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From Cell to Pack: Empirical Analysis of the Correlations Between Cell Properties and Battery Pack Characteristics of Electric Vehicles

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Executive Summary

Lithium-ion batteries are pivotal components in battery electric vehicles, significantly influencing vehicle design and performance. This study investigates the interactions between cell properties and battery pack characteristics through statistical correlation analysis of datasets derived from industry-leading benchmarking platforms. Findings indicate that energy densities are comparable across cell formats at the pack level. While NMC and NCA chemistries outperform LFP in energy density at both cell and pack levels, LFP's favorable cell-to-pack factors mitigate these differences. Analysis of cell properties reveals that increases in cell-level volumetric and gravimetric energy density result in proportionally smaller gains at the pack level due to the growing proportion of required passive components. The study also investigates the emerging sodium-ion battery technology and assesses pack-level energy densities derived from cell-level properties. The insights of this study provide a fundamental understanding of cell-to-pack relationships, guiding R&D toward improved energy storage solutions for electric vehicles.

Keywords: Electric Vehicles, Trends & Forecasting of e-mobility, Batteries, Energy storage systems, Vehicle manufacturing

1 Introduction

Given the global energy transition, electrochemical energy storage systems are crucial in future mobility concepts [1]. One of the main drivers for this development is the significant contribution of the transportation sector to climate change. For instance, the transportation sector currently accounts for approximately 22 % of total greenhouse gas emissions in Germany [2]. Therefore, reducing environmental impacts in this sector is particularly relevant for achieving climate protection goals [3]. Battery electric vehicles (BEVs) hereby offer a promising mobility alternative. When powered by electricity from renewable sources, they cause lower environmental impact over their lifecycle compared to vehicles with modern internal combustion engines [4].

Battery cells are of significant importance, accounting for approximately 60-80 % of the total value creation in battery systems [5]. Cell parameters such as energy density and capacity significantly contribute to the performance and efficiency of the entire battery system and play a crucial role in developing battery pack concepts. However, many interdependencies between battery cell selection and resulting pack characteristics remain insufficiently quantified. Consequently, numerous concepts for battery pack design exist, with no specific approach prevailing [6, 7]. A deep understanding of the interactions between

battery cell properties and the resulting battery pack characteristics is essential for optimizing the efficiency and practicability of future energy storage systems and advancing the energy transition.

This work aims to empirically analyze the fundamental relationships between battery cell properties and pack characteristics using a comprehensive database to identify interdependencies. We strive to contribute to the foundation for optimization strategies for future battery pack designs through a detailed analysis of these interactions. Therefore a systematic literature review was conducted to establish the current state of the art regarding cell-to-pack relationships and to identify research gaps.

Research on the relationships between battery cells and packs is limited. Hettesheimer et al. [6] evaluated the development potential of different lithium iron phosphate (LFP) cell formats using multi-criteria analysis, considering volumetric energy density, cooling requirements, safety, and costs. Their findings indicate that cylindrical and pouch cells exhibit the highest volumetric energy densities at cell and module levels, a trend expected to continue through 2025. However, pack-level analysis was not included in their study. Schöberl et al. [8] provided essential insights into the relationships between cell chemistry and pack performance. While investigating thermal runaway in lithium-ion batteries (LIBs), they analyzed gravimetric and volumetric energy densities at cell and pack levels with the resulting pack factors. Their findings demonstrate that nickel cobalt manganese oxide (NMC) and nickel cobalt aluminum oxide (NCA) cells experience significantly higher energy density losses during pack integration than LFP cells. While systems with NMC and NCA cells maintain higher gravimetric energy densities than LFP systems, the volumetric energy density remains comparable across all systems, primarily due to reduced safety requirements for LFP cells in battery packs [8]. These findings highlight the complex interplay between cell chemistry, safety requirements, and overall pack performance. Löbberding et al. [9] examined the differences between gravimetric and volumetric energy density at the cell, module, and pack levels using boxplots and regression analyses to determine cell-to-pack factors. Their study reveals that despite cylindrical cells showing the highest energy density at the cell level, pack-level energy densities remain similar across all three variants. This is attributed to factors including cell volume and system boundary conditions. They suggest that cell chemistry, rather than format, primarily influences pack-level energy density variations, though detailed chemistry analysis was not part of their study scope [9].

While existing research provides data on individual cell and pack characteristics, including cell-to-pack factors for various vehicles and cell types, most analyses are based on limited datasets and focus only on specific aspects of cell-to-pack relationships. A systematic analysis across cell formats, chemistries, and their influence on pack-level characteristics remains unexplored. This work addresses this gap by analyzing cell-to-pack relationships through statistical methods based on a comprehensive empirical dataset of contemporary electric vehicles.

