EVS36 Symposium
Sacramento CA, USA, June 11-14, 2023

Find the right cell for every application: A methodical approach based on cost-parity calculation

Tim Hettesheimer[1*], Steffen Link[1], Lukas Weymann[1], Maximilian Stephan[1], Olaf Teichert[2]

[1]*Fraunhofer Institute for Systems and Innovation Research ISI, Breslauer Str. 48, 76139 Karlsruhe, Germany,*
**tim.hettesheimer@isi.fraunhofer.de*

[2]*Technical University of Munich, School of Engineering & Design, Institute of Automotive Technology, 85748 Garching, Germany*

Executive Summary

The increasing performance of lithium-ion batteries and the continuous emergence of new manufacturers, formats, and cell chemistries enable the electrification of more applications. However, this heterogeneity and complexity make it difficult to anticipate all viable battery cells for specific applications. This paper presents a high-level techno-economic approach to identifying suitable battery cells for different applications. The methodology is based on an extensive cell database containing more than 350 real-world cells, the techno-economic characterization of emerging battery-relevant applications, and a Python-based model. This allows matching the application requirements to each battery cell performance to determine cell-specific cost-parity prices. We showcase the approach for passenger cars, forklifts, and passenger trains. Our results highlight large differences among applications in technical requirements and needed cost-parity prices, emphasizing the importance of tailored techno-economic cell selection.

Keywords: Battery; BEV; Standardization; Cost; Modeling

1 Introduction

The market for battery cells has developed rapidly in recent years, and the global demand for LIB increased to 250-280 GWh in 2020 with annual growth rates between 30 % - 40 % [1]. Today, this demand is mainly driven by passenger cars and home storage systems. However, recent battery innovations such as rapidly decreasing production costs, increasing energy densities, lifetime and improved fast charging capability allow for electrifying more and more applications [1,2].

This increasing heterogeneity and complexity pose a growing challenge for application manufacturers and cell producers. Cell suppliers are constantly looking for new applications for their cells, while manufacturers and cell integrators must identify the most suitable cells from the large number available. This also includes the question of which requirements an application poses on the battery system, e.g. power, service life or installation space, and whether an electrified application is also competitive due to high battery prices.

This paper proposes a high-level approach using a Python-based model with which the cost-parity price can be determined for different applications compared to an alternative, e.g., combustion-based applications [3]. This enables a tailored techno-economic cell selection rather than more generic selection methods such as the well-known Ragone Plot [4] or the ENPOLITE tool [5].

2 Methodological approach

General methodology

The systematic approach is based on three relevant steps, visualized in Figure 1. The procedure is briefly explained below; a more detailed explanation can be found in Teichert et. al [3], where this methodology was initially applied to trucks. First, the input data is defined that will be used in the energy simulation. This comprises the technical specifications of the respective product (e.g., passenger car, train, or forklift), synthetic and real-world load profiles (e.g., time-based standard speed profiles such as the WLTP driving cycle for cars or processed distance-based speed profiles from real driving conditions for trains), and other application-specific requirements that may affect the energy consumption. Technical product specifications depend on the application and may involve information such as weight, rated power, or number of passengers. Given these input values, the energy simulation determines the respective energy consumption for an electrified product version. Second, over 350 battery cells and their specific technical capabilities are fed into the battery sizing algorithm, determining the required number of cells and the final battery system capacity to fulfill all requirements and load profils. Technical capabilities involve, among others, battery chemistry, cell format, volumetric and gravimetric energy density, and C-rates for charging and discharging. The cell database is generated based on publicly available data sheet information and has been released open-source [6]. Third, the Total Cost of Ownership (TCO) or Levelized Cost of Energy (LCOE) are calculated based on the chosen battery capacity and the simulated energy flow and compare this result to the TCO or LCOE of the next best alternative (e.g., gasoline cars). From a first-user perspective, cost calculations cover all relevant capital expenditures (CAPEX) and operational expenditures (OPEX). The cost-parity price for the battery system, including eventual replacements and battery scrappage, is then obtained by the TCO delta between the battery version and the respective alternative. The cost-parity price per cell is calculated based on the number of cells, including potential replacements. If the cost parity price were negative, this battery cell would not be suitable for this application. A positive cost-parity price indicates that at this cost, given the specifications stated in the database and the assumed use case conditions and load profiles, this cell would perform as well as the corresponding alternative. Thus, the cost-parity price indicates a techno-economic upper price limit. If the cell were available at a lower price, there would be an advantage for the user and thus an incentive to buy, making these battery cells more attractive.

