World Electric Vehicle Journal

Article

Techno-Economic Suitability of Batteries for Different Mobile Applications—A Cell Selection Methodology Based on Cost Parity Pricing

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Abstract: Rapid advancements in lithium-ion battery (LIB) technology have paved the way for the electrification of diverse applications, with continuous improvements in performance, substantial cost reductions, and the emergence of new manufacturers, formats, and cell chemistries. However, this diversity poses challenges in identifying the most suitable battery cells for specific applications. Here, we present a high-level techno-economic framework for cell selection, leveraging an extensive database of over 500 real-world cells, techno-economic analyses of emerging applications, and a Python-based modeling approach. We apply this method to three electrifiable mobile applications with distinct characteristics: battery electric cars, industrial forklifts, and regional passenger trains. Our results emphasize substantial variations in technical requirements, from power capability to energy density or longevity. We observe no particular differentiation according to cell formats, but tendencies for most suitable chemistries per application. No cell is suitable for all applications, particularly regarding the required maximum cell costs to ensure profitability, ranging from a few to several hundred Euros per kWh to achieve cost parity with a state-of-the-art reference technology. These findings highlight the importance of tailored cell selection strategies for decision makers to optimize performance and cost-effectiveness across different applications.

Keywords: battery cell selection; battery electric vehicle (BEV); techno-economic assessment; cost modeling; passenger trains; forklifts

Citation: Link, S.; Stephan, M.; Weymann, L.; Hettesheimer, T. Techno-Economic Suitability of Batteries for Different Mobile Applications—A Cell Selection Methodology Based on Cost Parity Pricing. *World Electr. Veh. J.* **2024**, *15*, 401. https://doi.org/10.3390/wevj15090401

Academic Editors: Joeri Van Mierlo and Genevieve Cullen

Received: 23 July 2024
Revised: 23 August 2024
Accepted: 30 August 2024
Published: 3 September 2024

1. Introduction

Batteries are central to reducing greenhouse gas (GHG) emissions in various sectors. Accordingly, the global demand for lithium-ion batteries (LIBs) has substantially increased and reached an estimated 1000 GWh market in 2023 [1], with annual growth rates of approximately 30–40% and projections for 2030 approaching over 4–6 TWh [1,2]. Herein, the electrification of passenger cars (i.e., battery electric vehicles (BEVs) and plug-in hybrid vehicles (PHEVs)) is widely recognized as the key driver and enabler of future developments worldwide, while stationary storage systems from home to industrial scales are gaining momentum. The resulting battery innovations, such as rapidly decreasing production costs, increasing energy densities, longer lifetimes, and improved fast-charging capability, already allow for the technically feasible and economically viable electrification of an increasing number of mobile and stationary applications [1,3,4].

Increasing electrification also entails increasing complexity, specialization, and heterogeneity, since each application has specific requirements and particularities that must be considered when selecting battery cells and designing battery systems. On the one hand, cell suppliers are aiming to find new applications for their battery portfolio, but can barely keep track of all the applications and their specifics. On the other hand, manufacturers and cell integrators for various applications are searching for the most suitable batteries among many choices; however, they can barely keep track of all the available LIB cells and their characteristics. In the future, a wide choice of alternative battery technologies could further increase the variety of cell chemistries and formats [5].

This paper builds on an approach presented at the EVS36 Symposium 2023 [6]. It proposes a techno-economic framework that enables high-level yet tailored cell selection for different applications. This approach relies on a Python-based model in which cell-specific cost-parity prices (CPP) can be determined for different applications. The cost-parity price of a battery cell is defined as the maximum cell price to achieve cost parity with an existing reference technology [7]. A battery cell with a cost-parity price that exceeds its actual price offers the potential for significant economic benefit through its implementation [6]. These results can be compared to those of an alternative, e.g., combustion-based applications [7]. The main benefit of this approach is that the same cell can be examined for its suitability in several applications very easily, instead of studying applications isolated and independently. Plus, it allows for more tailored and specific cell selection rather than universal selection methods, such as the well-known Ragone plot [8] or the ENPOLITE tool [9].

This paper is structured as follows. Section 2 introduces our three selected applications and identifies the current research gap. Section 3 starts with presenting the methodology in general and then examines the particularities per application and ecological considerations. Section 4 presents the results, while Section 5 complements the discussion. Section 6 closes with summarizing the results, and provides key implications and recommendations.

2. Background and Research Gap

In the literature, the costs of internal combustion engine vehicles (ICEV) and battery-electric vehicles (BEV) are typically compared and evaluated using lifetime analysis approaches, i.e., total cost of ownership (TCO) or Life Cycle Costing (LCC). Recent TCO calculation discussions for BEVs are shown in [10–12], for instance. As a standard, the result is a monetary price (TCO) or CO_2 footprint (LCA) per kilometer driven. The TCO results vary depending on the type of application being compared and the assumptions made, for example, regarding driving cycles [13] or cost estimations with high influence and sensitivity of battery costs in BEVs [14,15]. Generic price projections are often used for the battery costs on cell or pack level [10]. Moreover [7], for long-haul trucks, there is currently no study in place to determine which cells at what price can support a (cost) parity with a reference application in comparison with the battery-electric alternative (i.e., ICEV with BEV) while incorporating the technical suitability. With this paper, we intend to fill this gap by presenting a method to determine the cost parity for three selected mobile applications. The applications of battery-electric vehicles, trains, and forklifts were selected to represent the highly diverse requirements for the battery in mobile applications, while keeping the complexity within reasonable limits.

The electrification of passenger cars through battery-electric vehicles is very likely a no-regret policy to decarbonize individual transport [16], with a promising outlook due to continued advancements in technology, supportive policies, and increasing consumer acceptance. However, challenges remain for single-battery technologies, necessitating tradeoffs regarding battery performance, life, cost, and safety [17], as well as advanced system integration [17,18]. To reach competitiveness with ICEV, the EUCAR stats cell-level target costs of 70 EUR/kWh by 2030 [19], while the BATT4EU Strategic Research and Innovation Agenda sets 75 to 100 EUR/kWh as pack-level target costs for mobility applications by 2030 [20]. BNEF [21] found that volume-weighted average prices in 2023 were 89 USD/kWh (cell-level) and 128 USD/kWh (pack-level).

To decarbonize rail transport, diesel multiple units are being replaced with battery electric multiple units (BEMUs). Modern BEMUs use combined battery–catenary power, drawing energy from overhead catenary or lithium-ion batteries if no overhead catenary is available. They charge while under catenary, or at stops and during braking, making them efficient on routes with mixed electrification, particularly with non-electrified sections below 100 km [22]. Battery requirements are high, balancing energy density to maximize passenger capacity, power density for fast recharging, safety characteristics, and long lifetime, making lithium-iron-phosphate (LFP) an attractive cell chemistry as the cathode-active material. However, different manufacturers also rely on lithium-metal oxides like nickel–mangan–cobalt (NMC) as the cathode material or lithium–titanate (LTO) as a substitution of the commonly used anode material graphite [23,24].