2 Methodology

The methodology is structured as shown in Figure 1. Initially, the structure of the empirical database that forms the analysis's foundation is described. Subsequently, the analysis of nominal and metric battery cell properties and their impact on pack characteristics is presented. Finally, an outlook on sodium-ion battery (SIB) technology's implications for battery pack characteristics is provided within the scope of the study. This study employs box-whisker plots and linear regression analysis to visualize data distributions and reveal correlations between battery cells and packs.

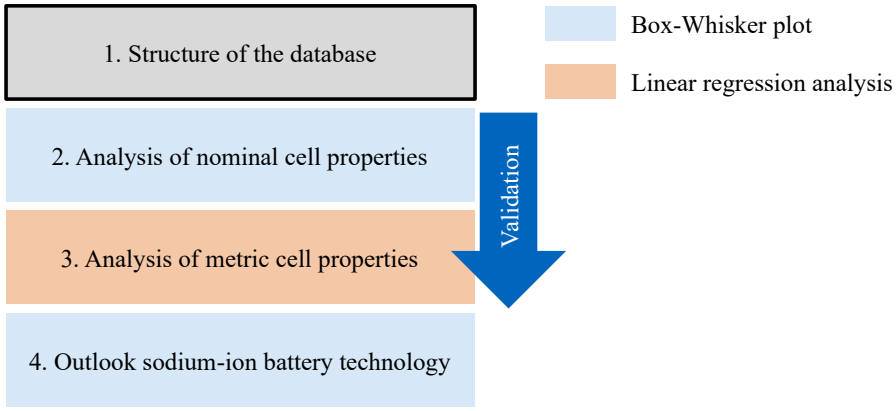

Figure 1: Structure of the methodology.

A comprehensive database of state of the art BEVs is required to perform the study. The database was designed to be sufficiently large to approximate a normal distribution of the investigated battery

properties. Data was collected from prominent electric vehicle benchmarking platforms, including the benchmark platform A2MAC1 [10], focusing exclusively on current electric vehicle models to ensure technical comparability of the analysis results and to avoid inconsistencies. The database comprises 145 vehicle models launched between 2020 and 2024, with 16 distinct variables extracted for analysis. Since obtaining all variables for every vehicle in the database was not possible, and analyzing relationships between variables requires the respective cell- and pack-level characteristics, only a subset of the complete dataset can be used for each specific analysis. Nevertheless, the database enables statistical analysis based on a substantial dataset and is therefore suitable for achieving the research objectives of this work.

To conduct the statistical analysis based on the compiled dataset, relevant cell properties are systematically compared and combined with pack characteristics. Figure 2 illustrates these properties and characteristics and categorizes them into nominal and metric variables. The nominal variables comprise cell format and cell chemistry. In contrast, the metric variables include the cell energy densities and properties such as the battery cell's mass, volume, and energy content.

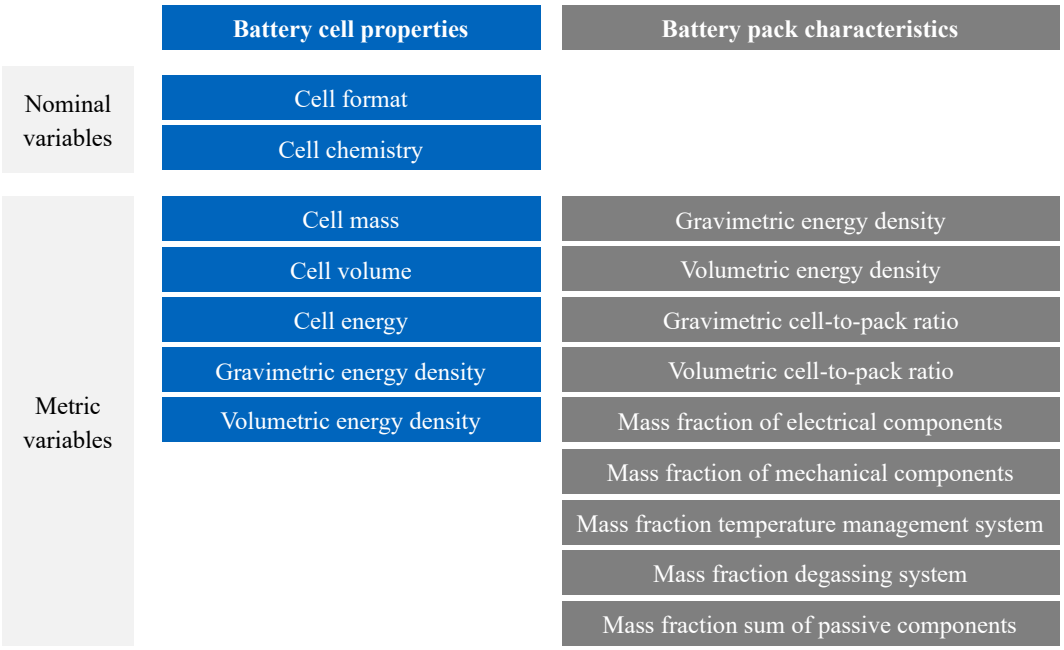

Figure 2: Classification of the analyzed battery cell properties and battery pack characteristics.

