

Cost, volumetric energy density, and fast-charging projections of Na-ion and Li-ion batteries from a European perspective

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Analysis

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Cost, volumetric energy density, and fast-charging projections of Na-ion and Li-ion batteries from a European perspective

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Abstract

Na-ion batteries (NIBs) are emerging as a complement to Li-ion batteries (LIBs). Owing to their reliance on more abundant raw materials, NIBs based on layered transition metal oxides (LTMOs) and hard carbon (HC) are frequently promoted as a low-cost alternative to LIBs, particularly LFP (LiFePO₄). However, their techno-economic competitiveness remains insufficiently quantified. Here, we employ a multi-objective optimization framework to jointly evaluate manufacturing cost, volumetric energy density (VED), and charging time for ~4,500 Na-ion and Li-ion cell designs across three production scenarios. We show that NIBs can achieve cell-level cost parity with LFP, but only at the expense of lower VEDs and longer charging times. Achieving a clear competitive advantage would require further reductions in material costs, improvements in performance, or sustained increases in lithium carbonate prices in the range of 20-39 EUR kg⁻¹ in China and 22-55 EUR kg⁻¹ in Europe. Furthermore, Europe faces a trade-off between low-cost battery cell imports from China and the substantially higher costs associated with fully domestic production increasing costs by 18-27 %.

Keywords: *Na-ion batteries, sodium-ion, Li-ion batteries, cost modelling, volumetric energy density, fast charging, multi-objective optimization*

Na-ion batteries (NIBs) are often considered a potentially low-cost alternative to LFP (LiFePO₄) due to their drop-in compatibility with existing Li-ion battery (LIB) production lines, the possibility to use cheaper aluminum instead of expensive copper as the negative current collector (CC), and the use of more abundant elements such as sodium, manganese, and iron in the positive electrode [1–3]. Furthermore, the use of hard carbon (HC) as the negative electrode, characterized by its near-surface storage mechanisms, together with the inherently higher Na-ion mobility, has suggested that NIBs offer in general superior fast-charging capabilities compared to LIBs [4, 5]. The expectations of imminent industrialization of NIBs peaked in 2022-2023, when battery-grade lithium carbonate (Li₂CO₃) prices rose up to ~ 80 EUR kg⁻¹ tremendously increasing LIB cell prices [6]. However, as lithium prices have since fallen by more than 85 %, industrial momentum for NIB commercialization has slowed considerably. Although first-generation NIB cells have successfully been manufactured on existing LIB production lines and have thereby proven their drop-in capability, they have not yet demonstrated advantages over LFP in the metrics most relevant to battery electric vehicle (BEV) applications, namely manufacturing cost, volumetric energy density (VED), safety, aging behavior (where favorable cyclic and calendar aging is often offset by significant internal resistance growth), and fast-charging performance [7–9]. Consequently, the future competitiveness of NIBs remains uncertain and is likely to be shaped by both technological progress and the evolution of battery material costs and supply chains [8, 10]. Nevertheless, while performance-related challenges and improvement pathways are well understood [11, 12], the economic aspects of NIBs remain largely unexplored. We reviewed existing

techno-economic studies on NIBs [8, 13–15] and identified several aspects that could benefit from further analysis.

To our knowledge, no existing study has yet modeled the manufacturing costs, VED, and charging time using a multi-objective optimization framework that covers both cell design and bottom-up cost analysis on both active material (AM) and cell production level. We argue that such an approach is essential, as it allows for a holistic identification of key limitations of state-of-the-art and future battery technologies. Safety and cycle life are excluded as optimization objectives because they are primarily governed by regulatory requirements, OEM specifications, and system-level integration rather than cell design alone [16]. Within this scope, we apply the proposed framework to NIBs employing Ni-based layered transition metal oxides (LTMOs) and LIBs based on LFP to examine whether NIBs can become a competitive alternative with respect to cost, VED, and charging time.