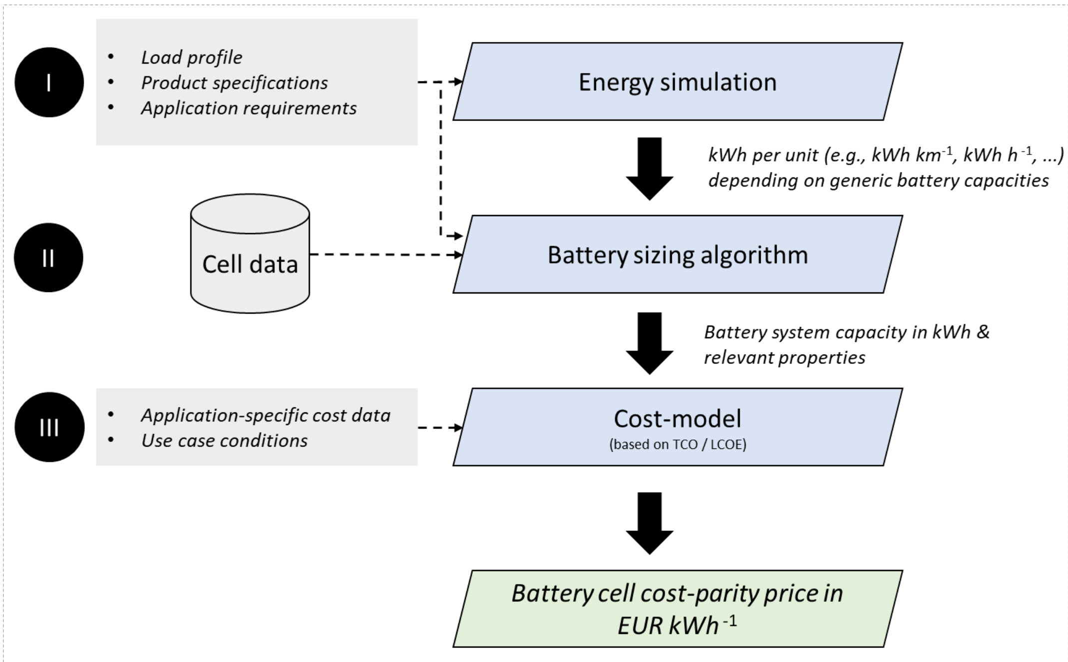

Figure 1: Schematic structure of the cost-parity model. Own illustration.

While the general methodology is described in Figure 1, the detailed procedure for each application is quite different. However, there are some similarities between the applications. For most of the mobile applications considered, the battery size depends on the weight of the application and the energy consumption. But there are significant differences in how the energy consumption is determined, as illustrated below for the three applications.

Particularities for passenger cars

The passenger car model is built on the WLTP driving cycle as a global standard for measuring energy consumption, levels of pollutants, CO_2 emission, or the all-electric of fully electric cars. This driving cycle specifies a target speed over time, covering urban, rural, and highway operations.

The vehicle simulation uses a quasi-static longitudinal-dynamics model to determine the energy consumption and average speed for a range of vehicle masses based on the vehicle parameters and the WLTP driving cycle. The VW ID.3 serves as a reference vehicle, leading to 408 km as the target range. Given this target range and the mass-dependent energy consumption, the battery sizing algorithm determines the required battery size based on the cell-specific properties defined in the cell database. The cost model uses the VW Golf VIII to determine cost-parity prices.

Particularities for passenger trains

The passenger train model mimics a route-specific application and train configuration since no standard case exists. Thus, we reference the commuting service from Nuremberg to Hof and vice versa. This covers the full operation schedule such as four stops, idle times (1 minute each), and station waiting times for turning around (20 min), route characteristics such as section distances, speeds (max. 160 km h^{-1}), gradients, and maximum permissible weights (22.5 tons), and other characteristics such as number of daily runs (3), operating days per year (320), the existence of overhead lines. Total distance is 167 km which equals 95 to 105 minutes, while the middle section of about 90 km is not electrified.

Similiar to cars, the vehicle simulation determines the energy consumption for a range of vehicle masses for this route using a quasi-static longitudinal-dynamics model. A three-section train with an overall length of 70 meters and a capacity for 410 people (220 seating and 190 standing) serves as a reference. Given the non-electrified middle section, the initial and final sections for charging via the overhead line, and the mass-dependent energy consumption, the battery sizing algorithm determines the required battery size based on the cell-specific properties defined in the cell database. Additionaly, battery sizing covers the restriction that potential battery replacements must happen within the revision cycles of the train (every 8 years) to avoid unplanned downtime. Finally, the cost model uses an equivalent diesel train to determine cost-parity prices.

Particularities for forklifts

The forklift model again, is based on a standardized driving cycle that has been defined within the framework of VDI Guideline 2198 "Type sheets for industrial trucks" [7]. The energy consumption per hour is determined by running through a standardized cycle. The VDI cycle includes driving with and without load as well as lifting and lowering the load and is, among other things, intended to show a comparability of the energy consumption of different vehicles and types through the specification in the type sheet of the vehicle. Since this is a standardized driving cycle, energy consumption cannot be specified for a specific use case example. Due to the large number of different forklift types and the variety of operational utilization scenarios, a specific yet practical use case scenario of an indoor counterbalanced forklift is defined for the further modelling to carry out the cost-parity calculation.

In a first step, a concrete use case in indoor warehouse operation for goods receipt was determined. The basis of the battery dimensioning is the characteristic energy consumption in terms of the time frame of operation and possible downtime periods to charge the forklift battery. Including the cell properties, the required battery size is determined, as well as the resulting battery volume and battery lifetime with respect to the forklift installation space for the battery and the assumed forklift lifetime. Compared to other mobile applications, the cost-parity comparison of a LIB electric forklift truck is compared to a status quo lead-acid (LAB) electric forklift truck with a maximum load capacity of 2 tonnes.

3 Results

3.1 Energy consumption and battery dimensioning

The energy consumption of a passenger car depends in particular on its vehicle weight. The vehicle simulation is carried out for different vehicle weights to determine the influence of weight on consumption. The results are shown in Figure 3. Energy consumption ranges from 13.3 kWh 100 km^{-1} with a vehicle weight of 1435 kg to 19.7 kWh 100 km^{-1} with a weight of 3000 kg. As the vehicle weight increases, energy consumption increases due to the increased rolling and acceleration resistance. For the electric vehicle, a consumption of 14.9 kWh 100 km^{-1} was calculated with a battery size of 64.3 KWh, which fits well to measured real-world data for a this kind of vehicle [8]. The consumption of the reference vehicle, the Golf VIII, is about 5.6 l 100 km^{-1} [9].