Figure 2 also shows the battery pack characteristics as metric variables. These include energy densities, cell-to-pack factors, and metrics addressing passive components. This is crucial as the passive components' mass fractions directly influence energy densities and pack factors, making them essential for interpreting differences in these metrics. While an analysis of passive components' volume fractions would be valuable for identifying volumetric effects, this was not feasible due to missing volume data in the current database. All analyses conducted within this study are derived from cell properties and pack characteristics combinations for nominal and metric variables. Since this work focuses on the influence of battery cell properties on pack characteristics, cell properties are consistently handled as independent variables. In contrast, pack properties are shown as dependent variables.

The effects of nominal cell properties on battery pack characteristics are analyzed using box-whisker plots. These plots provide statistical representations of the pack energy densities, pack factors, and mass fractions for different cell formats and chemistries. The resulting box-whisker plots reveal the comparative strengths and weaknesses of various cell formats and chemistries. The evaluation is conducted visually and through statistical measures in the box plots. The interpretation focuses on relative comparisons between cell formats and chemistries, explicitly examining the datasets' medians, quartiles, whiskers, and ranges. Outliers are excluded from interpretation due to their limited representativeness for the overall dataset.

The influence of metric cell properties on battery pack characteristics is investigated using linear regression analyses. This analysis focuses on identifying the direction and strength of relationships to determine correlations relevant to the study's research objectives. Key statistical measures include the Pearson correlation coefficient r and sample size n. According to Völkl and Korb [11], r quantifies the strength and direction of linear relationships between variables. The coefficient is normalized for sample size and units of measurement, resulting in values bounded between -1 and 1. Values near ± 1 indicate

strong correlations, while values approaching 0 suggest weak or no linear correlation. Correlations are classified as strong ($|r| \geq 0.7$), moderate ($0.5 \leq |r| < 0.7$), or weak ($|r| < 0.5$) [12]. A positive coefficient indicates variables increasing together, while a negative coefficient implies an inverse relationship.

The evaluation of correlations is based on both the correlation coefficient classification and statistical completeness. Visual assessment of diagrams and data points is essential, as r alone may be misleading for non-linear relationships. While correlations are evaluated against threshold values for r and n, the assessment is not bound to rigid criteria. Despite small sample sizes, this approach prevents the categorical exclusion of relationships with good correlation properties. Such flexibility in evaluation is significant, given the uneven distribution of cell properties in the database. Each result is individually assessed for significance, considering both n and r. Combining box plots and linear regression analyses yields 108 analysis plots, necessitating a structured evaluation approach.

The validation is based on data from [8,9,13]. This data includes gravimetric and volumetric energy densities at the pack level in relation to their respective cells, as well as corresponding cell-to-pack factors. This information is used to validate the value ranges and trends identified in both nominal and metric analyses. Care is taken to ensure that validation vehicles are not already included in the database to avoid circular references and subsequent false validation of results.

Estimation of SIB pack characteristics is based on the analysis results and literature values, starting with cell-level properties of SIBs derived from an extensive literature review. Both current and long-term expectations for gravimetric and volumetric energy density are derived alongside long-term expected values for the considered LIBs. Pack characteristics for SIBs are then calculated using appropriate pack factors. Building on this, a prediction of energy density ranges for current and long-term expected SIB packs is conducted, including a comparison to the considered LIB packs.

3 Results

The following section presents the statistical analysis results based on the empirical database. The results are organized into three sections. The first section examines the effects of nominal cell properties on battery pack characteristics. Subsequently, the metric relationships between battery cells and packs are analyzed. The final section derives insights for SIB packs from these findings. Given the extensive number of analyses, only the most relevant findings from each section are discussed and interpreted. All results not presented in this paper are available upon request.

3.1 Results of the Nominal Analysis

The analysis of nominal variables focuses explicitly on the gravimetric and volumetric battery pack energy densities and corresponding cell-to-pack factors, as these metrics provide the highest information content and are supported by the most extensive available dataset. Figure 3 illustrates the nominal analysis examining the cell format's influence on volumetric battery pack energy density and cell-to-pack factor.