For industrial applications and logistics, the economic comparison of forklift trucks over its lifecycle is key in the consideration for decision-makers [25]. In the past, the methodological focus was on comparing battery-powered and fuel-cell-powered forklift trucks from a technical point of view [26,27], in an economic or ecological utilization comparison [26,28–30], on impacts from the technology selection of the warehouse economics [31] and handling activities [32], or a combination of such different aspects [33]. Furthermore, different battery technologies are employed for the evaluation and comparison of forklift trucks. This entails a techno-economic comparison of the LIB with a conventional lead-acid battery (LAB) [31,34,35], life-cycle costing [36], as well as analyzing the utilization of LIBs in a second life use-case [37]. For several years, there has been a notable increase in the proportion of LIBs in the product portfolios of original equipment manufacturers (OEMs) of industrial applications and forklift trucks.

A review of the recent techno-economic analyses reveals a notable absence of consideration given to the large range of battery cells available. There is a paucity of analyses that take into account not only LIBs with defined cost and performance indicators, but also the broad array of (real-world) battery cell data based on their individual product specifications to make an economical best-fit technology selection for individual applications. At the same time, the total cost of ownership (TCO) metric is commonly used as an indicator for the cost-competitiveness of a technology [10,11,13–15,34,36,38], but cannot clearly answer the question of the price threshold at which a single cell becomes economically viable in battery-electric applications. It is our intention to address this gap by proposing a novel methodology for cell selection based on cost-parity pricing. In addition to the analysis in [6], this paper also presents a cross-application comparison of the results in three different mobile applications, and further supplements the CPP analysis with a calculated CO_2 footprint for each cell in the aforementioned applications.

3. Methodology

3.1. General

Our systematic approach involves three steps, as shown in Figure 1: energy simulation, battery sizing, and cost calculation.

First, we define the input data used in our 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 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. The input data are derived from public information based on desk research and assumptions based on expert consultations with various stakeholders in the car, train, or forklift truck industry, e.g., application manufacturers and operators.

Second, over 500 battery cells and their specific technical capabilities are fed into the battery sizing algorithm, which determines the required number of cells and the final battery system's capacity to fulfill all of the requirements and load profiles. The sizing algorithm from cell to pack level was implemented in accordance with [7]. Technical capabilities include, 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 is available for download [39].

Third, the total cost of ownership (TCO) or levelized cost of energy (LCOE) are calculated based on the chosen battery capacity and simulated energy needs. These results are then compared to the TCO/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 using 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 was 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 was 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.

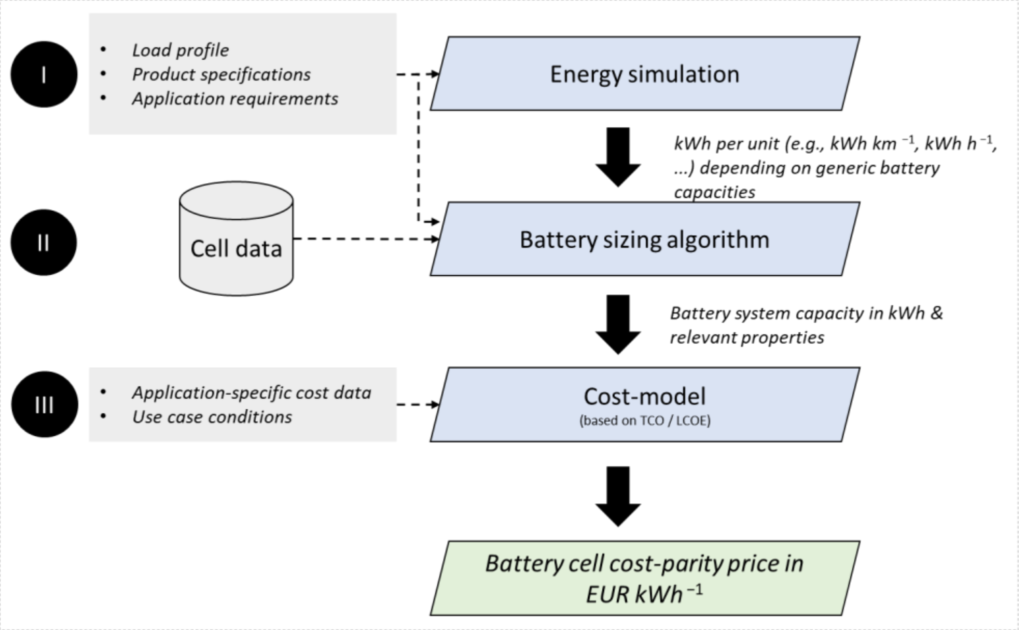

Figure 1. Schematic structure of the cost-parity model.

While the general methodology is described in Figure 1, the detailed procedure for each application is quite different and is described below. However, there are some similarities between the applications in the calculations. For instance, the battery size is mainly affected by weight and energy consumption for most mobile applications. Table 1 shows the main sources that are used for our calculations for the different steps in the cost-parity model. The calculations were carried out in accordance with [7] and with the relevant data for each application. For instance, the energy consumption during operation differs greatly, the battery capacity required for a driving profile taking into account the available installation space is highly application-individual, and costs like taxes for BEVs or worktime in logistics for forklift operation are added or even eliminated compared to the reference application. As generalized use-cases are required for this analysis, the limited data availability on typical driving scenarios and use-cases had to be filled by assumptions based on various studies and expert consultancy, as discussed in the following subchapters.

The methodology is applied to the three distinct mobility applications with different requirements to determine whether there are cells that are suitable for all the applications under consideration or whether different cells should be selected for these specific applications. This allows for an economic selection on the basis of the cost-parity price, taking into account the technical suitability of an LIB's cell chemistry and format.

Table 1. Main sources and model input data for own calculations in accordance with [7], adapted for each application use case.

		Main Sources for Each Application Type		
		Passenger Car	**Train**	**Forklift**
I	Energy simulation	[40]	[24,41,42]	[27,43]
II	Battery sizing algorithm	[39,40,44]	[39,44]	[34,39,44]
III	Cost model	[15,45,46]	[24]	[31,34]

3.2. Particularities for Passenger Cars

The passenger car model is built on the WLTP driving cycle as a global standard for measuring energy consumption, pollutant levels, CO_2 emissions, or the all-electric nature of fully electric cars. This driving cycle specifies a target speed over time, road gradients, and duration of stops along the route, 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 is the 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.

