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The impact of cell standardization on niche markets for battery applications: an analysis of various cylindrical cell formats

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Achieving cost and emission reductions in lithium-ion battery production requires gigafactory-scale battery manufacturing that leverages economies of scale and reduces energy consumption. While demand outside the EV sector remains comparatively small, battery-powered devices are used by billions of people across various applications. This study investigates whether standardized cylindrical cell formats can aggregate demand across fragmented battery niche markets and thereby transfer economic and sustainability benefits from giga-scale production to these applications. In addition, hypothetical improvements in market accessibility through novel cylindrical cell formats are evaluated. Cylindrical cells are particularly suitable for this approach due to their broad applicability and established format standardization. The scenario analysis demonstrates that aggregating niche market demand can support economies of scale and reduce energy consumption during production, while novel cylindrical formats further increase market coverage. Thus, this work provides a novel assessment of how large-scale production benefits can be extended to fragmented yet important battery niche markets, thereby enabling more sustainable production.

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Sustainability spotlight

Batteries have been a key enabler of energy transition and are expected to remain central to future sustainable electrification. However, battery cell manufacturing is energy-intensive, and the highly heterogeneous requirements of niche applications often prevent battery cell production at sufficient scale to realize economies of scale and reduce the energy demand per kilowatt-hour relative to xEV-oriented manufacturing. This work proposes aggregating demand across multiple niches to facilitate large-scale production and improve manufacturing energy efficiency, thereby supporting UN SDG 12. In addition, the substitution of lead-acid batteries with lithium ion technology eliminates hazardous materials while improving performance and service life. Finally, a theoretical framework identifies cylindrical cell formats with cross application applicability, enabling demand consolidation across various niche markets.

1. Introduction

The prevailing trend in studies and market forecasts is to focus on specific segments of the battery market landscape. Recent analyses primarily concentrate on the BEV market, with occasional consideration of the energy storage system (ESS) market.[1,2]

In a few studies, some battery niche markets are referred to as *computer, communications and consumer* market (3C-market), encompassing small consumer products such as wearables, smartphones, and laptops.[3,4] According to a report by McKinsey & Company, the battery market can be categorized into three main segments: batteries for mobility purposes, storage applications, and consumer electronics. However, it is evident that the majority of battery demand stems from BEVs and ESS systems.[5]

Despite their widespread use and large quantities,[6] battery market niches are rarely analyzed in depth.[7] There are several reasons for that: one key factor is the high heterogeneity across these niches, with devices having various battery requirements, particularly in terms of dimensions, system voltage (SV), and system capacity (SC). There is significant variation across use cases, ranging from tiny smart devices with energy capacities below 50 watt-hours to commercial applications with over 100 kilowatt-hours. Additionally, the market size of individual niches is relatively small compared to the BEV market.[8]

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From a commercial perspective, one of the most significant challenges currently faced by the battery industry is cost-effective and sustainable production of battery cells.[9–11] This mainly depends on a range of location-specific factors such as energy and labor costs.[11–14] Additionally, the cost-effectiveness also relies on product-specific considerations, such as cell format and especially intended production volume.[10,12,13,15,16]

Moreover, sustainability is a key consideration in battery cell production, given that batteries are a central technology for the clean energy transition. However, battery cell manufacturing is energy-intensive and may affect overall sustainability performance.[9,17] This energy demand can be reduced through production on a larger scale, as higher production volumes typically decrease energy consumption per kilowatt-hour.[10,11,17–19]

Notably, production costs and energy consumption per kilowatt-hour are reduced by increasing the quantity of manufactured units. This effect is commonly referred to as economies of scale. Both pose a significant challenge for these niches due to their small market volumes. As an example, increasing the production volume of a common 21700-NMC//G cell from 0.5 GWh per year to 2.0 GWh per year reduces energy demand by approximately 7.9% per kilowatt-hour of battery storage.[10,13]

In contrast, xEV batteries can achieve economies of scale and lower environmental impacts per kilowatt-hour by using common platforms and cells across multiple vehicle models, with annual demand often exceeding several gigawatt-hours. By comparison, many niche markets remain below 1 GWh, limiting scale advantages and thereby increasing both production costs and environmental impacts per kilowatt-hour.[10,13–15,20,21]

To address this issue, several strategies can be implemented. One approach is to establish agile cell production lines, allowing for simplified changes to cell parameters and shapes with shorter downtimes and lower costs.[20] Another concept involves using similar cells across various niches, thereby aggregating their individual market volumes. This strategy is already applied for some applications, such as *power tools*, *electric bikes*, and *electric scooters*.[22–24] These applications are often powered by standardized cylindrical cells such as 18650 or 21700 cells.[6,15]

A key question is whether this concept is adaptable to other market niches and whether greater market penetration is achievable by introducing further standardized cell formats. This study examines the battery market landscape and its requirements through an in-depth analysis of niche market applications. Cylindrical cells are selected due to their widespread use, as well as their cost-effectiveness in production.[6,25]

In the beginning, several battery markets were analyzed to identify relevant niches and their sizes. Subsequently, a model was developed to calculate several system architectures based on parameters such as SV and SC. Additionally, relevant cell types and sizes were identified. An analysis was conducted on the potential market penetration of existing cylindrical cell formats, as well as the optimization of battery production through the introduction of novel cylindrical cell formats, aiming to reduce environmental burdens and manufacturing costs while achieving economies of scale.[9,13]

2. Method

2.1. Market analysis

Initially, a comprehensive review of various market niches was undertaken. As a first step, those markets that cannot be served by cylindrical cells were excluded from the scope. Due to their limited form factors, devices such as smartphones and tablets, despite their ubiquity and relevance, were not considered. Additionally, medical and military systems were excluded due to limited access to representative devices and technical parameters. After this initial screening, eleven suitable battery market niches were identified, spanning from small to large devices and from consumer to commercial applications. For each of these niches, representative devices were analyzed, and parameters such as SC, SV, and cell chemistry were collected (Fig. 1).

If cell chemistry was not specified, it was estimated based on the nominal SV and compared to typical values for different battery types (*e.g.*, NMC811//G | NCA//SiG: 3.6–3.7 V, LFP//G: 3.2 V). Since further distinction between NMC811//G and NCA//SiG based on nominal cell voltage is not reliable, these chemistries will be referred to as NCX-based chemistry in the following analysis. The error associated with this method is expected to remain below approximately 12.5–15.3% ($\Delta\text{Voltage}/\text{Voltage}_{\text{LFP}}$). For smaller devices, such as *power tools*, *electric bicycles*, and *electric scooters*, an even lower error is anticipated, as system architectures are typically disclosed in patents and drawings.[22,23]

Furthermore, *k*-means and hierarchical clustering were applied to identify similarities and cluster niche markets into larger segments. The allocation of cell chemistry was summarized at the niche level, considering devices containing both chemistries (NCX-based & LFP//G). Finally, a dataset of approximately 300 devices across eleven market niches was compiled for further analysis.[26]

The primary objective of this analysis is to investigate how existing cell formats meet the system requirements of current niche markets in terms of voltage, capacity, and chemistry.

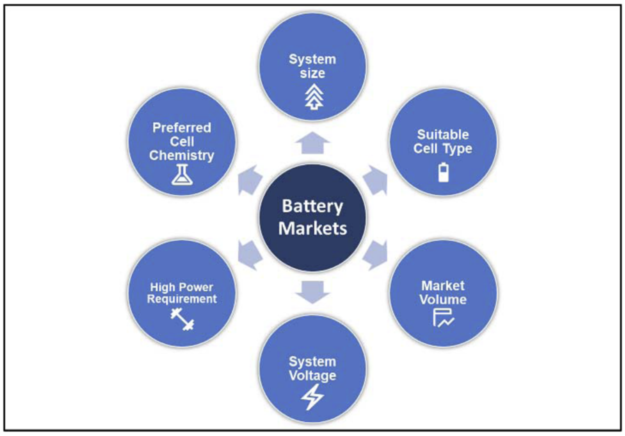

Fig. 1 Key performance indicators to be considered for each market segment.