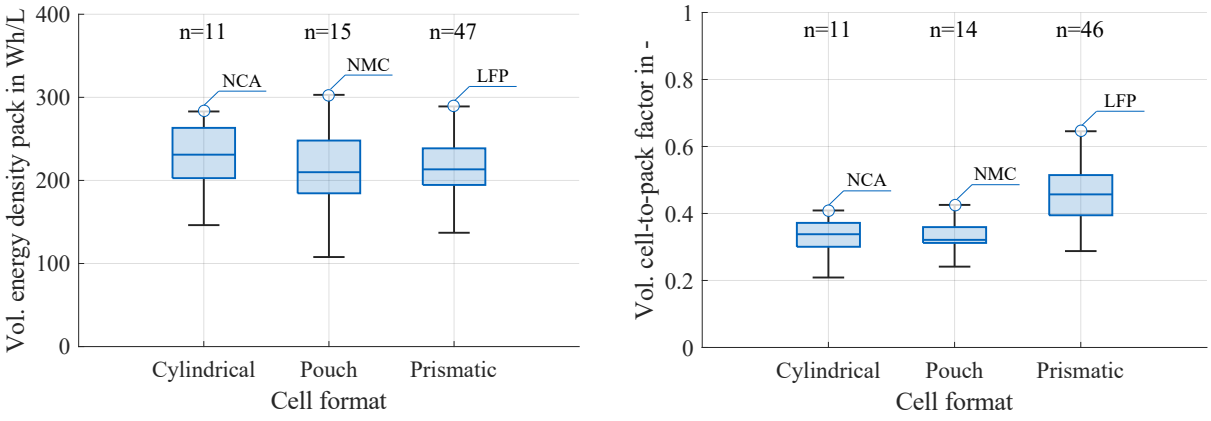

Figure 3: Nominal analysis of the cell formats according to volumetric energy density and cell-to-pack factor. The cell chemistry of the cells with the highest values is indicated.

Regarding volumetric energy density, battery packs with cylindrical cells range from 150-280 $\mathrm{Wh/L}$,

pouch cells from 110-305 Wh/L, and prismatic cells from 140-290 Wh/L. The corresponding median values are located near the center of these ranges. While pouch cells can achieve the highest volumetric energy densities at the pack level, they exhibit lower average values than cylindrical and prismatic cells.

A detailed examination of the analyzed vehicles within the database reveals that cylindrical and pouch cells consistently employ a module-to-pack (MtP) architecture. This architectural choice necessitates additional components, such as module housings and module contacts, leading to unutilized volume at the pack level. The modules' thermal management and volumetric efficiency vary significantly between cell formats. Due to geometric constraints, cylindrical cells inherently result in the highest dead volume within modules. Meanwhile, pouch cells achieve better volumetric utilization within modules than cylindrical cells. However, unlike hard-case cells with integrated structural stability, they often require increased module wall thickness as well as additional components within the modules to meet the additional mechanical requirements. In contrast, prismatic cells with a LFP chemistry in the database predominantly utilize cell-to-pack (CtP) designs, where cells are directly integrated into the battery pack rather than MtP architectures. This approach vastly reduces the overall number and size of passive components while maximizing packing efficiency. Consequently, prismatic cells show the best performance regarding the volumetric pack factor, while pouch and cylindrical cells yield lower packaging efficiencies. Prismatic cells' superior volumetric cell-to-pack factor can also be traced to their ability to be better stacked within the given battery pack space. This relationship does not result in better volumetric energy density at the pack level because prismatic cells generally have lower volumetric energy densities at the cell level due to the significant structural void spaces inherent to this cell type.

Figure 4 illustrates the nominal analysis examining the influence of cell chemistry on gravimetric energy density and cell-to-pack factor. For the gravimetric energy density, battery packs with LFP cells range from 125-145 Wh/kg, NCA cells from 150-174 Wh/kg, and NMC cells from 140-180 Wh/kg. While the median values for LFP and NMC cells are located near the center of their ranges, the median for NCA cells lies directly below the upper whisker and, thus, above the medians of LFP and NMC cells. Consequently, NCA cells achieve the highest gravimetric energy density at the pack level, followed by NMC and LFP cells. Compared to the volumetric energy densities in Figure 3, the variations between cell chemistries are less pronounced, with only NMC cells exhibiting larger spreads.