3.3. 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, which is not yet electrified and also represents a typical route that would be suitable for battery operation (in terms of length, topography, and traffic frequency). This covers the full operation schedule such as four stops, idle times (1 min each), and station waiting times for turning around (20 min); route characteristics, such as section distances, speeds (max. 160 km/h), gradients, and maximum permissible weights (22.5 tonnes); and other characteristics, such as the number of daily runs (3), operating days per year (320), and the existence of overhead lines. The total distance is 167 km, which equals 95–105 min, while the middle section of approximately 90 km is not electrified.

Similar 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-unit train with 115 tonnes of curb weight, an overall length of 70 m, a capacity for 410 people (220 seated and 190 standing), 1000 kW constant power, and 2600 kW peak serves as a reference. The combined installation volume (i.e., subfloor and rooftop) equals 7500 L as a reasonable installation space volume. 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. Additionally, battery sizing covers the restriction that potential battery replacements must occur 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.

3.4. Particularities for Forklifts

The maximum load capacity of forklift trucks plays a decisive role in their utilization and energy consumption. In a preliminary step, we evaluated 30 publicly available VDI Guideline 2198 [43] type sheets from LAB counterbalanced forklift trucks and found an energy consumption of 4 to 10 kWh per hour for class 1 trucks [33] with 1 to 3 tonnes in maximum lift load. This value is not specifically tailored to real use-cases, as the guideline is primarily aimed at comparing the energy consumption of different vehicles, but it shows a linear increase in energy consumption when the lift load increases. We have therefore recreated a use-case from a study with original vehicle data [27].

Firstly, we defined a concrete use-case for class 1 forklifts trucks. As the driving cycles vary strongly from use-case to use-case and battery sizes are not tailored to specific driving cycles, a hypothetic cycle was defined. It involves realistic stand-by times, characteristics, energy consumption within a single shift, and a 15 shift week, 3 shifts per working day, respectively. Instead of mimicking an actual driving cycle, it was defined to cover various aspects of characteristic forklift driving cycles simultaneously. The basis of battery dimensioning is the characteristic energy consumption in terms of the timeframe of operation and possible downtime periods needed to charge the forklift battery. Considering the cell properties, the required battery size is determined, as well as the resulting battery volume and lifetime with respect to the forklift lifetime and battery installation space. Forklifts are one of the few rare cases where the gravimetric energy density of the battery is not only irrelevant, but rather is inverse to other mobile applications. As the battery is used as a counterweight, a large battery mass is desired. The cost of additional counterweight for low-weight battery systems were also implemented in the model. Compared to other mobile applications, the cost-parity comparison of an LIB electric forklift truck is compared to that of a status quo lead-acid (LAB) electric forklift truck with a maximum load capacity of 2 tonnes. As LABs require regular battery swapping in these use-cases, whereas LIBs can be easily charged in stand-by times, the model was extended by additionally including a measure for the economic benefit of the working time saved, in accordance with the finding of [31].

3.5. Ecological Considerations

The life cycle assessment (LCA) of batteries and mobile applications is an essential tool for the analysis and comparison of technologies in terms of greenhouse gas (GHG) emissions and the individual carbon footprint. One of the most discussed use cases for LCA approaches in recent times is that of the lithium-ion battery [47] in electric vehicles [48–51], for instance, with cradle-to-gate results ranging from 12 to 313 kg CO_{2eq} per kWh of battery capacity [51]. One limitation of the LCA approach is that, for the purpose of comparing battery-electric applications with other technologies, it is necessary to include differing components and to consider all parts of the application in a whole life cycle assessment LCA [49].

In favor of our systemic view on different applications, real-world cell datasheets, and cost-parity comparisons, we state the carbon footprint of the batteries for the considered applications. This encompasses, i.e., how often a cell has to be replaced or if it has reached its calendric or cycling end of life. We compare this impact to the cost-parity price or technical characteristics. Our environmental assessment includes only battery-related GHG emissions depending on (1) cell materials, (2) production, and (3) formation (cf. Figure 2). We disregard other GHG emissions, comparisons to the next best alternative, or potential credits from recycling and reuse. The carbon footprint (in kg CO_{2eq} per kWh) for each individual cell is calculated as a function of cell chemistry, cell format, specific energy (in Wh/kg) or cell weight (in kg), and capacity (in Ah).

Finally, the overall CO_2 footprint at the application level (in kg CO_{2eq}) is calculated as a function of battery size (in kWh) and possible battery replacements in accordance with the lifetime determined in each cell data sheet.

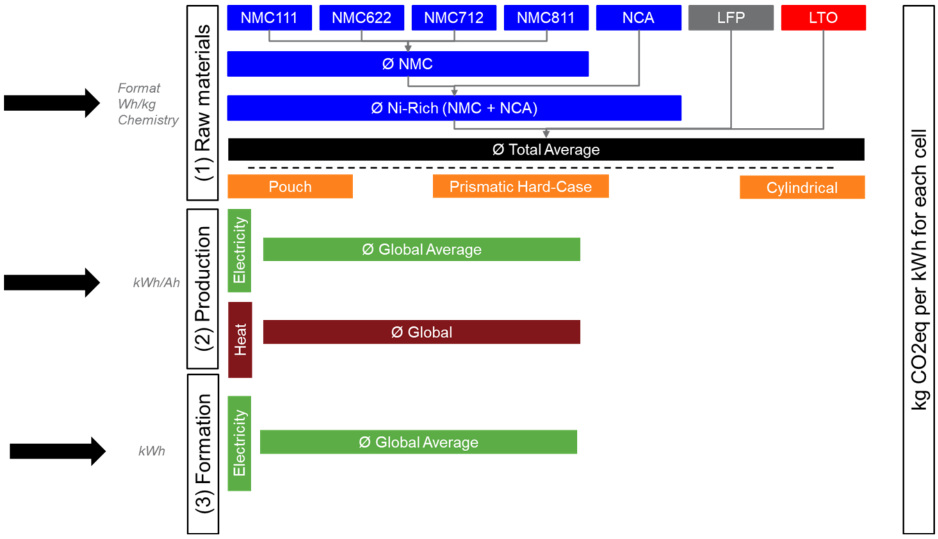

Figure 2. Overview of the CO_2 footprint methodology and characteristics.

4. Results

4.1. Energy Consumption and Battery Dimensioning

The energy consumption of a passenger car (apart from its use) depends particularly on its vehicle weight. A vehicle simulation was carried out for different vehicle weights to determine the influence of weight on consumption. The energy consumption ranges from 0.133 kWh/km with a vehicle weight of 1435 kg to 0.197 kWh/km with a weight of 3000 kg. As the vehicle weight increases, the energy consumption increases due to the increased rolling and acceleration resistance. A consumption of 0.149 kWh/km for the BEV was calculated with a battery size of 64.3 kWh, which fits well with measured real-world data for this kind of vehicle [40]. The consumption of the reference vehicle, Golf VIII, is approximately 5.6 L per 100 km [52].

