for this can be, for example, the amount of space required, the available network connection or a pause in operation. A Tab. 1 with all possible combinations is then created. For an example route with two potential locations, this results in 4 combinations.

Table 1

Combination of charging points

ID	Depot charging	Charging point 1	Charging point 2
(0/0)	1	0	0
(1/0)	1	1	0
(0/1)	1	0	1
(1/1)	1	1	1

It is assumed that depot charging always takes place so that it is not part of the parameter variation. Only the combination possibilities of charging point 1 and charging point 2 are varied at this point. The variation parameters of charging power and battery energy content are varied within (user-defined) limits in discrete increments.

All possible combinations of variation parameters are now calculated within the framework. The subsequent evaluation of the results is initially carried out with regard to technical feasibility. Often not all theoretically possible combinations are technically feasible. In the second step, the technically feasible configurations are economically evaluated and compared with each other. In the following chapters, the individual models of the system simulation are presented.

System modelling

The system simulation consists of two main modules: module 1 determines the power requirement of the vehicle during operation on a given route. The structure and functionality of this module are explained in [8] and will not be discussed in detail here.

In module 2 the dimensioning of the energy storage as well as the required charging infrastructure is carried out. The core of this module is a detailed, three-stage battery model. The system simulation is completed by an electrical model of the charging infrastructure as well as a cost model for the evaluation of the determined configurations. The individual models are explained below.

Battery model. The battery model consists of 3 sub-models (Fig. 1): electric, thermal and aging model. The sub-models are called serially.

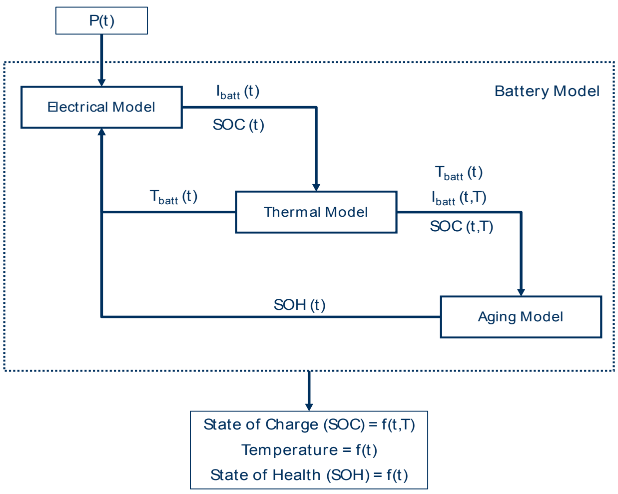

Fig. 1. Three-stage battery model

The power curve $P(t)$, which is calculated in module 1 for the considered vehicle serves as input to the battery model. In the electrical model, the battery current resulting from the power requirement and the State of Charge (SOC) are calculated. Both values are transferred to the thermal model. Now the battery temperature is determined. Then the battery current, the SOC and the battery temperature are transferred to the aging model, in which the aging of the battery resulting from the specific load is calculated.

Both the results of the thermal model and the aging model are fed back into the electrical model. On the one hand, the battery temperature determines the maximum permissible current, so that current limitation (and thus power limitation) may be necessary. On the other hand, due to battery aging, the parameterization of the electrical model must be adapted before a new calculation of the power curve can be performed.

Electrical model. An equivalent circuit diagram model is used to model the electrical behaviour of the battery. Different depths of modelling are known from the literature [9]. Common to all is the approach consisting of an open-circuit voltage source and an ohmic internal resistance. Then, depending on the desired accuracy, one or more *RC* elements are connected. As the number of *RC* elements increases, the accuracy of the results generally increases, but the computational and parameterization effort increases as well. As a compromise, an equivalent circuit diagram containing one *RC* element was chosen (Fig. 2).

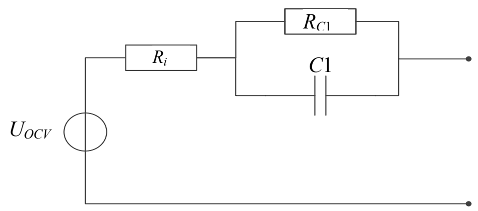

Fig. 2. Equivalent circuit diagram of a single battery cell

The equivalent circuit diagram is first parameterized for a single cell. Subsequently, an equivalent circuit diagram for the entire battery storage is drawn up using the known connections to the series and parallel connection. The following information is essential for the parameterization of the cell model:

- open circuit voltage (*OCV*);
- ohmic internal resistance R_i;
- capacity *C* and resistance value *R* of the *RC* element.