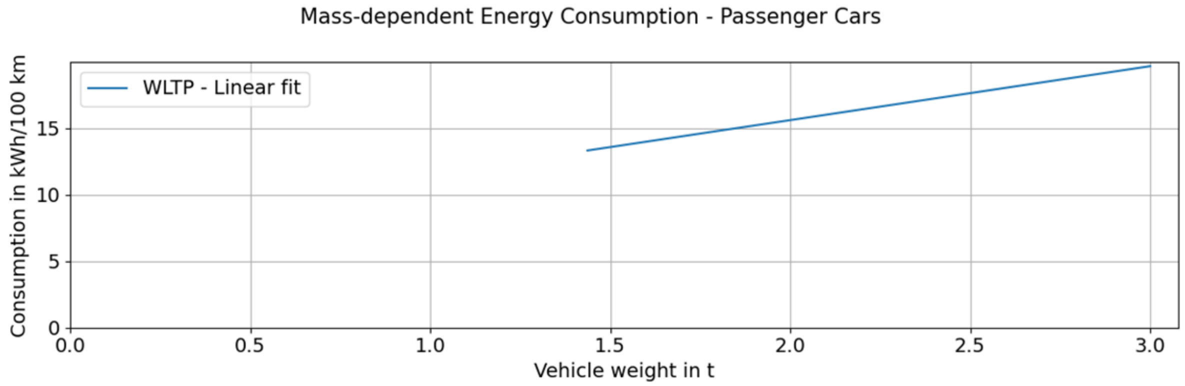

Figure 2: Energy consumption of passenger cars in relation to vehicle weight

The energy consumption of a passenger train at 25°C ranges from 4.6 to 5.3 kWh km^{-1}, depending on the train mass and direction of travel (see Figure 3). Recent studies and industry values indicate a range from 3-4 kWh km^{-1} in standard operations to 5-6.5 kWh km^{-1} in demanding operations, including all auxiliary consumers and heating in winter [10-12], indicating good representativeness of our simulation model. In contrast, the simulated energy consumption of the diesel train is between 9.5-10.1 kWh km^{-1}, which equals around one liter per kilometer. The calculated gross battery capacity is typically around 800 kWh and 4 500 to 11 700 kg. The median is 8.200 kg, while the lower quartile is 6 000 kg and the upper quartile is 9 800 kg.

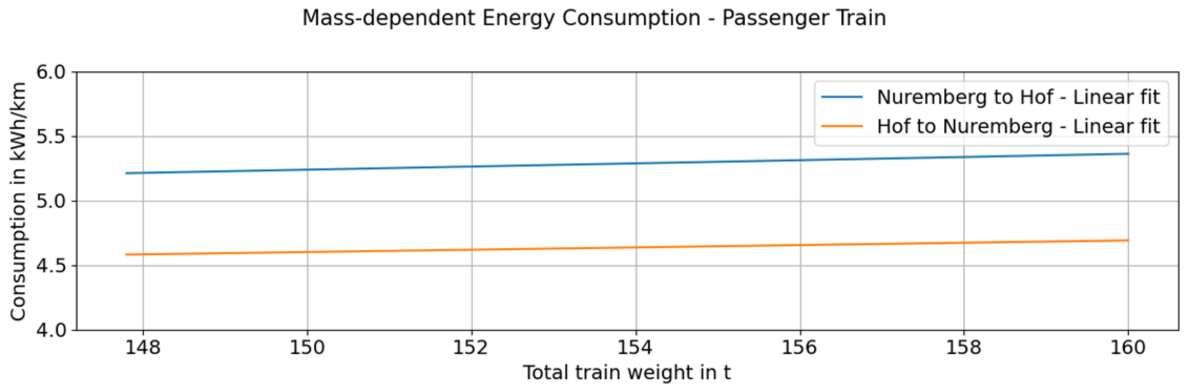

Figure 3: Energy consumption of passenger trains in relation to train weight

To support the investigation of a practical useage of a LIB electric forklift truck, a three-shift operation with a total of 15 shifts per week is assumed to detail the warehouse operation scenario. Figure 4 shows the dependence of energy consumption on the maximum load capacity of a counterbalance forklift truck. As the maximum load capacity increases, energy consumption increases partly due to the higher lifting load and the total weight of the forklift truck. Based on an evaluation of 30 VDI 2198 type sheets, a forklift truck with a maximum load capacity of 2 tonnes has for this use scenario an energy consumption of approx. 8 kWh h^{-1}.

However, the energy consumption based on the VDI cycle is not specifically designed for warehouse applications in a three-shift operation. Therefore, a specific characteristic energy consumption of 3 kWh h^{-1} was derived from [13, 14] for the following battery dimensioning.