Additionally, the analysis assesses the potential benefits of introducing new cell formats to expand market access. At this point, it is important to acknowledge that additional individual niche-related requirements, such as specific safety constraints or unique charge and discharge behavior, are not within the scope of this approach. The following analysis adopts a production perspective and examines which cylindrical cell formats and capacities best enable access to multiple niches, ultimately improving economies of scale and reducing the environmental impact of battery cell manufacturing.

2.2. System design and configuration

Before presenting the methodology, some key terms need to be defined. In this analysis, a "*system*" refers to a unique device, a device consisting of multiple battery cells, assigned to a relevant market niche. A "*system configuration*" represents a theoretical setup corresponding to a given *system*. These configurations are calculated using a *Python*-based algorithm. The number of *system configurations* associated with each *system* depends on the assigned *system size class*.

The actual *system configuration*, *i.e.*, the number of cells connected in series or parallel arrangements, is typically not disclosed. In this analysis, the number of cells in series is determined by dividing the system voltage by the nominal cell voltage. The individual cell capacity is determined by dividing the *system* corresponding SC by its number of parallel circuits.

To address the fact that the number of parallel circuits is usually undisclosed, a *system size class* was assigned to each market niche. The permitted parallel circuit value was determined based on representative market examples, where available, as well as additional qualitative criteria such as application size and geometry.[22,23,27] For larger applications in which cylindrical cells are technically suitable but currently underrepresented, this value may deviate from existing market practices. For example, *forklifts* or *home storage systems* commonly utilize larger prismatic cells, resulting in a relatively low number of parallel connections. However, due to the smaller capacity of cylindrical cells, a higher degree of parallelization is required. From this perspective, configurations of up to 10p represent a reasonable compromise between electrical complexity, and the inherently lower capacity of cylindrical cells.[24,28]

Subsequently, various *system configurations* were calculated based on this assignment. *The system size class* determines the maximum number of parallel circuits. The allocation of *system size classes* was based on the size and shape of systems within each market niche. For instance, *power tools* are assigned to *system size class* "XS", with a maximum of two parallel circuits (≤2) for further analysis (Fig. 2).

After assigning a *system size class*, different *system configurations* were developed using the method outlined below:

In this context, the number of cells in series determines the SV based on the nominal cell voltage. A *power tool* with an SV of 18.0 V and a SC of 6.0 Ah_{SC}, containing NCX-based chemistry, is used as an example. The corresponding *system size class* defines a maximum of two parallel circuits. The resulting *system configurations* are 5S1P, with each cell providing 6.0 Ah_{CC}, and 5S2P, based on 10 cylindrical cells with 3.0 Ah_{CC} each (Fig. 3).

System Size class	Icon	Parallel circuits
XS	🔋	≤2
S	🔋	≤4
M	🔋	≤6
L	🔋	≤8
XL	🔋	≤10

Fig. 2 *System size class*, corresponding icon and considered parallel circuit value.

Possible *system configurations* were calculated, and results were compiled across all *systems* related to a particular market niche. Configurations resulting in a CC below 2.0 Ah_{CC} were excluded due to the limited commercial availability of cylindrical cells with such capacities. Additionally, a threshold of 50.0 Ah_{CC} was defined as an upper limit for CC. This threshold is based on the calculated CC using a 50100-NCA//SiG cell. Only commercial prismatic or pouch cells offer larger CC.[29] The resolution of the calculation was set to Δ0.1 Ah_{CC}. Values in between were rounded to nearest CC.

In a subsequent step, the absolute prevalence of CCs was transformed into relative distribution. Initially, the number of *system configurations* was used as standardization parameter, accounting for variation in the dataset of *systems* within each individual market niche (Fig. 3). Furthermore, this relative distribution was multiplied by the global market volume for the year 2025 to assess the impact of different market sizes. This enables an evaluation of the market volume distribution across a wide range of CCs and niche applications.

2.3. Cylindrical cell design calculator

Additionally, a cylindrical cell calculator was developed to determine cell dimensions and corresponding CCs. The calculator considers three cell chemistries: low-energy LFP//G, mid-energy NMC811//G, and high-energy NCA//SiG. For each chemistry, two volumetric energy densities were determined to obtain a capacity range for each cell chemistry. The volumetric energy density values were selected based on commercial cell examples reported in the literature.[29–32] The calculator determines common standardized formats 18650 and 21700, as well as the newer BEV-related 4680 cell type.[33] Furthermore, a more advanced calculation was performed. Therefore, cells with a fixed height of 100 mm and a variable diameter ranging from 16 to 50 mm (Δ2 mm) were calculated for the different chemistries. The calculation method considers dead volume, as well as variations in cell wall thickness and hollow-core diameter

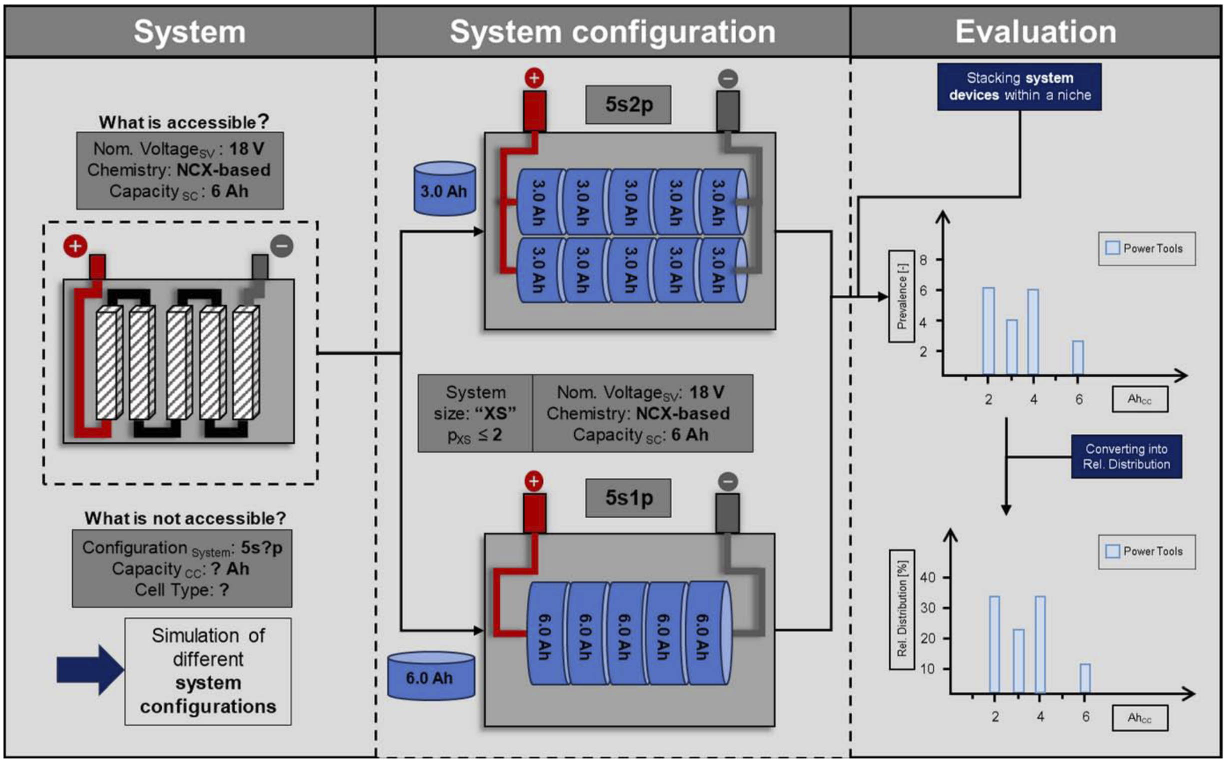

Fig. 3 Method of developing different *system configurations*. Left side: *System* and its accessible parameters. Middle: Developing of different *system configurations*. Right side: Evaluation of results from configuration development.

depending on cell dimensions, as described by Pegel *et al.*[34] The results of these cell calculations serve as input for the subsequent scenario analysis.