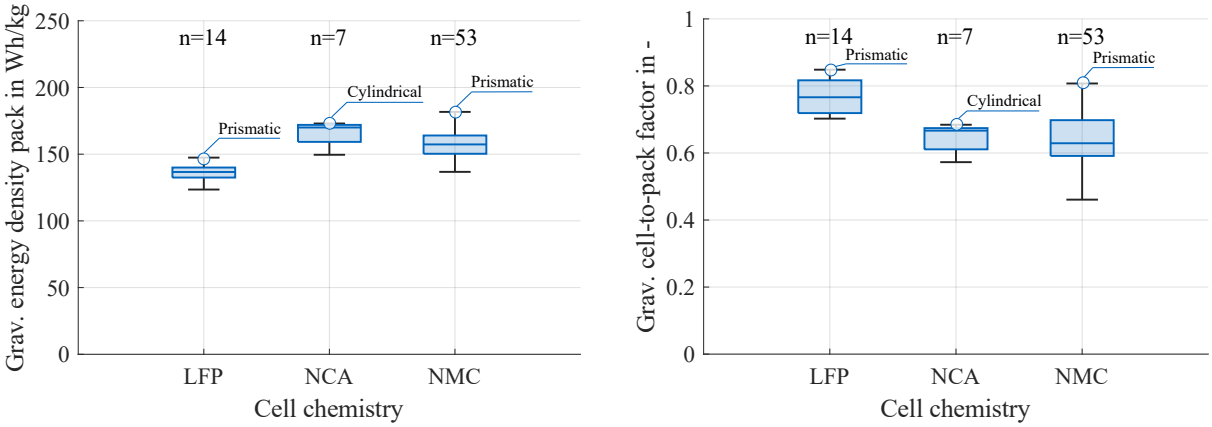

Figure 4: Nominal analysis of the cell chemistries according to gravimetric energy density and cell-to-pack factor. The cell format of the cells with the highest values is indicated.

Among the chemistries examined, NMC shows the highest variation in the gravimetric cell-to-pack factor, while LFP cells demonstrate significantly higher cell-to-pack factors compared to both NCA and NMC. Unlike NMC and NCA cells predominantly used in MtP concepts, many vehicles with LFP cells utilize CtP concepts, significantly reducing the mass proportion of passive components and increasing the gravimetric cell-to-pack factor. LFP vehicles are almost exclusively purpose-built BEVs, enabling optimal storage architectures dominated by flat storage designs. In contrast, NMC and NCA cell vehicles include purpose-built and conversion BEVs, often resulting in complex storage geometries that necessitate additional passive components, leading to increased weight and reduced cell-to-pack factors.

At the pack level, NMC and NCA cells achieve higher gravimetric energy densities due to their superior energy density at the cell level. However, these differences are substantially reduced compared to cell-level ratios, as LFP cells show distinct advantages in pack integration. They achieve notably better pack factors since the mass proportions of electrical and mechanical components in the battery pack are significantly lower than in packs with NMC or NCA cells. The spreads in the gravimetric cell-to-pack factor are more pronounced, which can be attributed to the various cell integration approaches in the pack.

Additionally, the pack integration efficiency is significantly better in the gravimetric case compared to the volumetric case shown in Figure 3.

3.2 Results of the Metric Analysis

Figure 5 depicts the impact of changes in cell-level volumetric energy density on pack-level volumetric energy density and cell-to-pack factor according to the cell formats. Analysis reveals that increasing cell-level energy density leads to higher volumetric energy density at the pack level across all cell formats, with battery packs using cylindrical cells showing the most pronounced response to cell-level energy density changes.

Pouch cells demonstrate the most substantial interdependencies with a moderate correlation factor of 0.67, while cylindrical and prismatic cells show only weak correlations. The volumetric cell-to-pack factor decreases for prismatic cells with a moderate correlation coefficient of -0.56. In contrast, no clear correlation can be established for cylindrical and pouch cells due to significant data scatter and weak correlations. Prismatic cells exhibit the lowest volumetric energy densities at the cell level, while pouch cells achieve the highest volumetric energy density at both cell and pack levels. Notably, prismatic cells demonstrate superior volumetric cell-to-pack factors compared to pouch and cylindrical cells, primarily due to their rectangular hard-case housing that minimizes unused space. When analyzing vehicles by energy density, prismatic cells with lower energy density are predominantly used in CtP concepts, while higher energy density cells tend toward MtP architectures. In contrast, cylindrical and pouch cells are particularly used in modular designs and typically employ higher energy density cathode materials like NMC and NCA. The observed decline in pack factors for prismatic cells can be attributed to increased proportions of passive components, particularly the additional mechanical structures required to ensure safety in the usage of high energy density cells.