All mentioned components are not constant quantities and have non-linear progressions, so that corresponding characteristic diagrams have to be defined in the simulation.

- *OCV*. The open circuit voltage depends on the SOC of the individual cell. In addition, a capacity is assigned, since a battery cell can only absorb and release a limited amount of charge. The capacity of the cell depends on the temperature.
- *Ohmic internal resistance.* The ohmic internal resistance depends on both temperature and SOC.
- *RC element.* Both components of the *RC* element are temperature and SOC dependent.

Some of the required parameters can be taken from cell data sheets. Especially the values of the RC element are rarely given, so that these values have to be measured in the laboratory. A procedure for this is explained in [10].

In addition to the parameterization of the individual equivalent circuit components, limit values for battery operation can be stored in the electrical model. In real operation, these limits are usually specified in the battery management system (BMS) and are intended to ensure safe and reliable operation of the battery. A simple and effective way of such a BMS parameterization are current characteristic diagrams depending on the battery temperature and the SOC (Fig. 3).

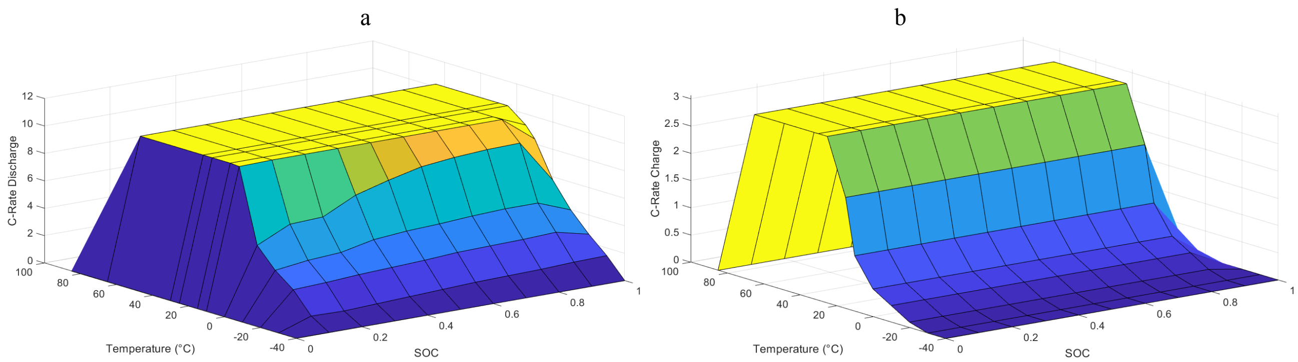

Fig. 3. Permissible battery current: a – discharge; b – charge

Thermal model. In the thermal model, the temperature of the entire battery storage device is deter-mined. From the literature different modelling depths for single cells are known. In [11] the principal representation of 0*D*-, 1*D*-, 2*D*- and 3*D*-models is shown. The relationship between parameterization effort, model complexity, result accuracy and calculation time is also shown.

For this methodology, a 0*D*-model is chosen due to the low parameterization effort and the short computation times. Analogous to the electrical model, a model at cell level is first created here as well. However, the interconnection to the full storage is not trivial. Often individual cells are grouped into modules, which in turn are connected in series and parallel to the full storage device. In order to determine the battery temperature, the consideration of such a module is essential.

In the 0*D*-model, a heat flow is injected in the middle of a rectangular body (Fig. 4a). Part of the heat is then released across all 6 body surfaces according to the thermal cell properties. If several cells are connected together to form a module, the cell does not release the corresponding proportion of heat from the contact surface into the environment, but transfers it to adjacent cells.

Thus, the interconnection of 0*D* cell models results in a 1*D*-module model (Fig. 4b), since the inner cells have a higher temperature due to the heat transfer from the outer cells and thus a temperature curve in the *x*-direction of the module results. The model used is only valid for rectangular bodies. Accordingly, only prismatic cells and pouch cells can be simulated. For round cells a differentiated analysis is required.

Aging model. The aging model was developed on the basis of the institute's own measurements. A detailed description of the model structure as well as the parameterisation and the required workflow for the determination of a concrete aging can be found in [12].

As state of the art, four essential influencing factors on the aging process of Li-ion batteries are known:

- battery temperature;
- SOC swing or ΔSOC;
- battery current (*C* rate);
- SOC.