2.4. Scenario analysis

A scenario analysis with four distinct scenarios was developed to examine accessibility of market niches using different cylindrical cell formats. *Scenario A* serves as the baseline, evaluating the market accessibility of the state-of-the-art 21700 cylindrical cell format containing NMC811//G or NCA//SiG-chemistry. *Scenario A1* builds upon *Scenario A* by adding the 18650 cell format with the same chemistry. In *Scenario A2*, the novel 4680 cell format is introduced, with NMC811//G, NCA//SiG, and LFP//G as cell chemistry, providing a broader range of possibilities. The market volume that is accessible with this cell format is referred to as the *Accessible Market Volume* (AMV). The AMV of an individual cell type is determined by summing the market volumes across the capacity range, obtained from the cell configurator. If cell capacity overlaps occur between two different cells, the corresponding specific volume is labeled as *Intersectional Volume*. Additionally, market volumes were only considered for AMV when cell chemistry matched the chemistry required by the niche application. For example, if the assigned niche chemistry is LFP-based, an NCX-based battery cell cannot not access corresponding to the market volume. For comparison, the market volume was distributed across the cell capacity range, independent of the required chemistry and subsequently analyzed using clustering. This approach resulted in two key outputs: first, the total market volume across the capacity range by cluster, and second, the AMV, representing the market volume accessible based on cell capacity and compatible chemistry.

Compared with *Scenarios A*, *A1*, and *A2*, *Scenario B1* takes a different approach. The underlying question driving this scenario is: "Does the introduction of a new cell format increase the AMV of battery niche markets, and to what extent?" To address this question, a scenario was developed in which the cell height was fixed at 100 mm, while the cell diameter

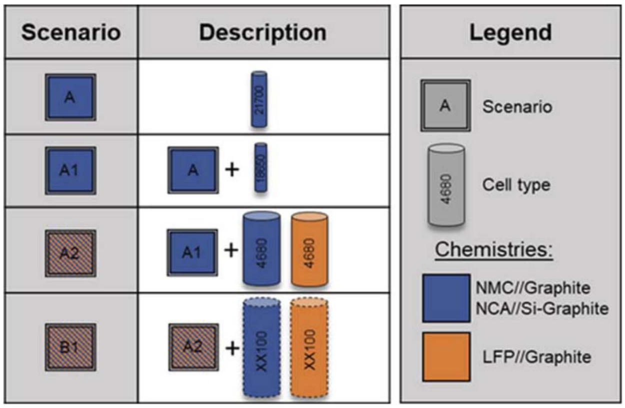

Fig. 4 Scenario A: One cell type, NCX-based chemistry | Scenario A1: Additional cell type, NCX-based chemistry | Scenario A2: Additional cell type, NCX-based and LFP-chemistry | Scenario B1: Fixed cell height, flexible diameter, optimization, NCX-based and LFP-chemistry.

remained variable and was optimized to maximize the increase in AMV, considering three different cell chemistries (LFP//G, NMC811//G, and NCA//SiG). The cell diameter was optimized across a range from 16 mm to 50 mm, with incremental steps of Δ2 mm (Fig. 4).

3. Analysis

3.1. Overview of various market niches

As mentioned earlier, a total of eleven relevant market niches were identified through a comprehensive analysis of various battery market segments. These niches were selected based on their suitability for cylindrical cells and the availability of representative *systems*.

It is evident that no single market segment exists where all cell types are commonly used. However, *industrial/maritime* and *home storage systems* exhibit a high degree of adaptability and fewer constraints regarding dimensions and form factors. Consequently, these *systems* may accommodate a wide range of cell types. Nevertheless, prismatic hard-case cells and, in some cases, cylindrical cells are the most prevalent cell formats in these applications. The primary reason for the limited adoption of prismatic hard-case cells in further market niches is dimensional and integration constraints. Specifically, prismatic hard-case cells are not feasible in smaller applications due to limited space and form-factor constraints, such as *electric bikes*, *power tools*, and *power banks*. In addition, prismatic hard-case cells are not suitable for niche applications requiring light-weight, compact designs or specific system geometries.[30]

Therefore, pouch cells are highly relevant in applications where space and weight are critical. However, they are less suitable for larger *systems* that may experience higher mechanical stress, such as *forklifts*, *boats/camping*, and *electric wheelchairs* applications.[25]