To address this question, we establish a baseline representing the current technological maturity of NIBs and assess plausible future material improvements. All analyses are conducted from a European perspective, reflecting Europe’s current reliance on battery cell and material imports due to the lack of a domestic low-cost battery value chain. We evaluate three production configurations: 1) a fully China-based value chain encompassing raw material processing, AM synthesis, and battery cell production, with finished cells imported to Europe; 2) a European battery cell production with AM imports from China; and 3) a fully Europe-based value chain. To further improve the robustness of the analysis, we provide a detailed breakdown of cost-optimized NIB and LFP cell designs to identify major cost hotspots, complemented by a sensitivity analysis capturing raw material price fluctuations. The results provide insights into the techno-economic competitiveness of LTMO-based NIBs relative to LFP and identify potential industrialization pathways for Europe.

Setting up the modelling framework

Optimization of cost and performance

At the heart of our optimization framework is an in-house-developed battery cell design tool that allows for modelling of battery cells across different formats and AM combinations. As shown in Fig. 1, the design tool is coupled with a process-based cost model (PBCM) primarily based on [17] that calculates manufacturing costs for each cell configuration, as well as with a charging time module that calculates fast-charging performance for every design. The costs of AM are provided by five integrated PBCMs, covering artificial graphite (AG), natural graphite (NG), HC, LFP, and two LTMOs. Each model includes country-specific cost parameters for raw materials, energy, labor as well as equipment and other production factors. Raw material cost differences between Europe and China are derived from historical price analyses based on publicly available sources [18, 19]. Of note, our analysis excludes the distortive and volatile effects both of import tariffs as well as unrecoverable export taxation (i.e., recent changes to product specific value-added tax refund rebates in China) [20]. All the tools are coupled, enabling a consistent evaluation of how material selection, manufacturing routes, and cell design parameters influence overall cost and performance. We then apply a multi-objective optimization approach that seeks to minimize manufacturing cost and charging time, while maximizing VED for every cell composition. Further details on the tools can be found in the Methods section.