All influencing factors mentioned lead to the aging of the battery with different quantities. This has the following effects: on the one hand the usable capacity (reduced range) of the battery decreases, on the other hand the internal resistance increases (lower performance, e. g. regarding acceleration, max. speed or charging time). By definition, a Li-ion battery reaches its End of Life (EoL) if at least one of the following two criteria is met:

- doubling of the internal cell resistance (to 200 %);
- reduction of usable capacity to 80 % of the nominal capacity.

In [12] it was shown by aging measurements that both the decrease of the capacity and the increase of the internal resistance can be approximated by linear functions. On the basis of these measurements, damage factors *S* were determined, which describe the respective share of an influencing factor on the total aging. This results in the following model equations for the determination of aging:

$$C_1 = m_{ref,C} S_{Temp,C} S_{\Delta\mathrm{SOC},C} S_{\mathrm{SOC},C} S_{C-Rate,C} Q + C_0;$$

$$R_{i1} = m_{ref,R} S_{Temp,R} S_{\Delta\mathrm{SOC},R} S_{\mathrm{SOC},R} S_{\mathrm{C}-Rate,R} Q + R_{i0},$$

were C_0 – initial capacity; Q – charge throughput; C_1 – resulting (reduced) capacity; S – specific damage factor.

a b

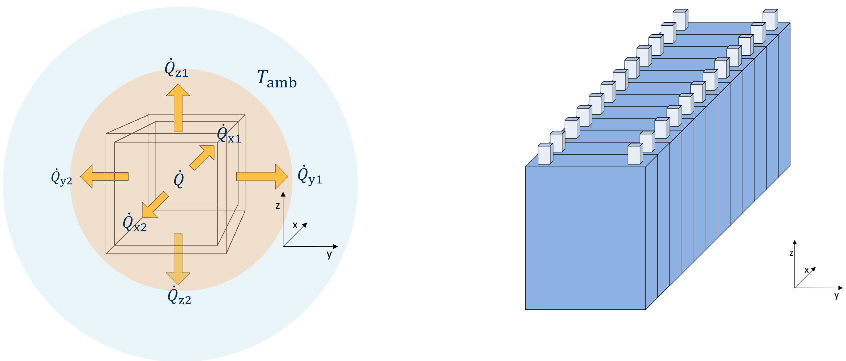

Fig. 4. Thermal model: a – single cell model; b – module model

The denominations apply analogously to the equation of internal resistance.

Model of charging points. A simple approach is used to model the charging points. They provide a constant power, which is composed of the charge voltage and the charge current. A constant efficiency can optionally be used to take conversion and transmission losses into account. A retroactive effect on the feeding grid is not considered. The selected constant charging power represents the maximum value. Depending on the operating point of the battery, a derating can be activated. In this case, the available charging current at the charging point is higher than the permissible battery charging current must be limited accordingly.

Cost model. A cost model is to be used to evaluate the technical configurations determined. The model does not aim at providing a classical TCO calculation, as it is done in [13]. Rather, at this point only the individual technical configurations are to be com-pared with each other. Therefore, a simple cost model is used here, which only contains the main cost components of an electric bus system, in which the considered configurations differ. Therefore, the term system costs is used here. The individual components of the model are shown in Fig. 5. The model is parameterized exemplarily for demonstration purposes (Chapter 4).

Conventional diesel buses are usually in service for 12–15 years. A similar period is also assumed for electric buses. It is expected that the traction battery will reach the EoL criteria at least once during this period and will have to be replaced. The number of battery replacements thus has a significant influence on the lifecycle costs of an electric bus, which is why the cost share for this is correspondingly two-stage (Fig. 5).

System simulation

In this chapter the functionality of the system simulation with parameter variation will be demonstrated by means of an example. The following scenario is given in Tab. 2.

Table 2

Operational data and parameter boundaries

Type of vehicle	18 m articulated bus
Type of battery	Lithium-Iron-Phosphate
Length of line	38 km
Number of rounds	6
Daily mileage	6 · 38 km = 228 km
Cycle time	20 min
Vehicle life cycle	12 years
Max. ΔSOC	0.9–0.1
Ambient temperature	15 °C
Battery voltage	420–710 V
Max. charging time CP 1	15 min
Max. charging time CP 2	10 min

The power requirement of the selected vehicle to cover the considered distance is determined by means of the approach described in [8] and is available as a function of time $P(t)$. The following limits are defined for the variation parameters defined in Chapter 2 (Tab. 3).