The energy consumption of a passenger train at 25 °C is approximately 4.6–5.3 kWh/km, depending on the train mass and direction of travel. Recent studies and industry values indicate a range from 3 to 4 kWh/km in standard operations to 5–6.5 kWh/km in demanding operations, including all auxiliary consumers and heating in winter [24,41,42], indicating the good representativeness of our simulation model. In contrast, the simulated energy consumption of the diesel train is between 9.5 and 10.1 kWh/km, which equals approximately one liter per kilometer. The calculated gross battery capacity is typically approximately 800 kWh and 4500–11,700 kg. The median was 8200 kg, while the lower quartile was 6000 kg and the upper quartile was 9800 kg.

The energy consumption of a forklift truck depends on the maximum load capacity of a counterbalance forklift truck. As the maximum load capacity increases, the energy consumption increases partly due to the higher lifting load and the total weight of the forklift truck. A characteristic energy consumption of 3 kWh/h was derived from [27,53] for the battery dimensioning. The battery is dimensioned so that the LIB forklift truck can fulfill the same operating conditions as an LAB forklift truck. Considering a shift with 8 h of working time, the operative usage time of the forklift truck in a warehouse was estimated to be a maximum of 5 h [27]. Our model assumed that half of the remaining 3 h are available for charging, as usually charging stations have to be shared among the different forklifts of the fleet. While specific time losses (e.g., driving to a charging station, connecting the charging wire) were subtracted, only a time of 90 min per shift was considered to be used for charging. 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 LIBs is much greater than that of LABs, the battery volume seems less important for battery dimensioning in electric forklift trucks. Nevertheless, a space requirement of 341 L was assumed, as derived from a commonly used 48 V 6 PzS 540 Ah lead-acid battery, i.e., [54], for 2-tonne forklift trucks. This serves as an installation space limit for the volumetric dimensioning of the LIB.

4.2. Cost Parity Analysis

For the cost comparison, a BEV similar to the VW ID.3 is compared with a corresponding combustion engine vehicle, the VW Golf VIII. The cost model considers all cost components of BEVs 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 specific energy of the cell influences the energy consumption. The costs for the battery depend on the required battery size, cycle stability, calendar life, and cell price.

The TCO breakdown in Figure 3 shows that the costs for the conventional vehicle amount to just over EUR 25,000. Assuming an average annual mileage of ~13,600 km in Germany, a large part of this cost is related to energy costs of approximately EUR 9700 as well as maintenance costs (EUR ~ 7850) and powertrain costs (EUR ~ 6900). Considering the tax advantage for BEVs, there is a remaining budget of almost EUR 15,000 for the battery layout to reach cost parity with the ICV. Above all, the maintenance and energy costs are significantly lower for BEVs.

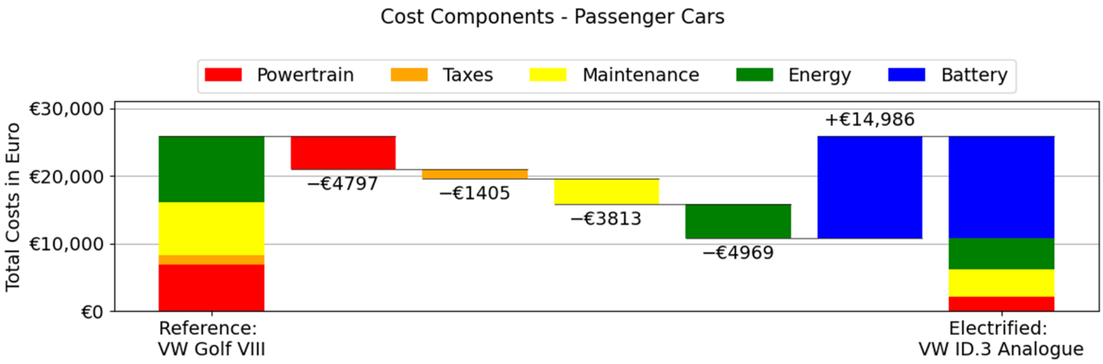

Figure 3. Cost comparison results for passenger cars over ten years.

For trains, the cost model compares the battery-electric version to its diesel equivalent over 30 years of service life (cf. Figure 4). Cost factors include powertrain (incl. chassis), maintenance, energy costs, and battery costs. Lower powertrain costs result from the cost advantages of electric versus diesel powertrains and are independent of 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 by considering the total number of required cells.

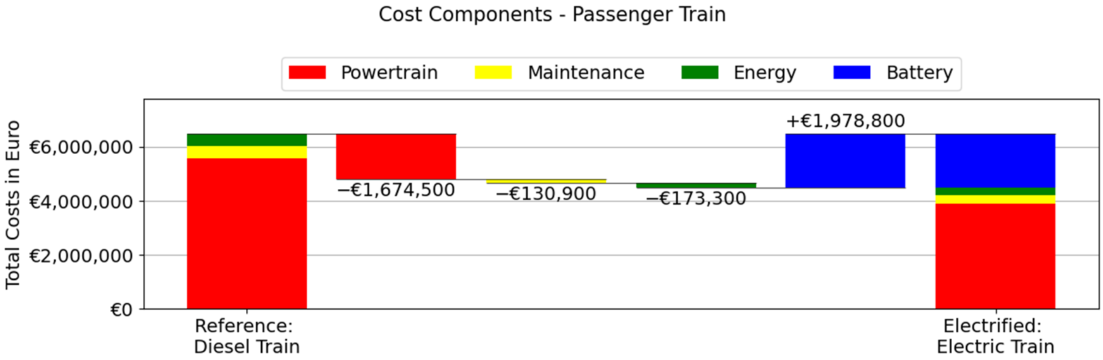

Figure 4. Cost comparison results for passenger trains over 30 years of service life.

For forklifts, the cost parity analysis 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) forklift truck: battery maintenance, energy efficiency, labor time losses, (additional) counterweight, and the cost of the battery itself, as shown in Figure 5. The LAB's cost includes three battery replacements of the LAB and the initial purchase price. This corresponds to the assumed lifetime of the LAB of 6000 operating hours compared to the expected lifetime of 20,000 operating hours for an electric forklift [27]. The LIB's cost is determined by the required battery size (influenced by the charging power), cycle stability, calendar life, and cell price.