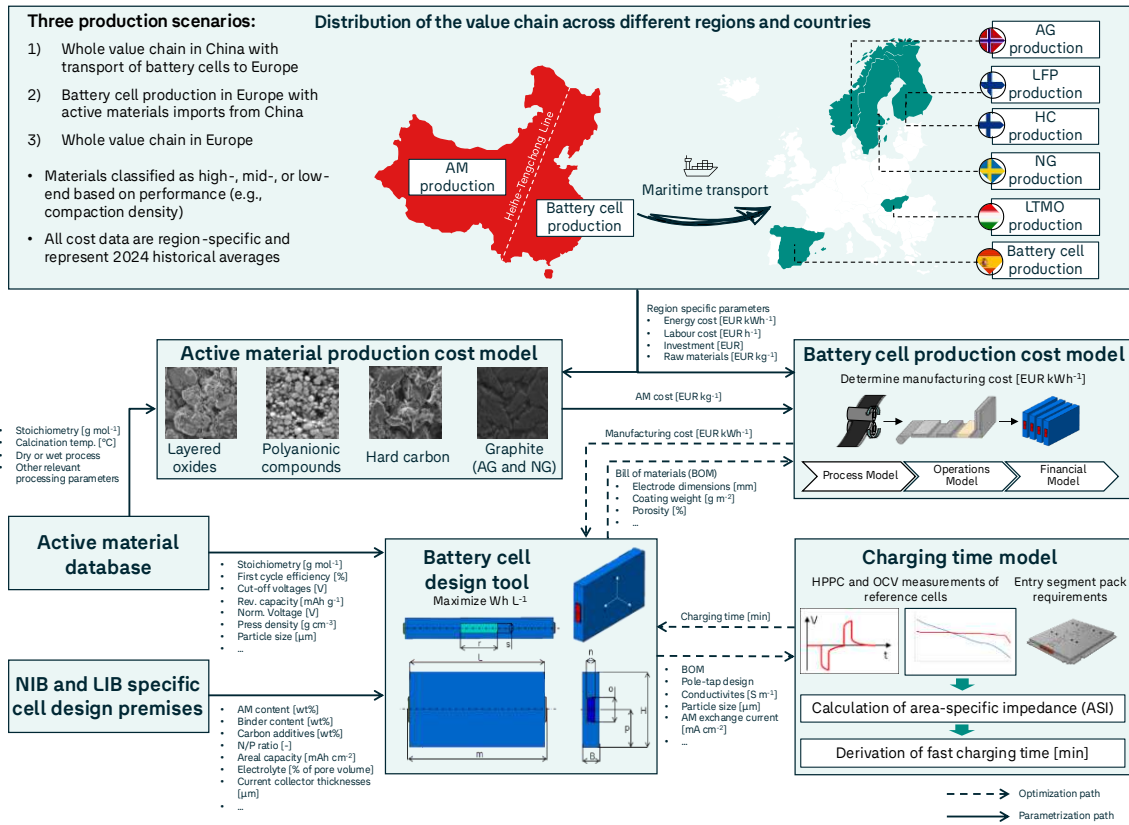


Fig. 1| Overview of the three production scenarios, the value chain and the cost and performance optimization framework.

Modelling of Na-ion and Li-ion active materials

For the positive electrode, we model as a baseline single-crystal (SC) O3-type $\text{NaNi}_{0.33}\text{Fe}_{0.33}\text{Mn}_{0.33}\text{O}_2$ (NFM) and more advanced SC O3-type $\text{Na}_{0.96}\text{Ca}_{0.02}\text{Cu}_{0.038}\text{Zn}_{0.053}\text{Ni}_{0.409}\text{Mn}_{0.315}\text{Ti}_{0.185}\text{O}_2$ (NCZNMT) from [21] with different HCs for the NIBs. We selected a SC NFM from various suppliers that best represents the industrial state-of-the-art in China for the reference year 2026. NCZNMT was chosen because it captures key industrial development trends in LMTOs toward higher Ni and Mn content in the electrode to increase energy density, while targeted Zn, Ca, and Ti substitution enables higher upper cut-off voltages (up to ~ 4.3 V) by suppressing Na^+ /vacancy ordering, thereby smoothing phase transitions to enhance cycle life [21]. Despite the Chinese NIB market currently undergoing a transition from LTMOs towards polyanionic $\text{Na}_4\text{Fe}_3(\text{PO}_4)_2\text{P}_2\text{O}_7$ (NFPP) [22], we focus solely on LTMO-based NIBs, as an internal assessment indicates that entry-level BEV applications require a minimum VED of 290 Wh L^{-1} for prismatic cells - a threshold that commercialized NFPP cells currently do not meet.

For negative electrode in NIBs, we model HCs. Despite HCs well-known disadvantages and them being the obvious bottleneck in NIB industrialization, they remain the most industrially mature negative electrode material [23]. Based on insights from different HC suppliers, we consider coconut shell and pitch-derived HC as the baseline and pair them with NFM, representing the current achievable state-of-the-art for NIBs, hereafter referred to as NFM/HC. Performance metrics are aligned with the respective precursor type, with coconut shell-based HCs categorized as high- and mid-end materials, and pitch-derived HCs as low-end due to their inferior performance. Following the argumentation of Yao et al. [8], we also consider a future (resin-based) HC to include a potential performance ceiling for future commercial HCs. To complete the advanced NIB design, we assume future HC (f-HC) only being available in combination with advanced NCZNMT, hereafter referred to as NCZNMT/f-HC. A detailed overview of the various material combinations is provided in Fig. 2.