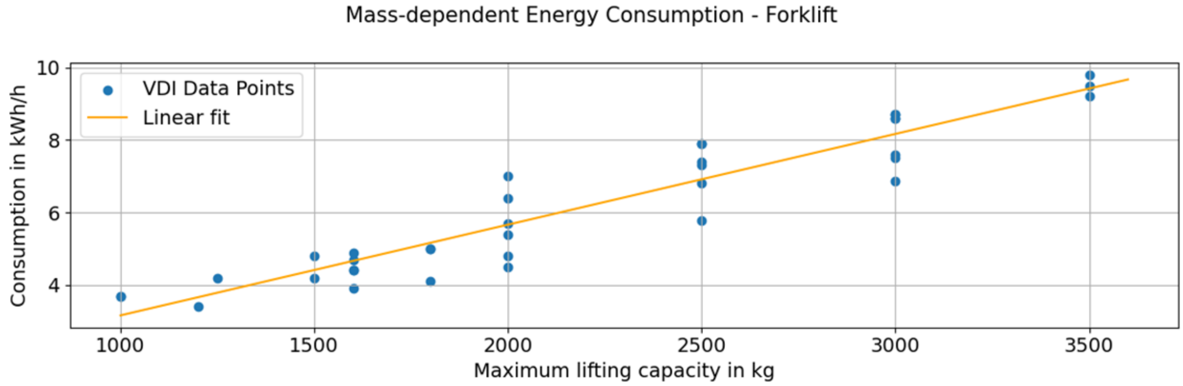

Figure 4: Energy consumption of forklifts in relation to lifting capacity

The battery is dimensioned in a way that the LIB forklift truck can fulfil the same operating conditions as a LAB forklift truck. Considering a shift with 8 hours working time, the operative usage time of the forklift truck in a warehouse was estimated to be a maximum of 5 hours [13]. In our model it was assumed that half of the remaining 3 hours are available for charging. While specific time losses (e.g. driving to a charging station, connecting the charging wire) were subtracted, only half of the available time was considered to be used for charging, to account for shared charging stations for forklift fleets. The required battery capacity is thus dependent on the charging rate of the cell and the available charging power.

As the volumetric energy density of LIB is way larger than that of LAB, the battery volumne seems to be less important for battery dimensioning in electric forklift trucks. Nevertheless, a space requirement of 341 liter was assumed, as derived from a commonly used 48V 6 PzS 540 Ah lead-acid battery in indoor 2-tonnes forklift trucks, thus serving as a installation space limit for the volumetric dimensioning of the LIB [15].

3.2 Cost parity analysis

For the cost comparison, a BEV similar to the VW ID.3 is compared to a status quo VW Golf VIII. The cost model considers all cost components of the BEV that differ from those of the VW Golf VIII: Powertrain costs, taxes, maintenance, energy consumption and battery costs. The first three cost components are independent of the cell selection. The energy consumption is influenced by the specific energy of the cell. The costs for the battery depends on the required battery size, cycle stability, calendar life and cell price.

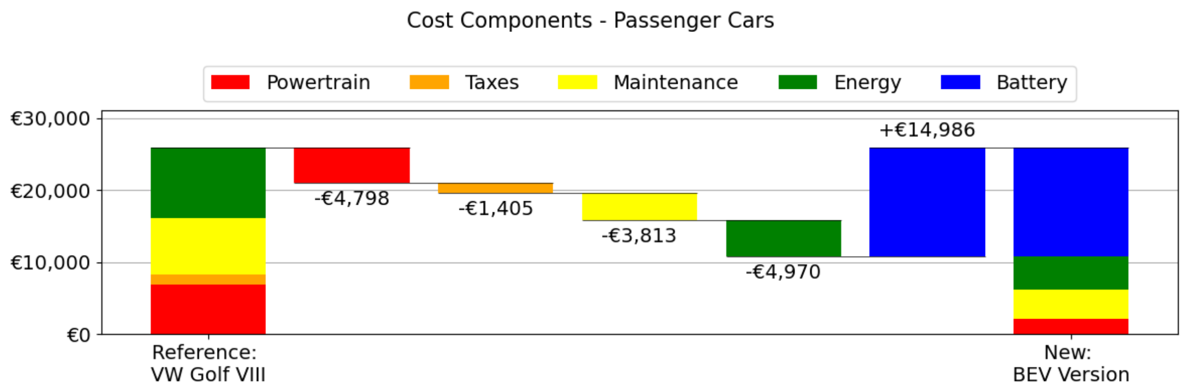

Figure 5: Results of the cost comparison for passenger cars over 10 years

The TCO breakdown in Figure 5 shows that the costs for the conventional vehicle amount to just over 25 000 EUR. Assuming an average annual mileage of ~ 13 600 km in Germany, a large part of this cost is related to energy costs of about 9 700 EUR as well as maintenance costs (~7 850 EUR) and powertrain costs

(~6 900 EUR). Taking into account a tax advantage for BEVs, there is a remaining budget of almost 15 000 EUR for the battery layout to reach cost parity with the ICV. Above all, the costs for maintenance and energy are significantly lower for the BEV.

For trains, the cost model compares the battery-electric version to its diesel equivalent over 30 years of service life. Cost factors comprise powertrain (incl. chassis), maintenance, energy costs, and battery costs. Lower powertrain costs result from cost advantages of electric versus diesel powertrains and are independent of the cell selection. In contrast, energy consumption is influenced by the battery weight and thus depends on the cell selection. Battery costs depend on the calculated battery size, cycle stability, calendar life, and cell price. Finally, the cell-specific cost-parity price is calculated so that the total costs for the diesel equivalent version are matched and by considering the total number of required cells.