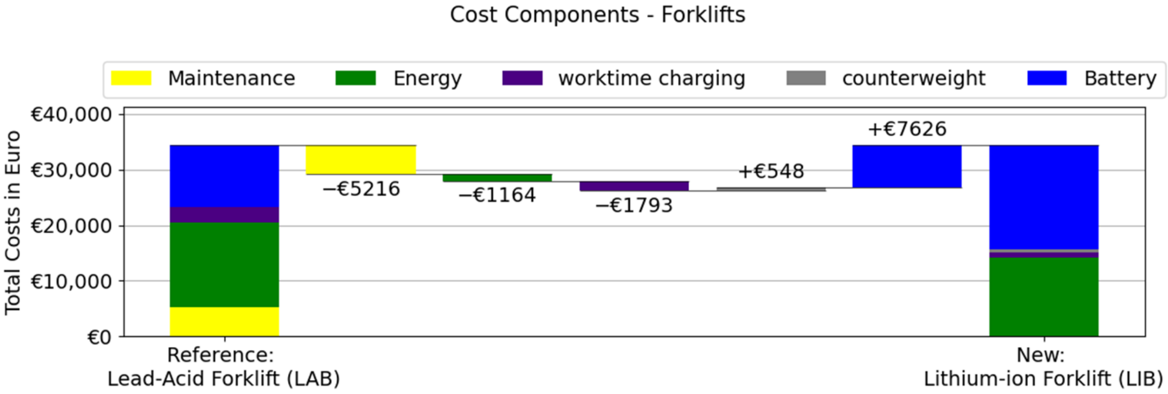

Figure 5. Cost comparison results for forklifts operating for more than 20,000 h.

Since no specific maintenance is required for LIBs compared to the maintenance of lead-acid batteries after every 1000 operating hours [27], cost benefits can be expected. Additional maintenance costs for the forklift itself (e.g., tire repair) were neglected, as this similarly affects both LIB and LAB forklifts [34]. The energy consumption during operation is considered equivalent for both technologies, but is influenced by the round-trip efficiency of each battery technology. The LIB technology eliminates the monetized loss of working time due to the necessary swapping of lead-acid batteries in three-shift operations. LIB forklifts need a counterweight for safe load handling because of the higher gravimetric energy density of LIBs, which is usually not needed for LABs. The costs of the counterweight are simplified, as the additional pure steel weight is multiplied by the weight difference that results from comparing the LAB and LIB.

4.3. Cost Parity and Technical Considerations

The following section shows exemplary cost-parity assessment results for passenger cars, trains, and forklifts. Although the weight of a battery system usually determines the additional energy demand, the available space for the battery is typically more limiting. Therefore, the plots show the cost-parity prices in EUR/kWh versus the required battery system volume in Figures 6–8. A dashed line indicates the available space from the reference case to facilitate comparison. Shapes and colors mark different cell formats and chemistries. For interpretation, the typical target direction to optimize is toward the top left quadrant, which signifies a high cost-parity price (indicating that the cell may be expensive due to its superior performance) while simultaneously requiring as little installation space as possible.

Figure 6 shows the results for the passenger car, considering all of the cells listed in the cell database. The battery volume of the VW ID.3 is plotted as a reference (dashed orange line). Different cell chemistries and cell formats are marked in color and with different markers. The differentiation of the cell chemistries could only be undertaken based on the nominal voltage of the cells, as further details are not included in the datasheet. In addition, the VW ID.3 cell is highlighted to indicate the status quo of the cells used in passenger cars.

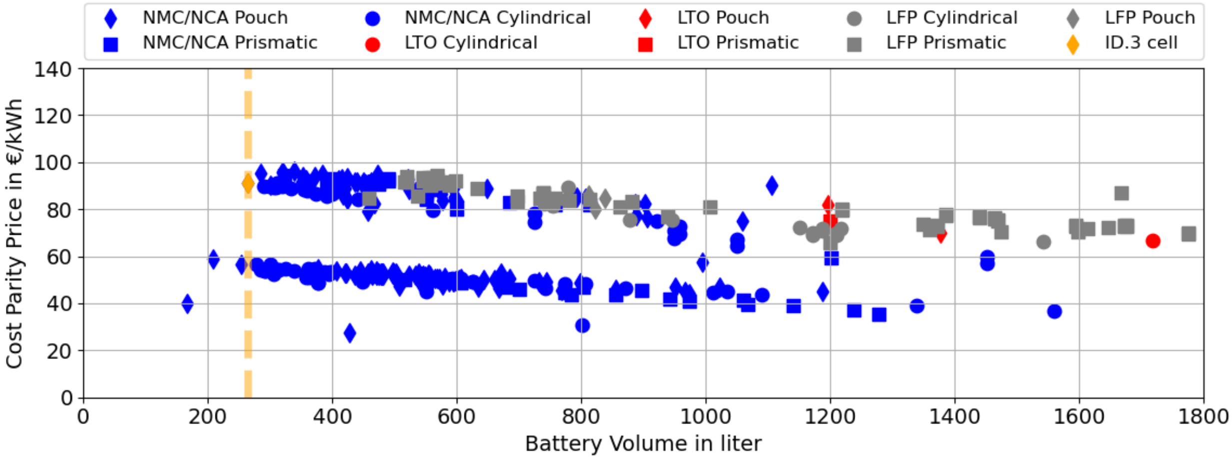

Figure 6. Results of the cost parity-based cell assessment for passenger cars. X-axis: required battery volume in liters. Y-axis: cost-parity price in EUR/kWh. Cell formats are represented by different shapes: pouch (diamond), cylindrical (circle), and prismatic hard-case (square). Cell chemistries are color-coded: Ni-rich cells (i.e., NMC and NCA) are in blue, LTO cells are in red, and LFP cells are in gray.

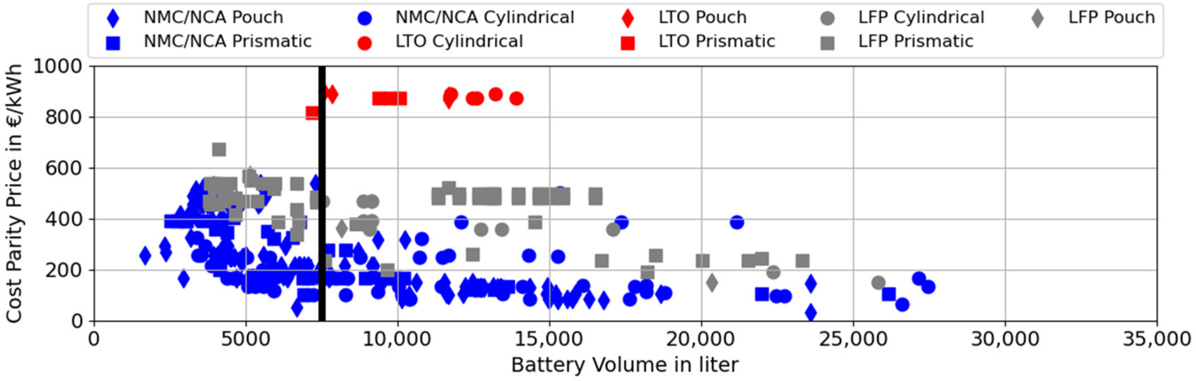

Figure 7. Results of the cost-parity-based cell assessment for passenger trains. X-axis: required battery volume in liters. Y-axis: cost-parity price in EUR/kWh. Cell formats are represented by different shapes: pouch (diamond), cylindrical (circle), and prismatic hard-case (square). Cell chemistries are color-coded: Ni-rich cells (i.e., NMC and NCA) are in blue, LTO cells are in red, and LFP cells are in gray.