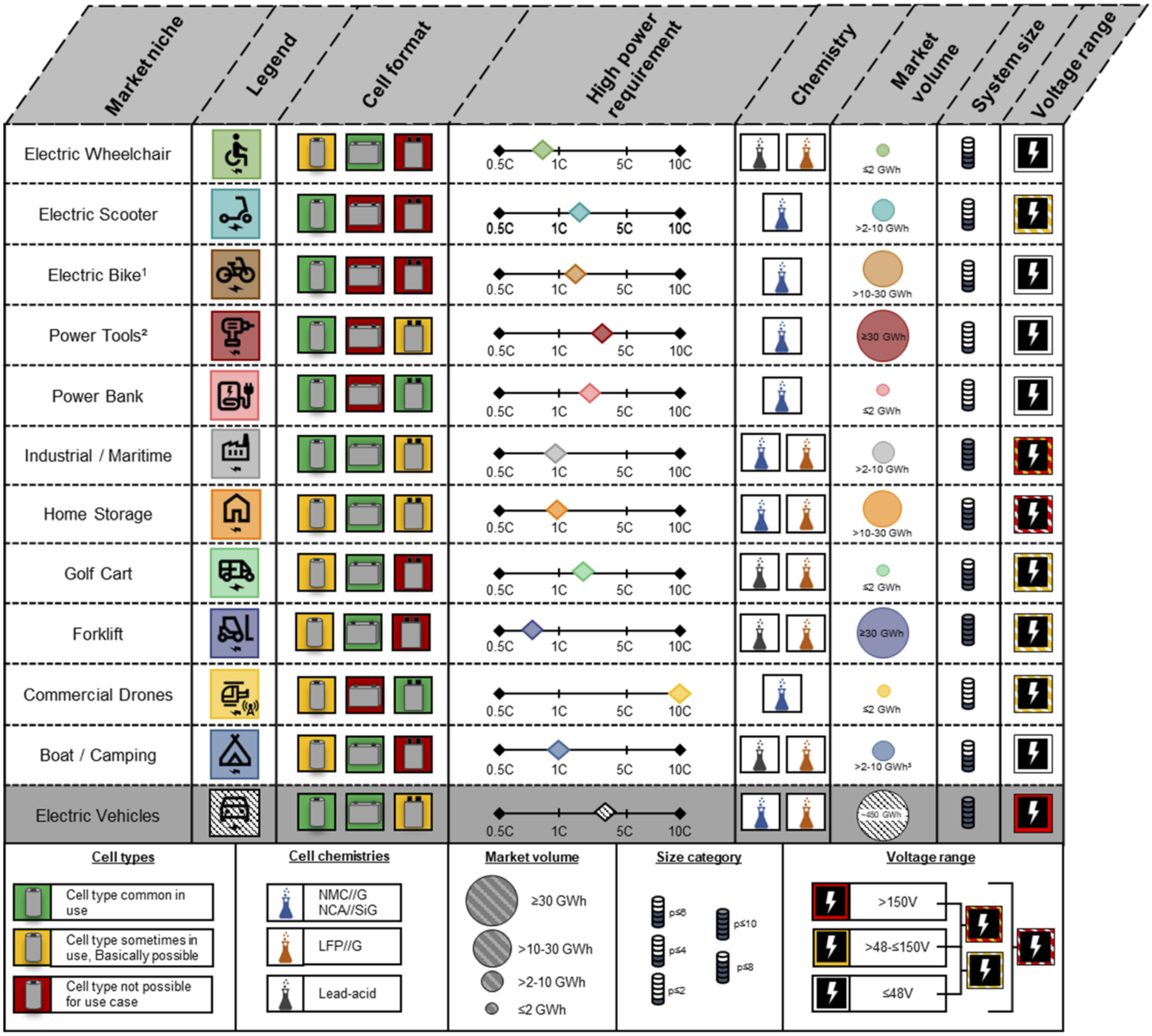

Fig. 5 Qualitative comparison of niche markets in contrast to EVs. ^{1}to C-rate estimation based on charging current, ^{2}C-rate estimated on basis of *electric scooter*, ^{3}estimated. Market volume based on a forecast of 2021.[6] System size and cell format are derived from teardown reports and fact sheets of relevant products corresponding within market. C-rate and chemistry are taken from fact sheets of relevant products corresponding to each market segment.

Furthermore, there are significant differences in nominal discharge rates across various market segments. While large *systems* typically exhibit lower nominal discharge rates, often less than 1C, smaller applications frequently require much higher discharge rates. This correlates with cell chemistries typically used in these niches. While large applications often contain lead-acid or LFP-chemistry, market segments with higher discharge requirements are dominated by high-power NCX-based chemistries.

In terms of market volumes, a substantial variation across various segments is evident. For some market segments a total market volume for 2025 of less than 2 GWh is expected, while others exceed 30 GWh. Additionally, there is no apparent correlation between market size and system size. For example, *power tools* are assigned to the smallest system class, yet their expected market volume is among the largest of all niches considered in this analysis.

3.2. Clustering analysis

To cluster market niches (Fig. 5, excluding EV applications) based on their key performance indicators (Fig. 5, excluding market volume), both *k*-means and hierarchical clustering were applied. An automatic optimization between 2-10 clusters identified a two-cluster solution with a *Silhouette Score* of 0.349 and an *ARI* of 1.0. *Cluster 1* comprises *electric scooters*, *electric bikes*, *power tools*, *power banks*, and *commercial drones* – primary small devices employing NCX-based chemistry that require medium to high power capabilities. *Cluster 2* includes larger systems predominantly using LFP or lead-acid chemistries, characterized by low to medium power requirements and moderate energy densities.

The hierarchical analysis reveals that some devices are grouped within the same clusters but still exhibit considerable distance from other niches within the cluster. For instance, in the first cluster, *commercial drones* show a pronounced hierarchical distance, likely due to their exceptionally high power requirements (Fig. 5 and 6). Conversely, certain applications such as *power tools* and *power banks*, or *golf carts* and *forklifts* show a high degree of similarity. The estimated market volume of *Cluster 1* is approximately 75 GWh, whereas *Cluster 2* accounts for about 71 GWh (Fig. 6).

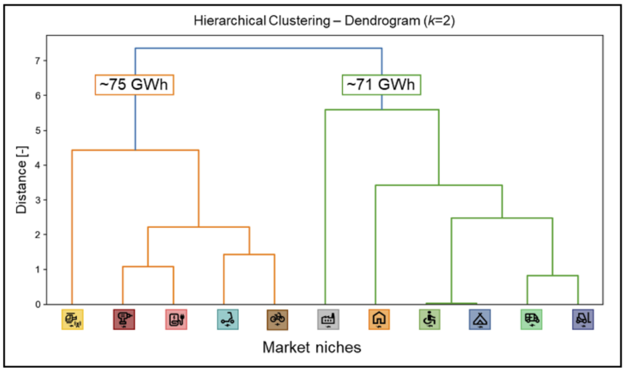

Fig. 6 Dendrogram of hierarchical clustering relevant market niches.

3.3. Lead-acid batteries

Lead-acid batteries (LABs) continue to play a vital role in various battery niche markets.[6] They are widely used as starting and auxiliary batteries for internal combustion engines. Moreover, LABs are still used in current applications, such as *forklifts* and batteries for *camping/boat* applications. Although their market share in certain applications is declining, their use is expected to persist in the coming years.[6]

Given the context of this study, it is essential to consider the current state of LABs. Generally, applications powered by lead-acid have lower requirements for energy density, and lead-acid technology is relatively inexpensive compared with LIBs, particularly those using NCX-based cell chemistries. From this perspective, LFP-based batteries represent a suitable substitute. In terms of gravimetric energy density, LFP is more comparable to lead-acid than NCX-based cell chemistry. Specifically, for applications like *forklifts*, where the battery pack is used as a counterweight, LFP is a viable alternative.[6] Nevertheless, for specialized applications – particularly those involving complex manufacturing processes, stringent certification requirements, or high cost sensitivity – LABs are likely to remain necessary in the future.

Notably, LABs often operate in 12 volt systems, comprising six cells in series (6S) with a nominal cell voltage of 2.0 V. A potential replacement with LFP would involve using four cells in series (4S) with a nominal SV of 12.8 V. In contrast, using NMC811//G with a nominal cell voltage of 3.6 V in three of four cells in series would result in SVs of 10.8 V (3S, NCX-based chemistry) or 14.4 V (4S, NCX-based chemistry), deviate more from 12.0 V than the 12.8 V provided by a 4S LFP configuration.

Reasons for substituting LABs with LFP-batteries include improved round-trip-efficiency, reduced hazardous materials, longer lifetime, and higher energy density.[35,36] Consequently, replacing LABs whenever feasible may enhance sustainability. In the subsequent analysis, these *systems* are assumed to be replaceable with LFP batteries. batteries. Other battery types, such as nickel-cadmium and nickel-metal hydride, were excluded from the scope due to their decreasing relevance.[6,35,37]

3.4. Comparison of system architectures

Throughout the research, a dataset of nearly 300 representative *systems* spanning the eleven market niches was compiled to support the following analysis.

Within the SV range below 100 V, distinct voltage levels are observed, excluding *power banks*. Notably, *power banks* are often advertised with capacities ranging from 15.0 to 30.0 $\mathrm{Ah_{SC}}$, but upon closer examination, their actual SCs are typically between 3.0 and 5.0 $\mathrm{Ah_{SC}}$ at higher SVs of up to 25 V. This configuration likely enables charging rates exceeding 100 watts. The stored energy, measured in watt-hours, is comparable to that of *systems* operating at lower SVs but with larger SCs.