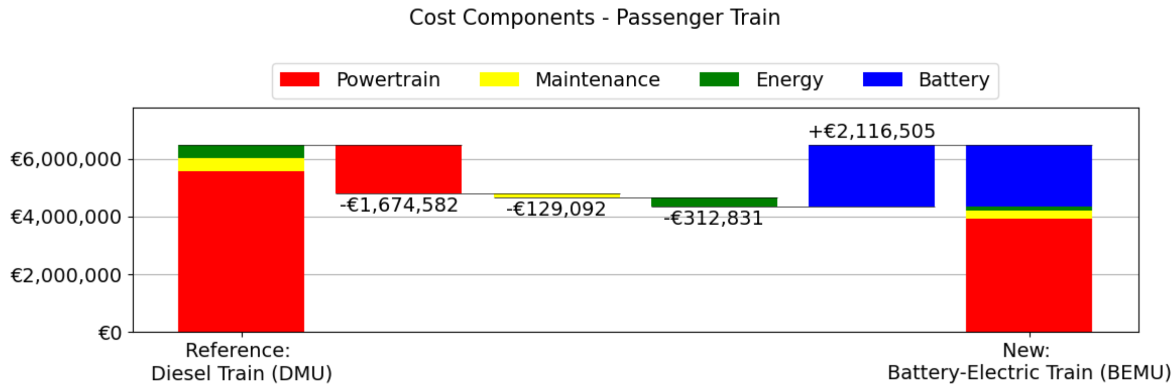

Figure 6: Results of the cost comparison for passenger trains over 30 years service life

The cost parity analysis for forklifts takes into account the cost components of a battery-electric counterbalance forklift that change when comparing a lithium battery (LIB) to a lead-acid battery (LAB) vehicle: battery maintenance, energy efficiency, labour time losses, (additional) counterweight and the cost of the battery itself, as shown in Figure 7. The LAB battery cost includes three battery replacements of the LAB in addition to the initial purchase price. This corresponds to the assumed lifetime of the LAB with 6 000 operating hours compared to the expected lifetime of 20 000 operating hours for an electric forklift [13]. The LIB battery cost is determined by the required battery size (influenced by the charging power), the cycle stability, the calendar life and the cell price.

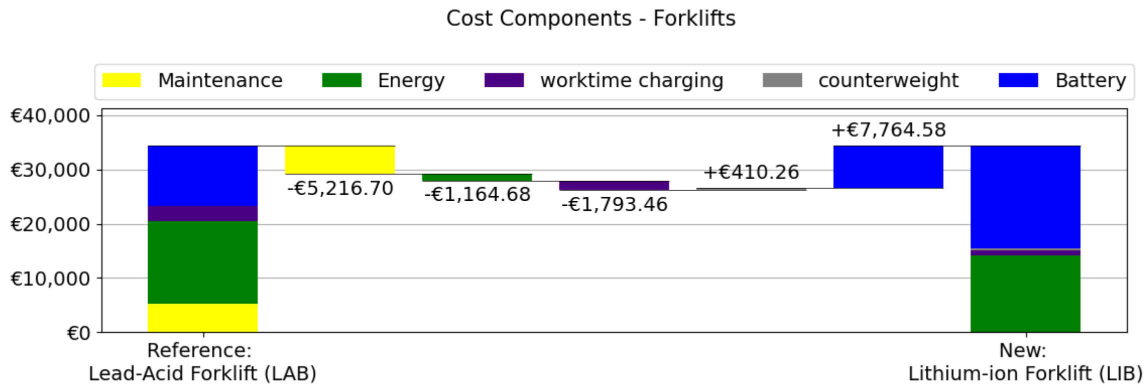

Figure 7: Results of the cost comparison for forklifts over 20 000 operating hours

Since there is no specific maintenance required for LIB compared to the maintenance of lead-acid batteries after every 1 000 operating hours [13], cost benefits can be expected. Additional maintenace costs for the forklift itself (e.g. tires) were neglected as this effects both LIB and LAB forklifts in the same way [16]. The energy consumption during operation is considered equivalent for both technologies, but is influenced by the round-trip efficiency of each battery technology. The monetised loss of working time due to the necessary swapping of lead-acid batteries in three-shift operation is eliminated by the LIB technology. The counterweight is needed for LIB forklifts because the higher gravimetric energy density of LIB requires a counterweight for safe load handling, which is usually provided by the LAB itself. The costs of the counterweight is calculated in a simplified way as additional pure steel weight multiplied by the weight difference, that results from comparing LAB and LIB.

3.3 Cost parity-based cell assessment

The following figures visualize the results of the cost parity-based cell assessment for passenger cars, trains and forklifts. Although usually the weight of a battery system determines the additional energy demand, in most mobile applications the available space for the battery is more of a limiting factor than the weight of the battery. Therefore, the plots shows the cost-parity prices in EUR kWh^{-1} versus the needed battery system volume. The red dashed line indicates the available space from the reference case to facilitate a comparison. Shapes and colors mark different cell formats and chemistries.

The results for the passenger car, considering all cells listed in the cell database, are shown in Figure 8. The battery volume of the VW ID.3 is plotted as a reference. Different cell chemistries and cell formats were marked in colour and with different markers. The differentiation of the cell chemistries could only be undertaken on the basis of the nominal voltage of the cells, as further details are not included in the data sheet. In addition, the VW ID.3 cell is highlighted in colour to mark the status quo of cells used in passenger cars.