The results show that LFP and LTO cells have the highest cost-parity due to their long battery life. However, these cells 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 approximately 60 EUR/kWh. This result is consistent with the higher prices for battery electric vehicles than for vehicles with combustion engines.

Figure 7 shows the final cost-parity-based cell assessment results for passenger trains. The black line indicates a reference volume of 7500 L. LTO cells have the highest cost parity due to their long lifetime and high C-rate, resulting in up to 900 EUR/kWh. LFP cells reach up to 680 EUR/kWh. In contrast, Ni-rich cells dominate the results, but only reach around 150–500 EUR/kWh. The available installation space is sufficient for many cells, indicating high practical feasibility. Assuming a cost parity price of 500 EUR/kWh for a battery size of approximately 800 kWh, the calculated acquisition costs would be approximately EUR 5.8 million, which is close to that reported in the other literature [24,41,42], which is approximately EUR 6.0–6.5 million.

Figure 8 shows the results of the cost-parity-based cell assessment for forklifts. The dashed purple line indicates the available installation volume of 341 L. The relative differences in the required installation space concerning 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 for NMC cells and even 700 EUR/kWh for an LTO pouch cell. LFP cells are in the range of 200–600 EUR/kWh. This means that a broad range of LIB cells can achieve cost parity for forklift trucks in warehouse operation if these cells can be sourced at that price.

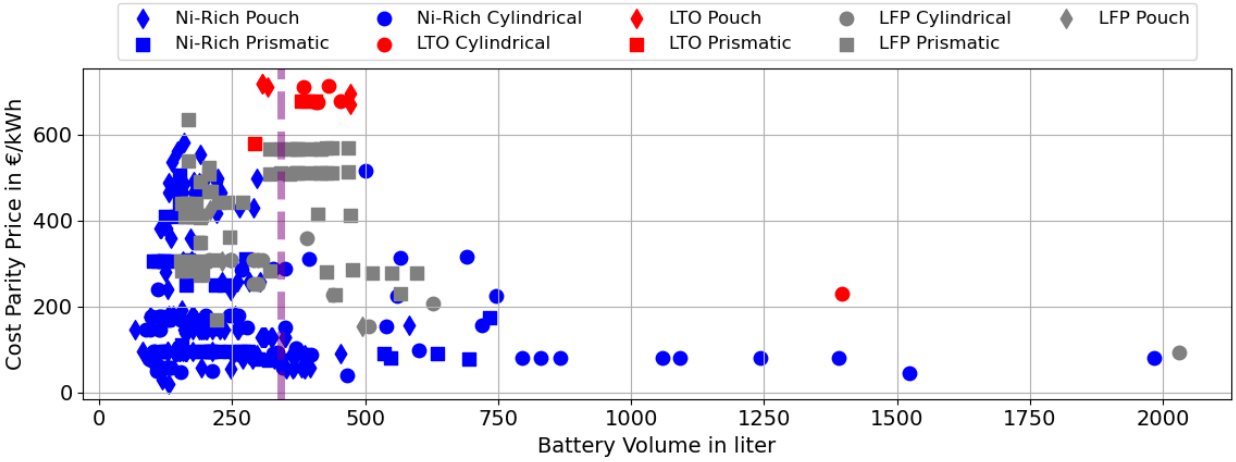

Figure 8. Results of the cost-parity-based cell assessment for forklifts. X-axis: required battery volume in liters. Y-axis: cost-parity price in EUR/kWh. Cell formats are represented by different shapes: pouch (diamond), cylindrical (circle), and prismatic hard-case (square). Cell chemistries are color-coded: Ni-rich cells (i.e., NMC and NCA) are in blue, LTO cells are in red, and LFP cells are in gray.

We found that LFP cells can be more expensive than NMC cells for achieving cost-parity. Some LFP and most LTO cells with lower energy densities are partly unsuitable for modeling, as a system-side fit is not always given concerning the available installation space. Thus, the battery cannot be sufficiently dimensioned with these cells to meet the needed capacity of 20 kWh. Although the methodology was only applied to a specific forklift application, it confirms the market's tendency to use LFPs instead of NMCs in industrial applications [55]. Since LFP cells and packs are already available on the market at a price of less than 150 EUR/kWh [21], using these cells for forklift applications may be more economically advantageous than using LABs. This result is also in accordance with recent studies on the economic competitiveness of LIB and LAB forklift trucks, which demonstrates that LIB generally offers economic benefits during the utilization phase [31,34].

4.4. Cost Parity and Ecological Considerations

Figure 9 shows the application-specific differences for cost-parity prices versus ecological footprint (CO_{2eq}). The actual battery size and the number of required batteries (i.e., battery replacements) strongly affect the results. The latter is affected by both calendar aging and the limited cycle life. We accumulate the total carbon footprint for each application to address the application-specific performance indicators, for instance, the size of the battery or accounting the entire application lifetime. For BEVs and forklifts, the impact is quite similar, from up to a few tonnes to approx. 50 tonnes CO_{2eq} absolute, whereas the operating lifetime and the required size of the battery in trains greatly multiplies its impact.