Table 3

Boundaries of variation parameter

Number of charging points	0–2
Position of charging points	At turning points of the line
Charging power	50–400 kW
Energy content of battery	68–377 kW·h

In the system simulation, all possible combinations of the variation parameters within the defined boundaries are calculated. In this example, the step size of the charging power is 10 kW. The step size of the energy content of the battery is 13 kW·h and results from the fact that the calculation is based on real cells available on the market.

In a first step, all technically possible configurations within the defined boundaries are determined. At this point, the evaluation criteria is the daily SOC curve, at which the lower limit SOC_{min} must not be violated.

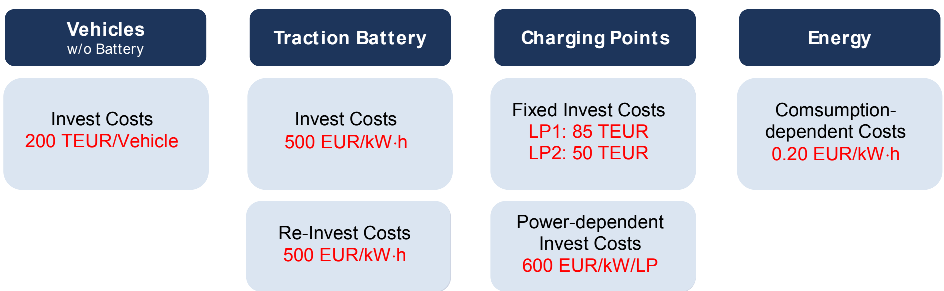

Fig. 5. Cost model including example parameters

Fig. 6 shows the minimum possible energy content of the battery, which can be achieved with the respective combination of number of charging points and charging power. It can be seen that no feasible configurations exist for variants of the charging point combination (0/0). Therefore, the considered route cannot be operated as a depot charger. The maximum energy content of 377 kW·h in connection with the defined SOC boundaries is not sufficient to cover the daily energy demand of the vehicle. Due to the lower available charging time (10 min), the charging point combination (0/1) has fewer feasible configurations than the combination (1/0) with 15 min charging time. The largest number of feasible configurations results consequently from the charging point combination (1/1).

The next step is to evaluate all calculated variants using the cost model (Fig. 5). The expected life time of the traction battery is calculated and on this basis the required battery replacement during the defined vehicle life of 12 years is calculated. In order to avoid a distortion of the results due to integer rounding, decimal numbers for the necessary number of battery changes are permitted. Fig. 7 shows the resulting system costs for all calculated configurations. It can be seen that the lowest system costs are for load point combination (1/1).

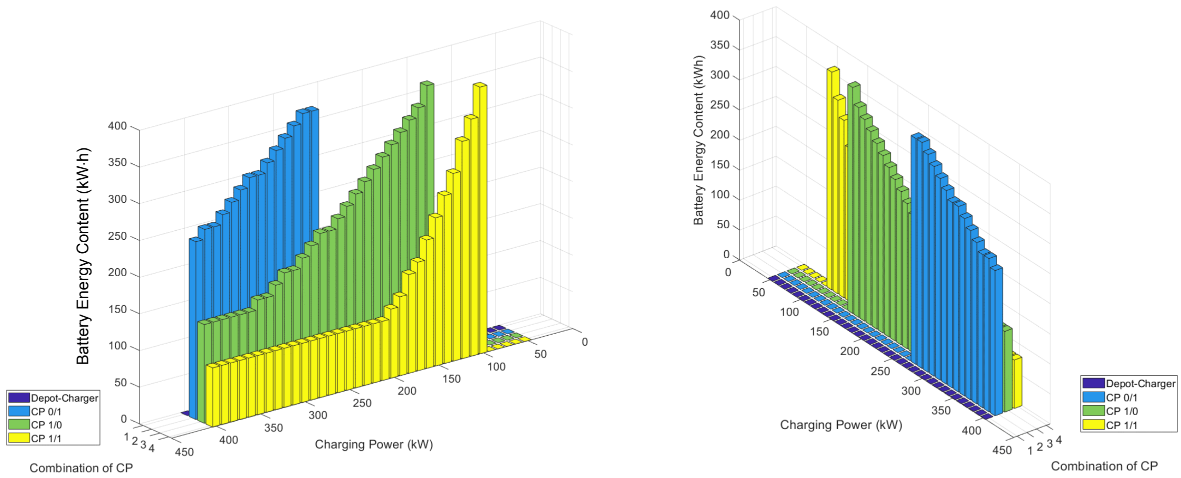

Fig. 6. Minimum energy content of the battery as a function of the charging point combination and the charging power