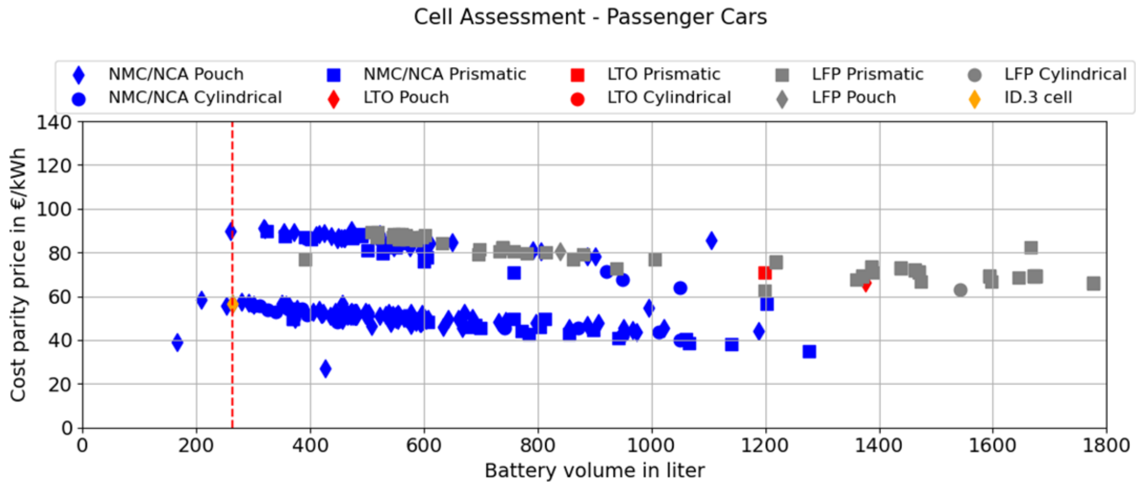

Figure 8: Results of the cost parity-based cell assessment for passenger cars

The results show that LFP and LTO cells allow the highest cost parity price due to their long battery life. However, these cells would also require significantly more installation space. Very few cells require less installation space than the cell installed in the VW ID.3. Cost parity is reached for the VW ID.3 cell at about 60 EUR kWh^{-1}. The result is consistent with the higher prices for battery electric vehicles compared to vehicles with combustion engines

Figure 9 shows the final cost parity-based cell assessment results for passenger trains. The dashed red line indicates a reference volume of 6 000 liter. Results only embed pouch and prismatic cells with nickel-rich or LFP cathodes. Cylindrical cells as well as other cell chemistries, such as LCO or LTO, are not included since either constraints in the battery sizing could not be matched, such as battery replacements must coincide with the revision cycles, or the calculated cost-parity price was negative. LFP cells allow the highest cost parity prices due to their high lifetime and higher C-rates, resulting in up to 550 EUR kWh^{-1}. In contrast, nickel-rich cells dominate the results and 150-500 EUR kWh^{-1} are possible. For many cells, the available installation space is clearly sufficient, indicating high practical feasibility. Assuming a cost parity price of 500 EUR kWh^{-1} for a battery size of about 800 kWh, the calculated acquisition costs would be around 5.8 million EUR, which is close to other literature assessement [10-12] ranging from 6 to 6.5 million EUR.

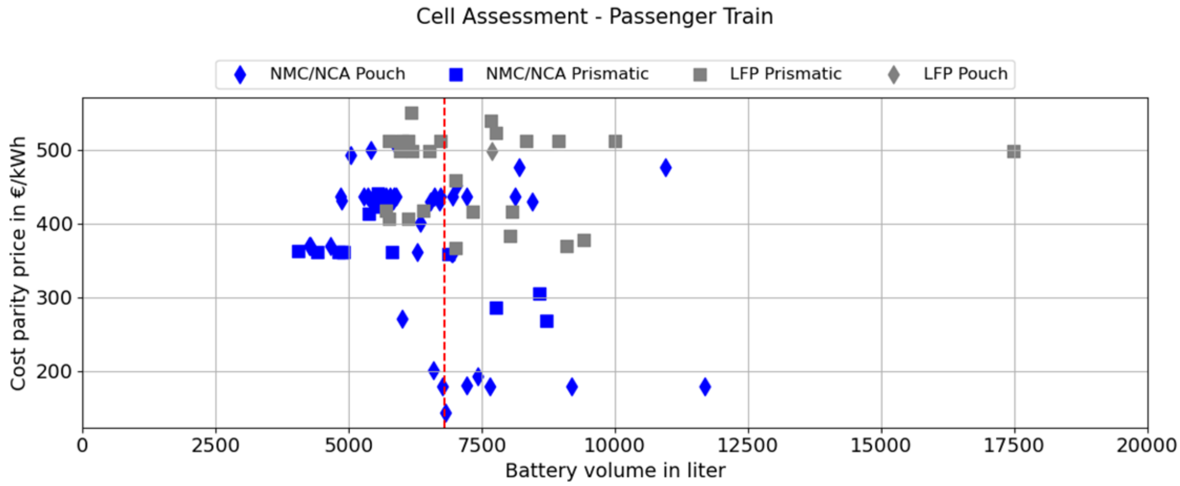

Figure 9: Results of the cost parity-based cell assessment for passenger trains

The results of the cost parity-based cell assessment for forklifts are shown in Figure 10. The relative differences to the required installation space with respect to the volumetric battery size are significantly greater. Only cells with medium to high energy densities can be accommodated in the installation space available for the battery. The suitable cells achieve cost parity prices of less than 100 EUR kWh^{-1} for NMC cells to even 700 EUR kWh^{-1} for a LTO pouch cell. LFP cells are in a range of 200 to 600 EUR kWh^{-1}. This means that cost parity for forklift trucks in warehouse operation can be achieved by a broad range of LIB cells, if these cells can be sourced at that particular price.