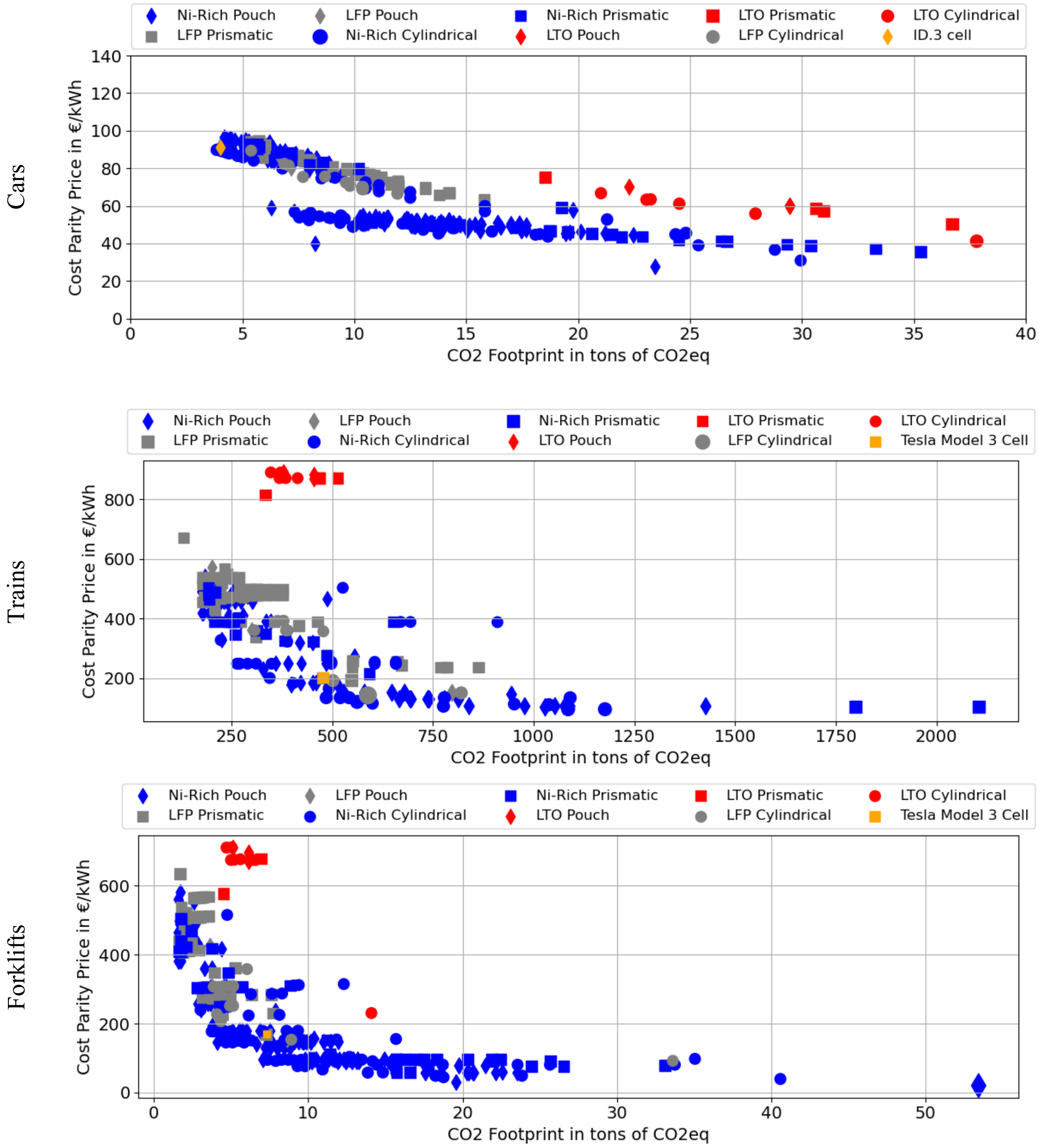

Figure 9. Comparison of cost-parity versus CO_2 impact on battery production. Upper: cars; middle: trains; lower: forklifts. X-Axis: CO_2 footprint in tonnes of CO_{2eq}. Y-Axis: cost-parity price in EUR/kWh. Cell formats are represented by different shapes: pouch (diamond), cylindrical (circle), and prismatic hard-case (square). Cell chemistries are color-coded: Ni-rich cells (i.e., NMC and NCA) are in blue, LTO cells are in red, and LFP cells are in gray.

We highlight the high spread in CO_{2eq} for Ni-rich cells (NMC and NCA) due to the large heterogeneity in their technical performance. However, Ni-rich cells can reach good trade-offs between high cost-parity and low CO2 footprint. Ni-rich cells and LFP represent the best economic-ecologic trade-off for cars, reaching approximately 80–100 EUR/kWh and 4.3–5.6 $tCO_{2eq,}$ respectively. In contrast, LTO cells swing at approximately 40–80 EUR/kWh and over 18 tCO_{2eq}. LFP and LTO cells become favorable over longer time windows for trains and forklifts since fewer replacements are needed.

4.5. Cross-Application Comparison for Selected Cells

Figure 10 compares cell-specific cost-parity prices (CPP), highlighting that the same cell might require cost-parity prices ranging from a few to several hundred Euros for different applications. It should be noted that only those cells are plotted that do not exceed the volumetric limitation of the application, especially for trains and forklifts (for further details, please refer to Section 4.3). It becomes obvious that the CPP of trains and forklifts are consistently observed to be in close proximity to one another. The CPP of the LTO cells for trains is slightly higher than that for forklifts. In the case of NMC and LFP cells, there is minimal differentiation in the application comparison. However, when comparing cars and trains, the pronounced economic constraints on cell prices for battery-electric passenger cars is noteworthy. This aligns with the postulated significance of battery costs for EV market diffusion [19,20] and simultaneously demonstrates that trains and forklifts can achieve cost parity with current reference applications, even with elevated LIB cell costs [34].

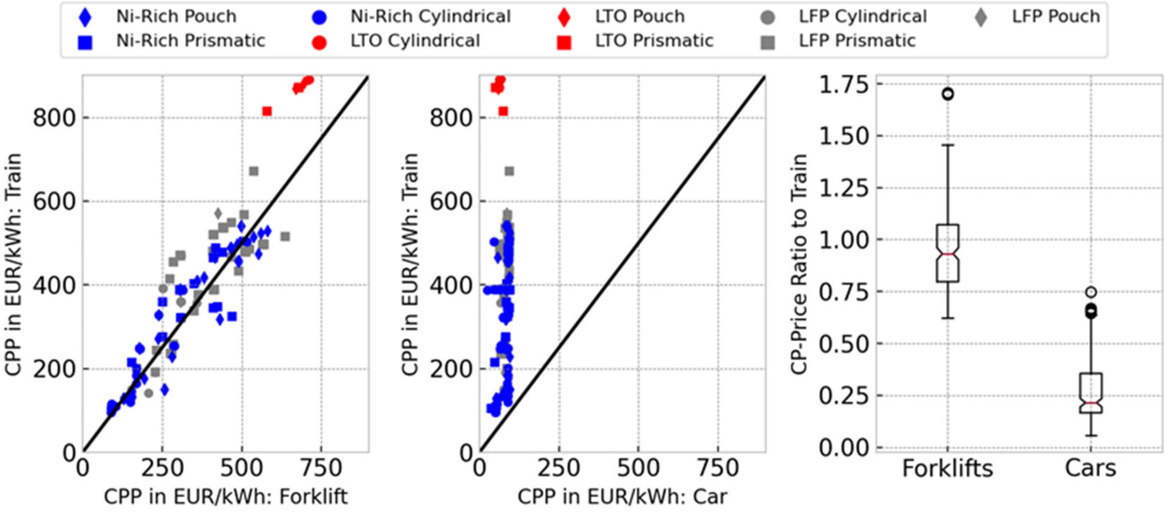

Figure 10. Left and middle: comparison of cell-specific cost-parity (CP) prices for forklifts and cars (x-axis) versus trains (y-axis). Cell formats are represented by different shapes: pouch (diamond), cylindrical (circle), and prismatic hard-case (square). Cell chemistries are color-coded: Ni-rich cells (i.e., NMC and NCA) are in blue, LTO cells are in red, and LFP cells are in gray. Right: cell-specific cost-parity price ratios for forklifts/cars versus trains.