The most common SVs are 12 V (*electric wheelchairs*, *boat/camping*), 18 V (*power tools*), 36 V (*power tools*, *electric bikes*, *electric scooters*), and around 48 V (*electric scooters*, *forklifts*, *golf carts*, *home storage systems*). Remarkably, 48 V exhibits the largest variety of market niches and capacity ranges, spanning

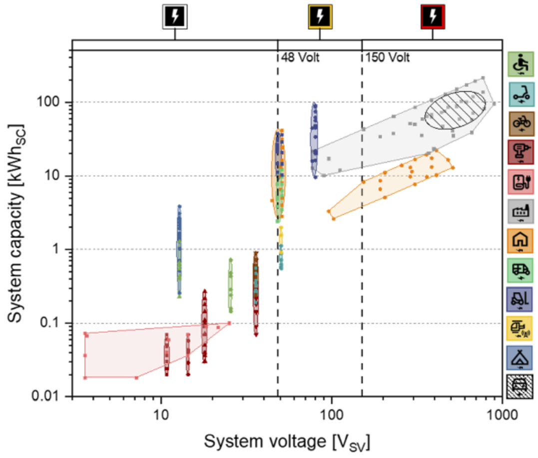

Fig. 7 Distribution of *systems*, niches are in different colors in comparison to BEVs (black-shaded area).

from below 1 kWh$_{SC}$ to more than 40 kWh$_{SC}$. Above 100 V, the SV distribution becomes more dispersed, with devices primarily belonging to two niches, namely *industrial/maritime* applications and *home storage systems*, being identifiable (Fig. 7).

In the next step, the distribution of SCs values across all devices is examined and visualized:

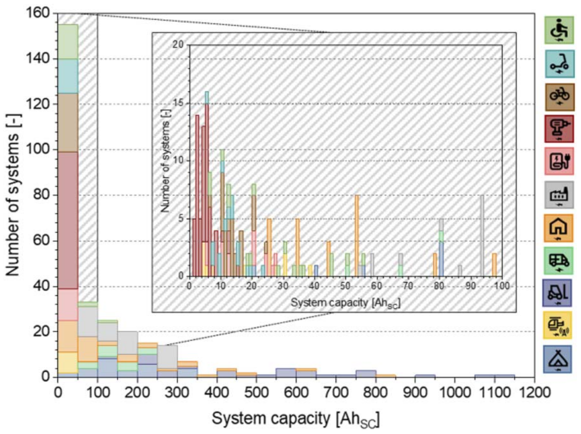

Fig. 8 Distribution of the niches *systems* across the system capacities up to 1200 Ah$_{SC}$ [resolution: Δ50.0 Ah$_{SC}$] and enlarged range up to a threshold of 100 Ah$_{SC}$ [resolution: Δ1.0 Ah$_{SC}$]. BEVs are not considered in the quantitative evaluation.

The largest device in this dataset has a SC of approximately 1150 Ah$_{SC}$. *Forklifts* and *industry/maritime* applications generally represent the largest systems in this dataset. Notably, a gap around 350 Ah$_{SC}$ can be observed, with most of the devices below this threshold and only a few above it. Overall, the distribution of SC in this dataset is skewed toward lower capacities, with most devices having SC below 50.0 Ah$_{SC}$. The median SC of the dataset is approximately 36.0 Ah$_{SC}$, whereas the arithmetic mean is 122.0 Ah$_{SC}$. In summary, the main concentration of *systems* with capacities below 50.0 Ah$_{SC}$ and the median SC of 36.0 Ah$_{SC}$ suggest that a considerable share of these *systems* may be accessible using cylindrical cells (Fig. 8).

3.5. System distribution and system configurations

In accordance with the methodology, the *system configurations* were calculated and distributed across CCs values:

The spread becomes more pronounced when the gap between the smallest and larges SC within a market niche increase. For instance, the SC for *power tools* ranges from 2.0 to 12.0 Ah$_{SC}$, whereas the SC for *boat/camping* systems spans from 30.0 to 300.0 Ah$_{SC}$. This results in a broader distribution, making it more difficult to access a large share of *system configurations* using a single cell type (Fig. 9).

In summary, market niches classified as system size class "XS" or "S", with a small spread between the smallest and largest device, exhibit narrower distributions. This results in higher relative shares of fewer different cell sizes compared to market niches classified as size "L" or "XL", which have a broader capacity range between the smallest and largest device. For example, *power tools* (XS, small spread) in comparison to *forklifts* (XL, broader spread) (Fig. 9).

The typical capacity of NCX-based 21700 cells ranges from 3.8 to 5.0 Ah$_{CC}$. Indeed, the results from system modeling indicate that larger applications are not accessible by those cells. For instance, the minimum suitable CC for *forklifts* is 20.0 Ah$_{CC}$. To access these market niches with smaller cells, the permitted parallel circuits value defined by the system size class would need to be increased. Even a larger 4680 cell containing LFP//G (13.7 to 18.9 Ah$_{CC}$) is not suitable under the given conditions. However, the goal is not to serve all applications with a single cell, which would require a high parallel circuit value to equate all *systems* to the lowest common denominator. A large number of parallel circuits has disadvantages, including increased system complexity, higher inactive material mass, and potential performance or lifetime issues arising from cell-to-cell variability.[38–40] Smaller cells also increase the share of inactive materials, which can reduce the system's volumetric and gravimetric energy density.[41] Moreover, from a sustainability perspective, producing smaller cells requires substantially higher energy consumption per kilowatt-hour.[14]

At this point, it is also worth noting that some calculated *system configurations* are not inside the relevant capacity range of 2.0 to 50.0 Ah$_{CC}$. As a result, the coverage rate measured across all *system configurations* for a certain niche is relatively low. For example, *forklift systems* have a coverage rate of approximately 21%. Consequently, only 21% of all calculated *system configurations* associated with *forklifts* are within the determined range for cylindrical cells. The coverage rates for further market niches are listed in the Table S2. In this context, it is noteworthy to display the share of systems from the dataset which are coverable with a certain cell size, independent of their actual *system configuration*.

In contrast, the poor configuration coverage rate and lower accessibility of *forklifts systems* raise questions about the feasibility of using cylindrical cells for *forklifts* under the defined parameters. As noted earlier, increasing the permitted parallel