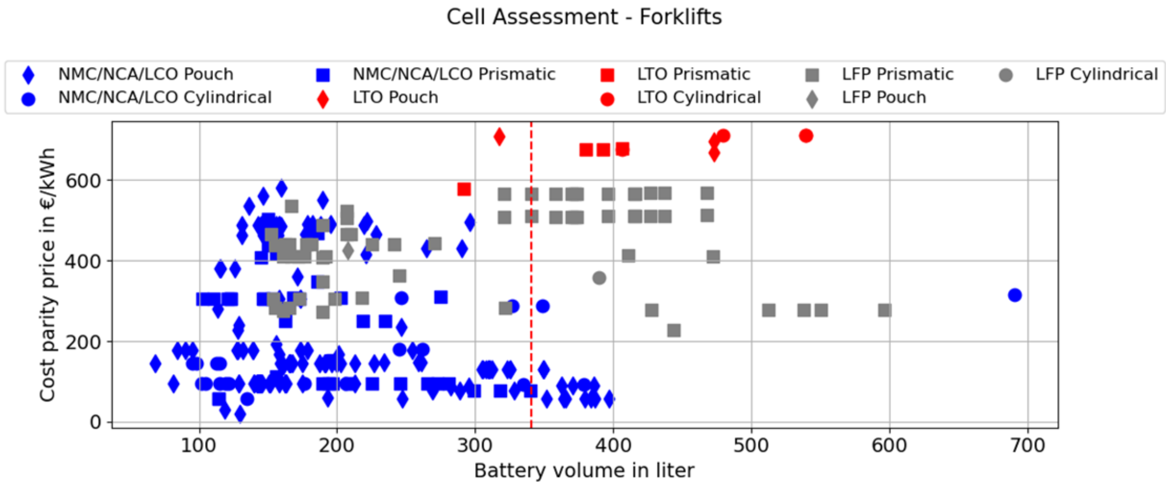

Figure 10: Results of the cost parity-based cell assessment for forklifts

It is evident that LFP cells can be relatively expensive compared to NMC cells in order to achieve cost-parity. Some LFP and most LTO cells with lower energy densities are partly unsuitable based on the modelling, as a system-side fit is not always given with respect to the available installation space. Thus, the battery cannot be sufficiently dimensioned with these cells to meet the needed battery capacity of 20 kWh. Although the methodology was only applied to a specific forklift application use case, it confirms the tendency of the market to move towards the use of LFP instead of NMC in industrial applications [17]. Since LFP cells are already available on the market at a price of less than 200 EUR kWh^{-1} [18], the use of these cells for forklift applications may be economically more advantageous than the use of LAB.

4 Discussion

The use of the method and the comparison across the three applications considered has shown that the method is suitable for a cost-parity based cell selection. While the general methodological approach is the same for all applications, the concrete procedure has to be slightly adapted for the individual applications. Some differences in the approach have emerged:

- For the determination of the underlying load profile for cars and forklifts, existing standardized driving cycles could be used, whereas for passenger trains the load profile had to be defined by imitating a specific route.
- While the train and car applications were compared with conventional vehicles with an internal combustion engine as reference, a reference vehicle with a lead-acid battery was used for the forklift.
- For trains and cars, the weight of the vehicle is decisive for the energy consumption, for forklifts it is the maximum possible lifting capacity.
- Differences can also be observed in the costs. While the costs for powertrain and chassis dominate the overall passenger train costs, the costs for the powertrain in the case of the car are roughly in the same order of magnitude as the costs for energy or, to a certain extent, the costs for maintenance. The calculation for forklifts again shows some other peculiarities: Not only are the costs for a battery already part of the reference case, but additional costs for a counterweight have to be considered if a lighter LIB is used.

Despite these partly different approaches, the method could be used to make an application case-based cell selection. The results shown also reflect the common cost requirements (e.g. costs for BEV battery cells below 100 EUR kWh^{-1}) or developments in the field (e.g. substitution of LAB by LFP cells in the case of forklifts). The method can therefore be used to make an initial choice of cell type for an application. Nevertheless, the following limitations should be considered:

- Only one usage pattern was used as a baseline for each of the applications. And the cell selection can change with a different usage pattern.
- Although there are more than 350 cells in the cell database, it does by no means claim to be complete, and there is a possibility that cells that are better suited are not listed in the database. Plus, datasheet information must not match the actual cell performance when installed in the application.
- To get from the cost parity prices at the battery level to the cell level, a cost-based cell-to-pack factor had to be assumed, which can be influenced significantly the battery pack design.
- The results show the cost parity price, i.e. the maximum price the cell is allowed to cost. The price the customer has to pay in the end, however, is very individual and depends, for example, on the purchase quantity or the customer-supplier relationship.

5 Conclusion and outlook

In this paper, a methodical approach for a cell assessment based on cost-parity was presented and demonstrated using three different mobile applications as examples: Passenger cars, passenger trains and forklifts. The developed methodology allows a high-level, yet tailored, matching of publicly available technical cell data, application requirements and use case conditions to determine the cost parity price for each specific cell for a certain application.