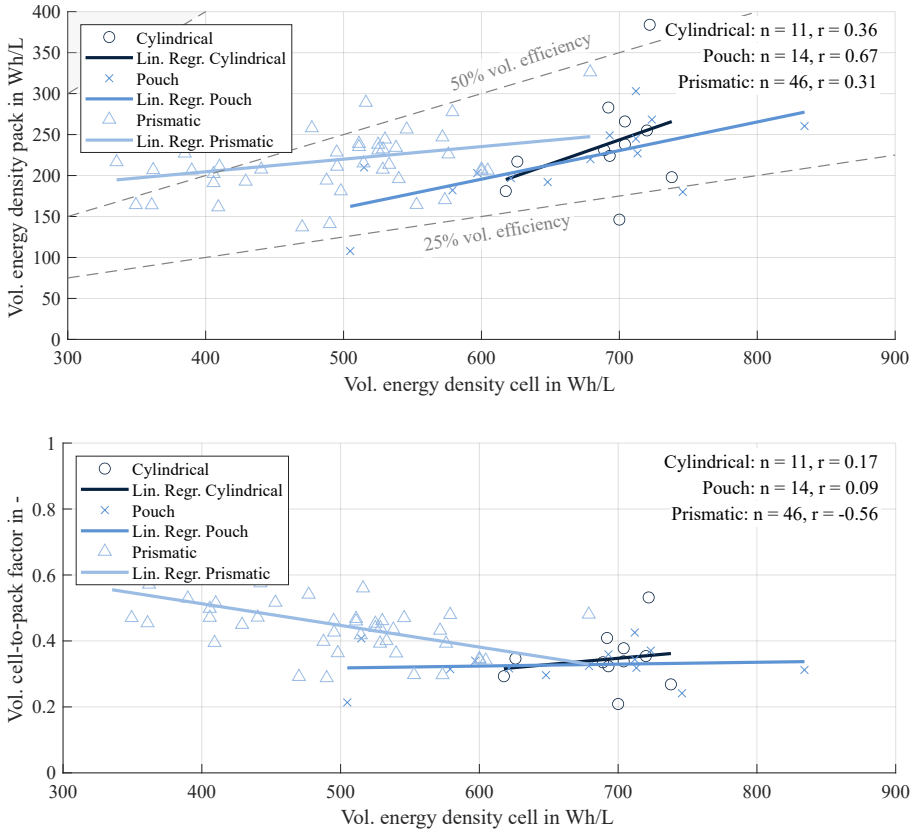

Figure 5: Metric analysis of the impact of cell volumetric energy density on pack volumetric energy density and cell-to-pack factor considering cell formats.

Figure 6 illustrates the impact of changes in cell-level gravimetric energy density on pack-level gravimetric energy density and the gravimetric cell-to-pack factor for the investigated cell chemistries. Notable differences in cell-level energy densities are evident among the three cell chemistries compared. NMC cells show the broadest spectrum of cell energy density, including the highest cell and pack gravimetric

energy densities. In contrast, LFP cells exhibit the lowest energy density values on the cell and pack levels. NCA cells rank in the upper mid-range for gravimetric energy density at the cell level and in the upper range at the pack level.

Due to the scattering of values, the correlation coefficients for all cell chemistries are below 0.5, indicating weak correlations. The correlations are more pronounced for cell-to-pack factors, with LFP and NMC showing correlation coefficients just above -0.50, while NCA exhibits a moderate correlation coefficient of -0.66. Linear regression analysis reveals that an increase in cell-level gravimetric energy density leads to higher pack-level energy density, with one notable exception considering NCA cells, which negatively correlate with pack-level gravimetric energy density. This anomaly may be attributed to the limited statistical significance due to the small sample size of NCA cells. Despite the general increase in pack-level energy density, cell-to-pack factors decrease with increasing energy density across all cell chemistries. LFP demonstrates the best cell-to-pack factors among all cell chemistries, primarily due to the prevalent use of CtP approaches, as discussed in the previous section. In contrast, NCA and NMC show similar, lower cell-to-pack factors, which can be attributed to their predominant use in MtP architectures with higher energy-density cells. The decline in cell-to-pack factors for all cell chemistries can be attributed to the growing proportion of passive components required as cell-level energy density increases.