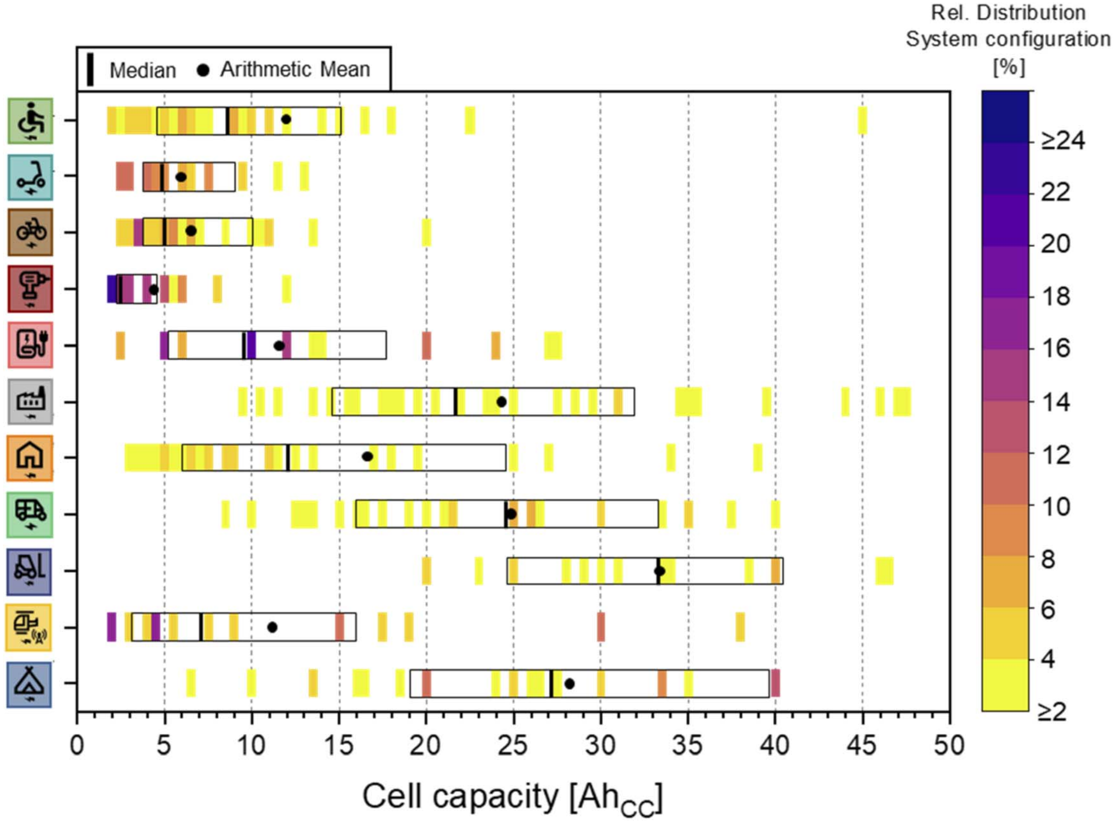

Fig. 9 Relative distribution of cell capacities of certain system configurations below 50.0 AhCC [resolution: Δ0.5 AhCC, aggregated]. The threshold is set at 2% of all niche-related system configurations.[29] BEVs are not considered in the quantitative evaluation. System configurations were obtained while dividing SC by considered parallel circuit values.

circuit value may improve coverage rates, but this approach is not the subject of this investigation.

Currently, each market niche is evaluated independently, based on its associated *systems* and the distribution of *system configurations*. In the subsequent step, the cumulative market volume of each individual market niche is considered to facilitate a comparative evaluation across all niches in terms of their market volume. To achieve a comparative evaluation, the individual distribution of *system configurations* for a unique niche is multiplied by its corresponding global market volume projected in 2021 for the year 2025.

The distribution of market volumes reveals a notable concentration of CCs below 10.0 Ah$_{CC}$. Additionally, the substantial market volumes occur for CCs of 20.0, 25.0, and 40.0 Ah$_{CC}$. This is largely driven by the significant market volume of *forklift* and *home storage* system (Fig. 10).

In contrast, *power tools* and *electric bikes* primarily drive the observed distribution at lower CCs. Other segments, such as *electric wheelchairs*, *golf carts*, and *power banks*, exhibit a relatively small cumulative market volume for individual CCs. This results from the relatively small market volumes associated with these niches.

Because the distribution is broad while the total market volume is small, only a limited number of cell sizes exceed a market volume of 0.1 GWh. The minimum threshold was therefore set deliberately low to avoid excluding niches with small market volume and broad distributions, such as *power banks*.

The market volume was distributed according to the relative distribution of *system configurations* within the defined scope. However, this approach only accounts for individual CCs and neglects important factors such as cell chemistry. To address this limitation, a scenario analysis is required to determine the actual AMV, which incorporates additional requirements.

3.6. Scenario analysis

Following the outlined method, four different scenarios were developed (Chapter 2.4). *Scenario A* and *A1* represent a state-of-the-art case, limited to NCX-based chemistry and the commonly used 21700 and 18650 cell formats. An advanced *Scenario A2* represents an extended case that evaluates potential market accessibility while introducing the BEV-related 4680 cell format with both LFP and NCX-based chemistries.

In *Scenario B1,* a fixed cell height is assumed, while the cell diameter is optimized in this approach to maximize the AMV share (Fig. 11).The resulting analysis illustrates the market accessibility of battery niche applications when relying on currently established cylindrical cell formats from existing markets and BEV-related applications. Furthermore, *Scenario*

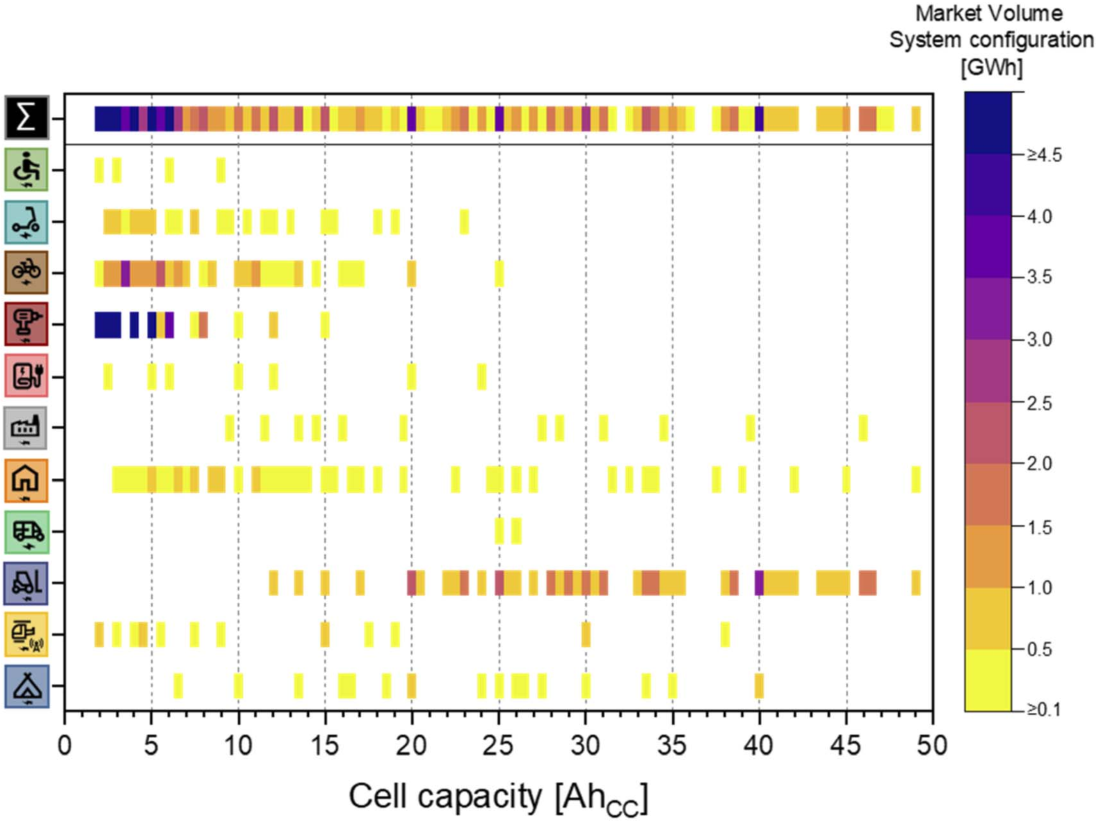

Fig. 10 Distribution of market volume across the market niches in scope [resolution: Δ0.5 Ah$_{SC,}$ aggregated]. Threshold set to market volume ≥0.1 GWh. BEVs are not considered in the quantitative evaluation.

B1 demonstrates how a potential new cylindrical cell format could enhance market accessibility under the given assumptions.

Scenario A shows a moderate AMV. The AMV is approximately 17.7 GWh, with comparable contribution from NCA//SiG and NMC811//G. In *Scenario A1*, the introduction of the widely used 18650 cell format with NCX-based chemistry results in an additional AMV of 15.8 GWh. Compared with *Scenario A*, the share requiring high-energy NCA//SiG chemistry is substantially smaller. Notably, most of the AMV can be covered by mid-energy NMC//G-chemistry, specifically for 18650-NMC//G cells, including the intersectional volume shared with NCX-based chemistry. The intersectional volume refers to the overlap of CCs between NMC//G- and NCA//SiG-based cells. Consequently, the demand for 18650 cells requiring exclusively high-energy NCA//SiG-chemistry is low compared with the other scenarios. More than 90% of total market volume from *Scenario A* and *Scenario A1* corresponds to *Cluster 1*. This shows a strong match between requirements of *Cluster 1* applications (small devices, high power requirements, NCX-based chemistry) and the cell sizes used in these scenarios. Therefore, a high accessibility of more than 98% for both scenarios is reached.