A comparative analysis between forklifts and trains reveals similar required cost-parity prices (median: 93%). In contrast, when comparing cars to trains, cell-specific cost-parity prices must be substantially lower than for trains (median: 22%) to render them attractive for the automotive sector. However, we observe no particular differentiation according to cell chemistry or format.

5. Discussion

We extend the TCO to include the technical aspects of the application with the technical aspects of each individual LIB cell. Cell chemistry and formats are crucial due to their impact on performance, costs, and application suitability. As a result of the comparison, this not only provides a comparative value for an economic assessment, but also enables the economic selection of a technology—in this case, the battery cell—based on its technical suitability for an individual application and usage scenario in a techno-economic assessment approach. This supports cell integrators in their technology management, as well as providing insights for the further optimization of cell technologies for specific applications.

While our systematic approach involves the same three steps for each application, specific adaptations are necessary to tailor the procedure to certain particularities; see Section 3. First, load profiles for cars and forklifts are derived from existing standardized driving cycles, whereas a custom load profile imitating a specific route is devised for passenger trains. Second, train and car applications are compared against conventional vehicles with internal combustion engines as a reference, while a reference vehicle equipped with lead-acid batteries is employed for forklifts. Third, vehicle weight is the most influential factor on energy consumption for trains and cars, whereas this is the maximum lifting capacity for forklifts. Fourth, cost considerations vary, since CAPEX and OPEX items depend on the application.

Although we determine the cost-parity price specifically for each application, we note that there may be countless load profiles and utilization patterns behind each application instead of just one. We also refer to real-world uncertainties and usage patterns, leading to different energy requirements, as witnessed with the standard WLTP driving cycle [56]. Thus, future studies may include more differentiation within an application. However, our approach is effective for application-specific cell selection, aligning with common cost thresholds and industry trends, such as 100 EUR/kWh as the common threshold for BEV battery cells [1] or the extinction of LAB-powered forklifts. Our results indicate that the discussed BEV to ICEV parity from 2026 [15] or 2030 [19,20] onwards could already be met, especially with today's cell prices of below 100 EUR/kWh [21], which is significantly lower than the calculated prices for some suitable cells in the database.

Other limitations involve our battery cell database, assumptions for cost parity, and the variability of final retail prices. Firstly, our database relies on publicly available battery cell datasheets, encompassing only a fraction of all available cells. Some cells may already be outdated, while the latest cell generation is likely underrepresented due to unpublished data. Additionally, we highlight potential uncertainties when utilizing datasheet information. The values presented are mainly obtained from standardized test environments and conditions, which may not precisely depict real-world cell performance due to variable ambient conditions and specific charge–discharge load profiles inherent to applications and embedded use-cases. Secondly, our approach required us to scale cell-level costs to the system level and vice versa. However, no information was available on battery chemistry or format dependency, and we used the same scaling for all applications. The advanced system integration and engineering per application, potentially also cell-format- and chemistry-specific, is, however, a decisive aspect to enhance battery performance and lower costs [17,18]. Third, we emphasize that the calculated cost-parity price (i.e., the maximum allowed cell price) may substantially differ from cell retail prices that are affected by purchase quantities or supplier contracts.

6. Conclusions 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: passenger cars, passenger trains, and forklifts with highly specific characteristics. The developed methodology allows for a high-level yet tailored matching of publicly available technical cell data, application-specific requirements, and use-case conditions to determine the cost parity price for each specific cell for a certain application. We draw three main conclusions from our analysis.

First, only a certain number of the considered battery cells are suitable for all applications. On the one hand, this is mainly related to low energy densities, meaning that the available installation space could be exceeded. On the other hand, low specific energies may lead to weight-based limitations. However, suitable cells have been identified for all of the considered applications.

Second, the calculated cost-parity prices differ greatly for different applications. We emphasize that costs are the primary criterion in selecting battery cells, but technical aspects are gaining importance. While prices well below 100 EUR/kWh are required for passenger cars, prices for trains and forklifts can be substantially higher, reaching up to 950 EUR/kWh or 750 EUR/kWh, respectively. There are fewer format-specific dependencies, but there are major differences between the chemistries. Herein, we showcase LTO chemistries with high lifetimes (cyclic and calendar) but low energy densities versus NMC chemistries with higher energy densities but usually lower lifetimes.

Third, ecological considerations during the battery cell selection depend on the application-specific lifetime (i.e., the number of required batteries) and battery size. The former is affected by both calendar aging and the limited cycle life, whereby different formats and chemistries may reach similar levels in long-term applications (i.e., forklifts and trains). In comparison, LFP and NMC batteries dominate LTO for cars by achieving substantially lower CO_2 footprints. The CO_2 footprint is employed solely for the purpose of relative comparison between the cells. With a view to global CO_2 labeling, a CO_2 price could be incorporated into the cost parity price at a subsequent stage. This becomes particularly pertinent when alternative battery technologies with high sustainability promises are included in the analysis and assessment alongside different LIB cells.

We highlight that the proposed cell selection methodology is a valuable decision-support tool for manufacturers/cell integrators and cell suppliers to solve the trade-off between technical restrictions and economic considerations for specific applications. For cell suppliers, this approach facilitates comparisons of their cells with others, enabling them to identify potential new applications or assess the impact of performance enhancements. For manufacturers and cell integrators, this approach facilitates the comparison of available cells, enabling them to identify the most suitable cells for their applications. Finally, we emphasize that our analysis is based on a single underlying usage pattern per application so that future studies may include more distinctions within an application, which is likely to cause even greater variation.

Author Contributions: Conceptualization, T.H. and S.L.; Methodology, S.L. and T.H.; Software, S.L., L.W. and M.S.; Formal analysis, T.H., S.L., L.W. and M.S.; Data curation, T.H., S.L., L.W. and M.S.; Writing—original draft preparation, T.H. and S.L.; Writing—review and editing, L.W. and M.S.; Project administration, T.H.; Funding acquisition, T.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Federal Ministry of Education and Research Germany within the project "BetterBat" under grant number 03XP0362.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: Special thanks to Olaf Teichert for modeling the passenger cars.

Conflicts of Interest: The authors declare no conflicts of interest.

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