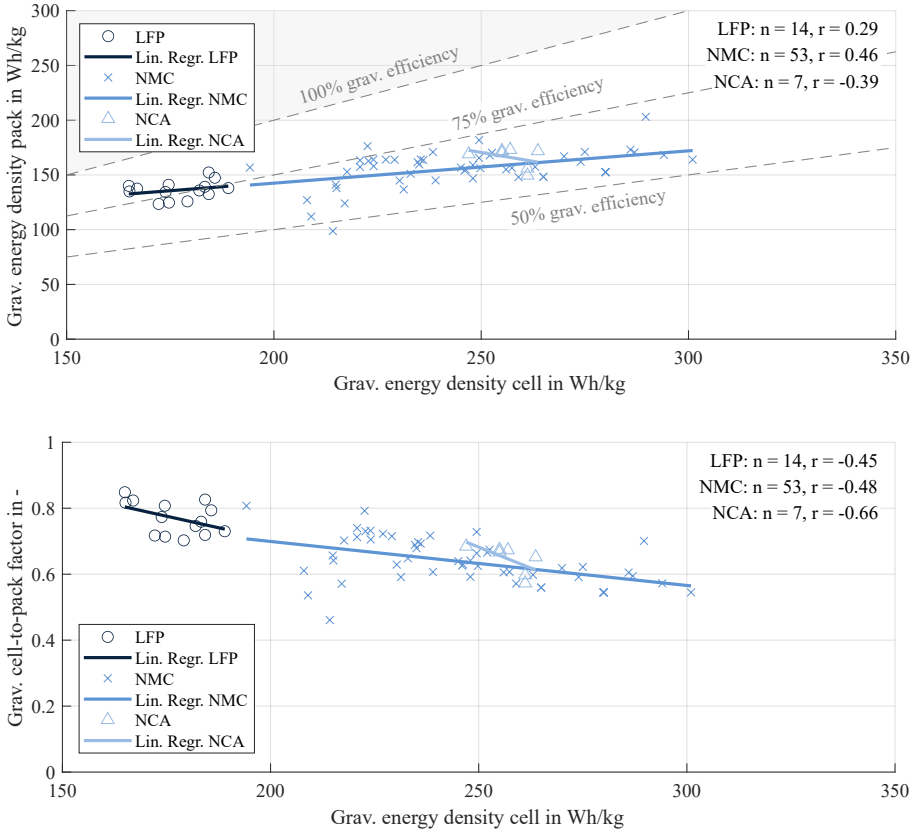

Figure 6: Metric analysis of the impact of cell gravimetric energy density on pack gravimetric energy density and cell-to-pack factor considering cell chemistries.

3.3 Outlook Sodium-Ion Battery Technology

Based on the interdependencies between the battery cells and packs of LIBs presented thus far, the following section aims to provide an outlook on current and future developments of the gravimetric and volumetric energy density of LIBs and SIBs at the battery pack level. This requires determining a cell-to-pack factor for SIBs, which can be used to estimate pack-level characteristics from cell-level properties. Table 1 presents the current gravimetric and volumetric energy densities of LFP, NMC, and NCA cells and their corresponding cell-to-pack factors. Additionally, gravimetric and volumetric energy densities for SIBs were derived from a comprehensive literature review. Long-term projections for cell-level energy densities are also presented to assess future implications for all cell chemistries.

Table 1: Current and long-term expected cell energy densities and cell-to-pack factors for LIBs and SIB.

	Unit		LFP	NMC	NCA	SIB
Grav. cell energy density	Wh/kg	Current:	165–190	195–300	250–265	140–160 [14, 16–21]
		Expected:	200–250 [14]	300–400 [14]	300–400 [14]	180–220 [14, 17–19, 21–24]
Vol. cell energy density	Wh/L	Current:	340–450	440–750	600–720	290–350 [14, 18, 25]
		Expected:	500–550 [14]	750–1000 [14]	750–1000 [15]	380–500 [14, 18, 24]
Grav. cell-to-pack factor	-		0.77	0.63	0.67	0.77*
Vol. cell-to-pack factor	-		0.52	0.40	0.34	0.52*

* theoretically estimated based on Mei et al. [26], Kim [27] and Rudola et al. [28]

The comparison of LIBs and SIBs regarding pack properties can be based on either cell formats or cell chemistries. Since SIBs utilize the same cell formats as LIBs and primarily differ in chemical composition, the comparison in this study focuses solely on cell chemistries. The gravimetric and volumetric cell-to-pack factors for SIBs can only be estimated theoretically based on the literature. These estimations are based on Mei et al. [26], Kim [27] and Rudola et al. [28], demonstrating that SIBs exhibit thermal stability characteristics similar to LFP cells, suggesting that SIBs can employ a battery pack design with a cell-to-pack ratio comparable to an LFP system — consequently, the same cell-to-pack factors as LFP were applied for SIBs.

Figure 7 compares current pack-level energy densities between LIBs and SIBs, along with future projections. The results indicate that energy densities of battery packs with SIBs are situated at the lower boundary of LIB pack energy densities, given the assumption of similar pack factors. Considering expected cell-level developments, the analysis reveals that SIB packs can achieve energy density levels comparable to current lower and mid-range LIB packs, reaching up to 150 Wh/kg and 200 Wh/L.