In *Scenario A2*, the 4680 cylindrical cell format, evaluated with different chemistries, results in a substantially lower increase in AMV compared with the 18650 format using NCX-based chemistry. Interestingly, unlike the automotive industry, NCX-based chemistry appears less relevant for 4680 cells in niche applications. This is primarily because Lead-acid or LFP are commonly used in larger niche applications requiring larger battery cells, whereas small devices are predominantly dominated by NCX-based chemistries (Fig. 5). This observation is also supported by the results of the cluster analysis. *Scenario A2* shows an AMV increase of approximately 7.5 GWh. Consequently, in comparison to the previous scenarios, the 4680 cell format shows a weaker match with the requirements of battery niche applications.[42] Total market volume within the corresponding cell capacity range in *Scenario A2* amounts to approximately 24.7 GWh. In contrast to scenarios before, *Cluster 2* has the largest share with more than 85%, while the AMV (7.5 GWh, Fig. 11) represents only 30% of this volume. In conclusion, *Scenario A2* does not provide a sufficient match between market requirements and available cell formats. In particular, the individual cell capacity of a 4680-LFP//G cell is too low to access the relevant market niches under the given assumptions. This motivates the final scenario, which investigates how a novel cylindrical cell format could enhance market accessibility, particularly for niches belonging to *Cluster 2*.

In *Scenario B1*, the cell height is fixed while the diameter is optimized to identify the cell format that yields the highest additional AMV for each chemistry. While the optimal format for NCX-based chemistry corresponds to one of the smallest diameters, the largest evaluated format provides the greatest AMV increase for LFP//G chemistry. Notably, *Scenario B1* achieves a greater AMV

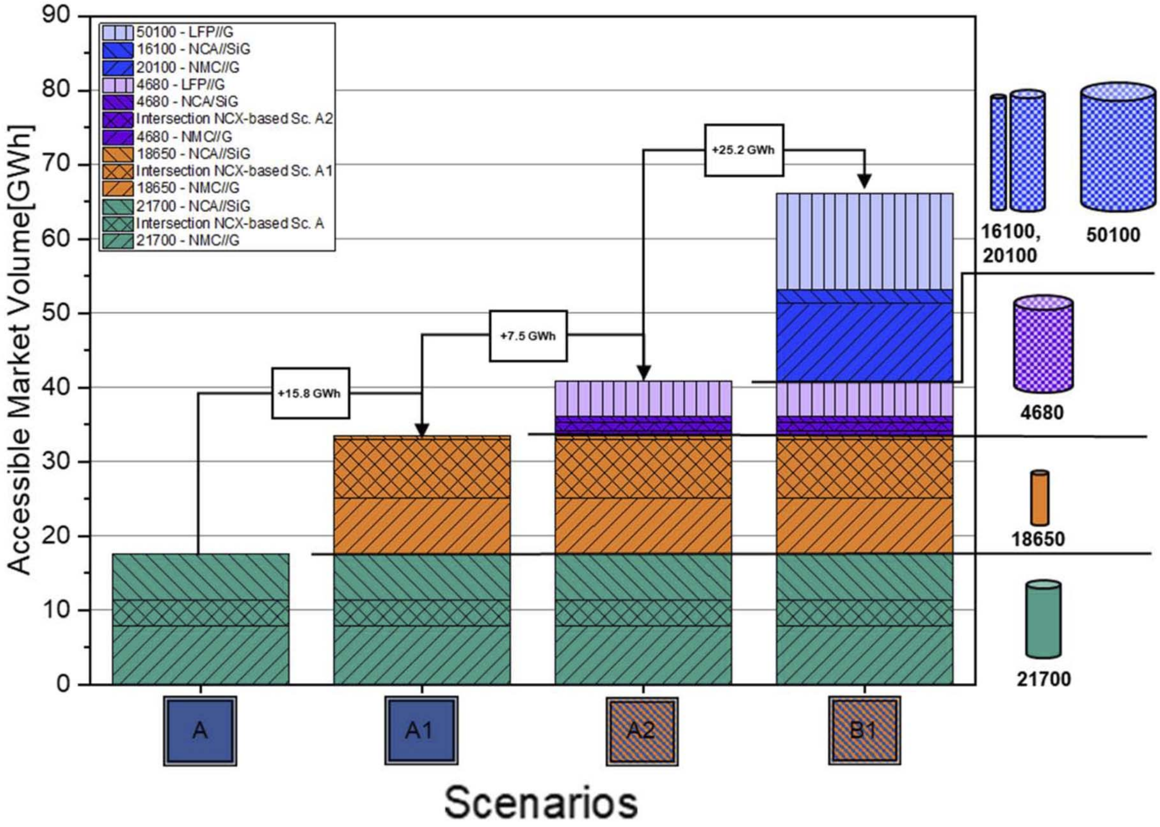

Fig. 11 Displaying AMV gathered from scenario analysis dependent on applied scenario.

increase than *Scenario A* and *A1* though the introduction of diameters 16 mm, 20 mm, and 50 mm. This finding supports the consideration of introducing additional standardized cell formats. The 50100-LFP//G and 20100-NMC//G cells demonstrate a notable increase in total AMV under the given conditions and assumptions. The 50100-LFP//G cell appears particularly favorable compared to the 4680-LFP//G due to its higher individual capacity. As previously discussed, increasing the number of parallel strings could also render the 4680 cell suitable for these applications; however, this aspect was not within the scope of the present study. These findings suggest that cylindrical cells with capacities above 5.0 $\mathrm{Ah_{CC}}$ and NCX-based chemistries, such as the 20100-NMC//G, warrant further investigation.

However, it is important to note that the 20100 and 16100 cell formats, with diameters of 20 mm and 16 mm respectively and a height of 100 mm, represent unconventional designs may be limited in their applicability due to its geometry. In addition, the 16100 cell format could be challenging to manufacture due to high diameter-to-height ratio resulting in limited mechanical stability.

Larger cylindrical cells, such as the 50100, may exhibit less favorable thermal distribution characteristics, which may affect their lifespan.[43,44]

Moreover, larger cells exhibit a wider range between their minimum and maximum achievable capacities. From modelling perspective, this results in a larger number of individual CC values being covered. For example, a low-energy 21700-LFP//G cell has a capacity range of 2.4 to 3.3 $\mathrm{Ah_{CC}}$, whereas a 4680-LFP//G cell has a broader capacity range of 13.7 to 18.9 $\mathrm{Ah_{CC}}$. A comprehensive list of all relevant cells calculated using the cell configurator is provided in the Table S3.

In conclusion, *Scenario B1* yields an AMV of approximately 65 GWh, which is still modest compared to the overall market volume of approximately 150 GWh. It should be noted that an equally weighted distribution of cell capacities is assumed based on the absolute distribution obtained from *system configuration* modeling. An advanced approach could involve evaluating *system configurations* based on the number of parallel circuits. However, this approach may be challenging to implement due to the lack of available information regarding actual *system configurations*.

Nevertheless, the results support the potential introduction of additional standardized cell formats, particularly for cylindrical cells using LFP-based chemistry. Furthermore, a standardized NCX-based cell with a rated capacity of 6.0 $\mathrm{Ah_{CC}}$ appears particularly relevant, in addition to commercially available cylindrical formats below 5.0 $\mathrm{Ah_{CC}}$. This capacity represents a key factor contributing to the observed AMV increase in *Scenario B1*, particularly through the 20100-NMC//G cell (Fig. 11).

3.7. Energy demand during production

This analysis identifies a total market volume of approximately 146 GWh across the considered battery niche markets.