The following conclusions can be drawn about all applications: (1) Due to the often existing restrictions on installation space, today's battery cells are not suitable for all applications because of their sometimes too low energy density. However, suitable cells can be identified for all the applications considered. (2) The calculated cost-parity differs greatly for the different applications. While prices of well below 100 EUR kWh^{-1} may be required for passenger cars, prices for trains can theoretically be up to 550 EUR kWh^{-1} and for forklifts up to 700 EUR kWh^{-1}. (3) In this respect, it can be stated that significant differences between the various cell chemistries and formats and their respective properties - e.g. LTO chemistries with high lifetime but low energy density versus NMC chemistries with higher energy density and lower lifetime - influence the cost parity price.

The cell selection methodology can therefore be used by, for example, manufacturers or suppliers of applications as a tool to solve the trade-off between available installation space and low cell costs for their application. For cell manufacturers, the method provides a way to compare their cell in use with other cells and, where appropriate, to identify new fields of application or to evaluate the impact of cell performance improvements.

However, it should be taken into account that cost is often the most significant criterion when deciding on a particular battery cell, but not the only one. Furthermore, only one underlying use case per application was considered and the results may vary depending on the usage pattern. For this reason, future work will focus on conducting further sensitivity analyses and including additional scenarios, as well as incorporating other criteria such as the carbon footprint of a cell.

Acknowledgments

This work was sponsored by the Federal Ministry of Education and Research Germany within the project "BetterBat" under grant number 03XP0362C.

References

[1] T. Schmaltz; T. Wicke, T.; L. Weymann; P. Voß; C. Neef; A. Thielmann: Solid-State Battery Roadmap 2035+. Fraunhofer ISI. Karlsruhe. April 2022

[2] B. Nykvist and O. Olsson, "The feasibility of heavy battery electric trucks," Joule, vol. 5, no. 4, pp. 901–913, 2021, doi: 10.1016/j.joule.2021.03.007.

[3] O. Teichert, S. Link, J. Schneider, S. Wolff, M. Lienkamp - Techno-economic cell selection for battery-electric long-haul trucks, eTransportation, Vol. 16, 2023, 100225.

[4] D. V. Ragone, Review of battery systems for electrically powered vehicles, Tech. rep., SAE Technical Paper (1968).

[5] P. Dechent, A. Epp, D. J¨ost, Y. Preger, P. M. Attia, W. Li, D. U. Sauer, Enpolite: Comparing lithium-ion cells across energy, power, lifetime, and temperature, ACS Energy Letters 6 (2021) 2351–2355

[6] https://github.com/TUMFTM/TechnoEconomicCellSelection.

[7] VDI Guideline 2198, " Data Sheet for Industrial Trucks," Beuth Verlag, Berlin, 2021.

[8] W. Nikolaos, M. Steinsträter, M. Schreiber, P. Rosner, L. Nicoletti, F. Schmid, M. Ank et al. "Quantifying the state of the art of electric powertrains in battery electric vehicles: Range, efficiency, and lifetime from component to system level of the Volkswagen ID. 3." ETransportation 12 (2022): 100167.

[9] https://www.adac.de/rund-ums-fahrzeug/autokatalog/marken-modelle/vw/vw-golf/

[10] J. Pagenkopf; T. Schirmer, Marktanalyse Alternativer Antriebe im Deutschen SPNV; NOW GmbH: Berlin, Germany, 2019.

[11] VDE 2020: Alternativen zu Dieseltriebzügen im SPNV Einschätzung der systemischen Potenziale

[12] C. Streuling, J. Pagenkopf, M. Schenker, K. Lakeit, Techno-Economic Assessment of Battery Electric Trains and Recharging Infrastructure Alternatives Integrating Adjacent Renewable Energy Sources (2021, mdpi sustainability)

[13] W.A. Günthner, R. Micheli (2015). H2IntraDrive – Einsatz einer wasserstoffbetriebenen Flurförderzeugflotte unter Produktionsbedingungen, Forschungsbericht, Lehrstuhl für Fördertechnik Materialfluss Logistik Technische Universität München, ISBN: 978-3-941702-58-5

[14] Expert consultation with a forklift truck manufacturer and user, August 2022

[15] https://online-batterien.de/a/q-batteries-48v-gabelstaplerbatterie-4-pzs-560-ah-din-a-832-523-784mm-l-b-h-trog-57017020-inkl.-aquamatic/9879580

[16] Jiao, M. et al., „Evaluation on Total Cost of Ownership of Electric Forklifts with lithium-ion battery," in 2021 IEEE 4th International Electrical and Energy Conference (CIEEC), Wuhan, China, 2021.1

[17] C. Pillot 2022. The rechargeable battery market 2021-2030. Avicenne Energy, 29th Edition, June 2022

[18] BNEF 2021. Battery Pack Prices Fall to an Average of $132/kWh, But Rising Commodity Prices Start to Bite, November 30, 2021, https://about.bnef.com/blog/battery-pack-prices-fall-to-an-average-of-132-kwh-but-rising-commodity-prices-start-to-bite/

Presenter Biography

Tim Hettesheimer is researcher at Fraunhofer ISI since 2010 and project leader in the Competence Center Energy Technologies and Energy Systems at Fraunhofer ISI since 2017. He studied general mechanical engineering at the Technical University of Kaiserslautern and the Karlsruhe Institute of Technology (KIT). He completed his doctorate at the Karlsruhe Institute of Technology. His research focuses on battery technologies and energy efficiency in industrial production processes and value chains.