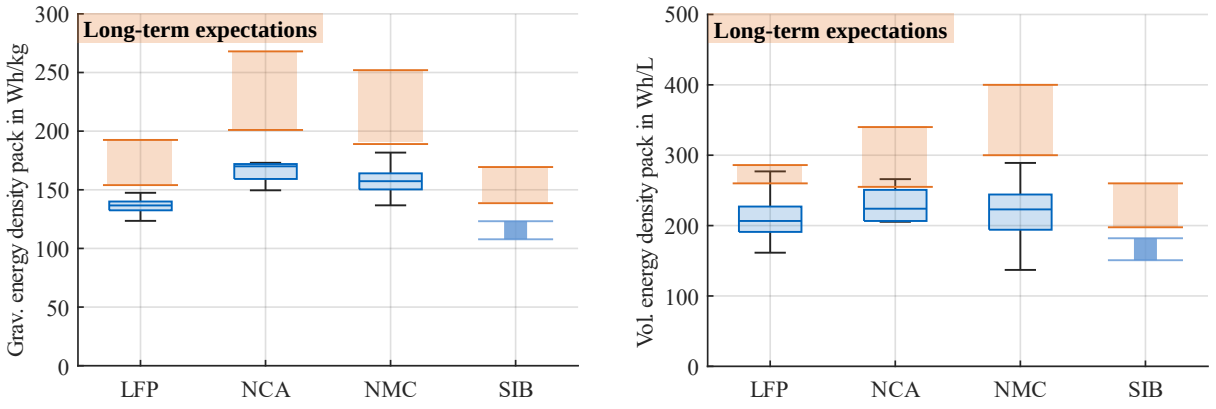

Figure 7: Comparison of the current energy densities at pack level of LIBs and SIBs and long-term expectations.

4 Conclusions and Outlook

This study investigates the interactions between cell properties and battery pack characteristics through statistical analysis of empirical datasets derived from industry-leading benchmarking platforms. This comprehensive analysis contributes to the ongoing discourse on battery design optimization and offers a robust methodology for evaluating cell-to-pack relationships. By addressing critical trade-offs in energy density, pack factors, and passive component integration, the study provides a valuable resource for researchers in energy storage systems.

- Analysis of nominal cell characteristics reveals that volumetric energy densities at the pack level exhibit comparable values across all cell formats. The results demonstrate that this comparable behavior of cell formats is attributed to pack factors being higher for prismatic cells than cylindrical and pouch cells. Regarding cell chemistries, NMC and NCA cells show higher gravimetric energy densities than LFP cells at both cell and pack levels. However, these differences at the pack level are reduced due to the advantageous pack factors of LFP cells.
- Analysis of metric cell characteristics demonstrates that increases in volumetric and gravimetric cell-level energy density lead to proportionally smaller increases in corresponding pack-level energy density. This effect is particularly pronounced in prismatic cells, where the volumetric cell-to-pack factor significantly decreases with increasing volumetric cell energy density. A similar trend is observed in the progression of the gravimetric cell-to-pack factor for NMC and LFP cells. These correlations can be attributed to the growing proportion of passive components required as cell-level energy density increases. Furthermore, cells with lower energy density are predominantly implemented in CtP architectures, with the database showing this approach is primarily represented by vehicles using prismatic LFP cells. This architectural choice results in superior cell-to-pack factors for this specific cell format and chemistry combination in gravimetric and volumetric terms.
- The outlook for SIBs shows that, due to the lack of pack factors for SIBs, these can only be estimated based on pack factors of LFP cells. This approach is justified by the similar thermal characteristics exhibited by sodium-ion and LFP cells. Results indicate that SIBs position themselves at the lower boundary of LIB energy densities at both cell and pack levels. As both technologies are expected to advance, similar relative performance levels are projected for the long term.

Expanding the database with additional data points is recommended for future research to increase data coverage, alongside enhanced analytical methods for identifying non-linear relationships. Developing a specialized neural network is proposed as one approach for analyzing these non-linear correlations. Additionally, as commercial SIBs become available on the market, the analysis should be extended to include SIB data to verify or adjust their positioning within the current findings. All results of this paper are available upon request.

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Presenter Biography

Jan Koloch received a bachelor's in engineering science and a master's in automotive engineering from the Technical University of Munich (TUM). He is currently pursuing a Ph.D. degree with the Institute of Automotive Technology at TUM. His research focuses on innovative battery technologies and their influence on the system design of battery-electric vehicles.