Assuming an average product lifetime of 5 years and an average annual market growth rate of 10% due to ongoing electrification, this corresponds to an additional battery demand of approximately 44 GWh per year.

As a conventional baseline, it is assumed that market demand is supplied by pouch, prismatic, and cylindrical cells, each available in three sizes and three different chemistries. Under an equal distribution assumption, each cell type would require a production capacity of approximately 1.6 GWh per year.

The scenario analysis indicates that about 36% of the AMV across all niches could be addressed by only four cylindrical cell formats: 50100-LFP//G, 16100-NCA//SiG, 18650-NMC//G, and 20100-NMC//G. This consolidation increases individual cell demand to up to 3.9 GWh per year and reduces production energy demand by approximately 3–4% per kilowatt-hour of battery storage, depending on chemistry.

Notably, the common 21700 format does not rank among the top four cells in this analysis. However, the accessible AMV of the 21700-NMC//G (3.8–4.6 Ah_{CC}, 11.39 GWh) is only slightly lower than that of the 16100-NCA//SiG (3.6–4.3 Ah_{CC}, 12.01 GWh), since their accessible capacity ranges are comparable. Encompassing the 21700-NMC//G would increase AMV by only about 1.3 GWh beyond what is covered by the 16100-NCA//SiG. In this analysis, the 16100 format is preferred due to its slightly higher AMV and thus greater potential to reduce energy consumption per kilowatt-hour produced. Nevertheless, given its widespread industrial adoption, the 21700-NMC//G may represent a more practical choice. At this point, it should be noted that this analysis considers only energy consumption during battery production. Additional sustainability aspects, also including energy consumption changes in upstream and downstream processes, are not considered.

3.8. Model limitations

Despite the thorough analysis, some limitations exist. First, the approach to aggregate niche market volume is theoretical and relies on a qualitative determination of system size categories based on drawings of representative devices and considerations of system size and geometry.[23,24,27,28,45,46]

However, not all niches have an equal number of relevant *systems* in the database. Some applications, such as *power tools*, have numerous examples, whereas others, like *golf carts* or *commercial drones*, are represented by a few devices. This disparity is largely due to differences in the accessibility of representative systems, which also resulted in the exclusion of some otherwise suitable market niches.

Regarding volume distribution, an equally weighted distribution across all relevant *system configurations* was assumed. Nevertheless, this assumption may be inaccurate, particularly for larger *systems* with multiple *system configurations*, such as those classified in the *system size class* "XL". Future work could evaluate the relevance and likelihood of different *system configurations*. Minimizing the number of parallel circuits is likely important due to higher complexity, especially compared to simplified electrical circuits with fewer parallel circuits.[47,48] As a result, *system configurations* with exceptionally high parallel circuits are probably less common than others.

Another limitation is the low coverage rate of determined *system configurations*, particularly for *forklifts*, which is represented by approximately 21% of all related *system configurations*, as illustrated in Table S2.

Regarding scenario analysis, for *Scenario B1*, a fixed cell height was assumed, which limited the flexibility for evaluating of novel cell formats. Nevertheless, previous findings indicate that an NCX-based 2.0 Ah_{CC} is of significant interest, for some niches such as *power tools*, *electric scooters* and *commercial drones*. However, it should be noted that under the constraints imposed by the cell calculation method, the chosen cell formats, and the underlying assumptions, an illustrating NCX-based 2.0 Ah_{CC} cell is not feasible. Furthermore, it is acknowledged that considering less common cell formats, such as the 18500 and 26650 sizes during optimization process, would substantially change the outcomes of the scenario analysis.

4. Conclusion

In summary, battery niche markets exhibit significant heterogeneity in terms of application cases and battery system parameters, such as SV and SC. Notably, LABs still maintain a substantial presence across various niches. However, the trend towards substitution with lithium-ion batteries, particularly LFP cells, is expected to continue due to beneficial performance and improved sustainbility.[8]

In terms of market volume, the aggregated global market volume of approximately 150 GWh is significantly smaller than the BEV market. Moreover, the requirements for battery niche markets are more heterogenous and complex than those for BEVs. The range of individual SCs within a single market is substantial, with some niches approaching the one gigawatt-hour threshold, while others exceed 30 GWh.

Despite these challenges, the analysis reveals that most niches which are considered in this study can be assessed with small cells having capacities below 10.0 Ah_{CC} (Fig. 9).

Moreover, some niches require larger individual cell sizes, primarily driven by the results of *forklifts* and *home storage systems*. Therefore, the analysis indicates a demand for additional standardized cylindrical cell formats, especially for larger applications powered by LFP batteries, currently LABs, respectively.

The results of the scenario analysis highlight the limited accessibility of some *systems* with current cell formats, emphasizing the need for further optimization. As shown in *Scenario B1*, the AMV can be increased by 25.2 GWh (+62%), excluding intersectional volume with previous scenarios.

Moreover, from sustainability perspective, this analysis demonstrates that a substantial share of the accessible market volume of 36% of total AMV can be covered with only four cylindrical cell formats. By aggregating market demand and increasing the annual production capacity of each configuration, energy consumption and consequently the environmental impact can be reduced by approximately 3–4%, or 0.5–1.0 kWh/

$kWh_{battery}$. This reduction is particularly relevant given the energy-intensive nature and production volume of battery cell manufacturing.[9,14,17]

Future research directions could include the incorporation of additional relevant market niches and corresponding devices, as well as introducing further cell formats, such as prismatic or pouch cells. Specifically, pouch cells offer an interesting area of investigation, due to their widespread use in applications such as wearables, laptops, and smartphones, which are not considered in this analysis. Moreover, additional sustainability and cost implications associated with the implementation of further standardized cell formats should be evaluated. Another aspect to examine is the inclusion of different chemistries. As an emerging technology, sodium-ion batteries may compete with LFP if lithium prices are increasing, particularly for applications where size and weight are of minor importance.[49] However, considering emerging cell chemistries is not subject of this approach.

Another approach is to focus on the module or sub-module level. Manufacturing standardized sub-units could enable cross-application compatibility. For instance, a five-module pack with nominal voltage of 18 V, typically used in *power tools*, could also serve as a replacement for common *electric bike* or *electric scooter* batteries when two modules are connected in series. This concept could remain feasible even when different cell technolgies are used, provided that the cell format and overall design remain consistent.

Author contributions

Jan-Hendrik Richter: conceptualization, methodology, data curation, analysis, visualization, software, writing – original draft. Martin Gouverneur: conceptualization. Joris Spikker: conceptualization. Maurice Herben: conceptualization. Sebastian Thiede: conceptualization, supervision. Simon Lux: conceptualization, supervision.

Conflicts of interest

There are no conflicts to declare.

Abbreviations

BEV	Battery-electric vehicle
ESS	Energy storage system
3C	Computer-communications-consumer
LFP	Lithium-iron-phosphate
LIB	Lithium-ion-batteries
SC	System capacity
SV	System voltage
CC	Cell capacity
NCX-Cells	Cells containing nickel/cobalt-based chemistry
AMV	accessible market volumes
LAB	Lead-acid batteries

Data availability

The data sets used and generated in this study comprise three categories. First, publicly available data sources, as cited within the manuscript, were used to provide general market and technology information. Second, proprietary analyses (data sets with relevant devices) were generated by the authors and are available under https://doi.org/10.5281/zenodo.20214035. Further information (applied cells obtained from cell modelling) is listed in supplementary material. Third, part of the underlying market data was obtained from licensed commercial reports and databases. Due to copyright and licensing restrictions, these data cannot be shared publicly.

Supplementary information (SI): the derivation of the underlying market volumes, summarizes the analyzed niches, and describes the simulated cell types. See DOI: https://doi.org/10.1039/d6su00151c.

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