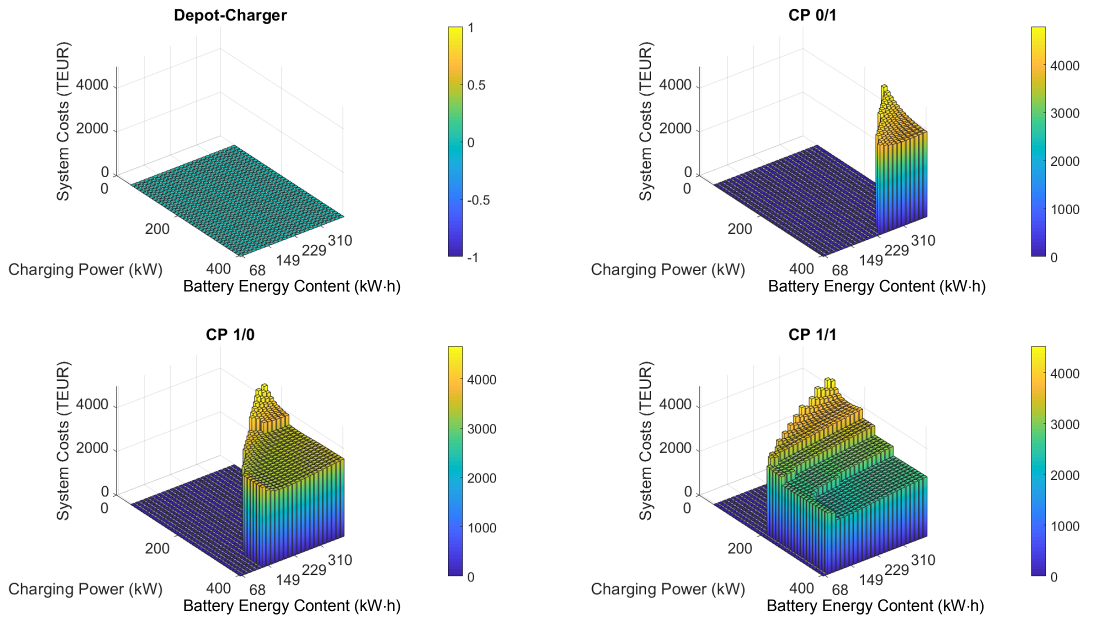

Fig. 7. System costs of all technical feasible configurations

The absolute minimum is not directly recognizable due to the very low variance of the results. The optimum cost can be determined using a minimum search function:

- charging point combination (1/1);
- energy content of the battery: 122 kW·h;
- charging power: 320 kW.

In order to classify the found optimum, this is to be compared with the minimum technically feasible configuration with the same charging capacity and CP. The minimum possible energy content of the battery is 81 kW·h (Fig. 6).

In Tab. 4, both configurations are compared with each other.

Table 4

Predicted lifetime of the traction battery at EoL-criteria

Min. feasible energy content of the battery acc. to Fig. 6	Energy content of the battery at cost minimum acc. to Fig. 7
81 kW·h 100 %	122 kW·h 150 %
1072 days of operation (2.9 years) 100 %	1822 days of operation (5.0 years) 170 %
2761 TEUR 100 %	2300 TEUR 83 %

The results show that choosing a 50 % larger battery results in a 70 % increase of battery life. Ac-cording to the cost model (Fig. 5), the cost of a single battery set also increases by 50 %. However, the system costs over the vehicle life cycle can be reduced by 17 % due to the extended lifetime.

CONCLUSIONS

1. In this paper a methodology was presented which enables the dimensioning of energy storage and charging infrastructure of electric bus lines. Therefore, a framework was developed which varies the parameters battery energy content, charging power as well as location and number of charging points within definable limits. Within this framework, individual lines can be analysed by means of system simulation. The core of the system simulation is a three-stage battery model consisting of electrical, thermal and aging model.

2. The functionality of the methodology was demonstrated by an example. In this example, all technically feasible configurations within the set variation limits were first determined. A cost model was used to evaluate these configurations. It could be shown that an economically optimal combination does not necessarily correspond to the combination with minimum technical effort. This is mainly due to the aging of the energy storage device. In this example, a battery with a larger energy content leads to a longer service life of the storage device and thus to a reduction in system costs over the vehicle life cycle.

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