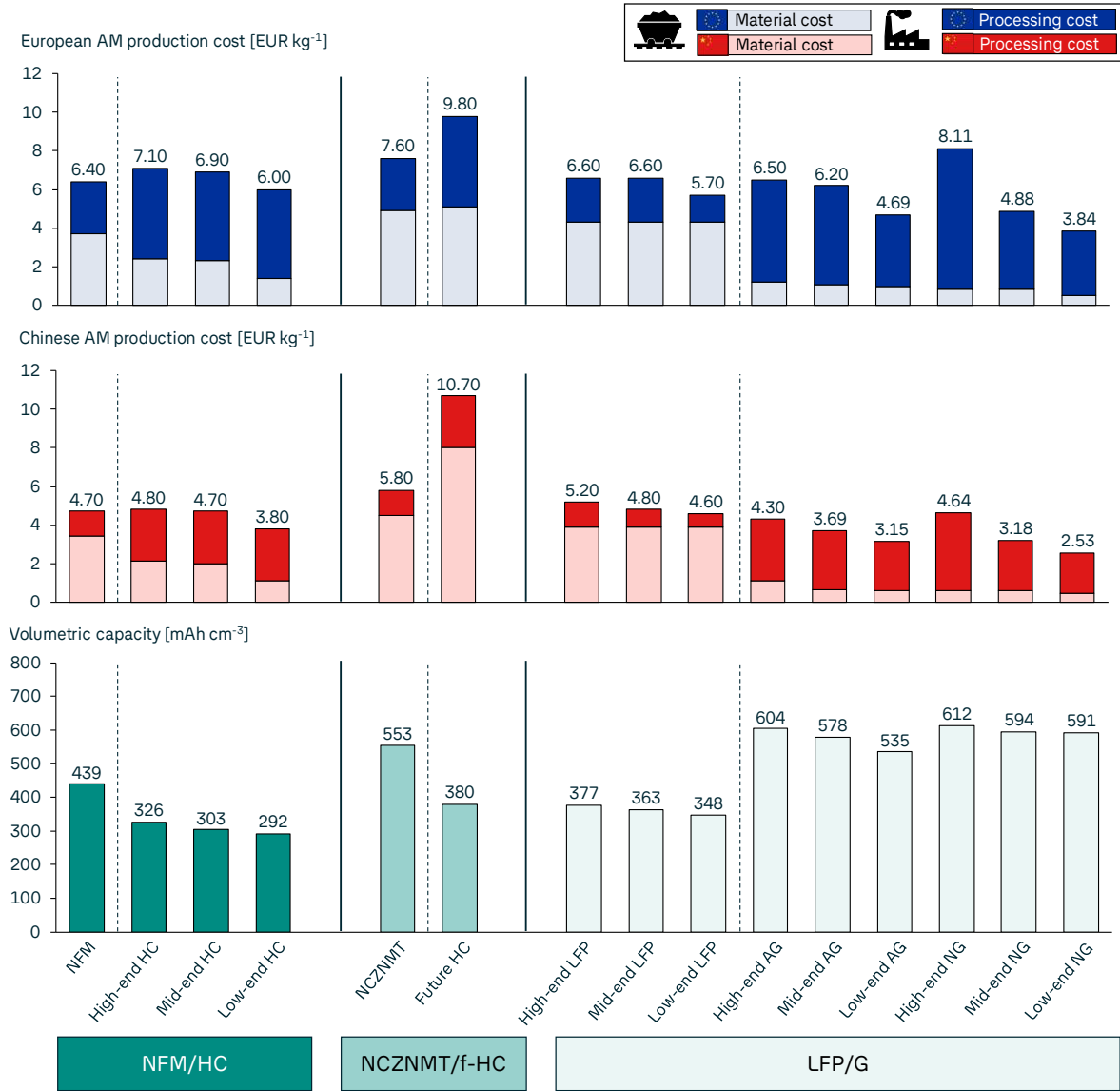


Fig. 2| Investigated AM combinations (NFM/HC, NCZNMT/f-HC and LFP/G), their respective volumetric capacity (bottom) and the modelled production cost for China (middle) and Europe (top). The volumetric capacity of the respective AMs refers to reversible capacity at 1/3 C.

For the European value chain, we also choose coconut-, pitch- and resin-based HCs over e.g. locally sourced biomass HCs such as lignin [24] for two main reasons. First, at the time of writing large-scale HC production does not exist in Europe, so local materials do not reflect the current industrial baseline, which remains centered in Asia. Second, using well-established materials ensures data consistency, as reliable performance data for European HCs are either unavailable or non-publishable due to limited supplier diversity.

All NIBs are benchmarked against LIBs employing LFP as the positive electrode paired with either AG or NG, hereafter referred to as LFP/G. Current industrial efforts for LFP focus on increasing compaction density to improve both VED and fast-charging behavior [25]. Accordingly, we classify LFP materials from different suppliers in our analysis into high-end, mid-end, and low-end categories, with compaction density ($2.3\text{--}2.7\text{ g cm}^{-3}$) as the key criterion. We consider both AG and NG, each further classified into high-, mid-, and low-end material grades based on performance. Even though AG currently dominates BEV applications due to its favorable cost-performance balance, we include NG to capture potential future relevance, particularly in Europe, where NG resources may support regional supply chains [26].

Analyzing the competitiveness of NIBs in different scenarios

Comparing the cost, VED and charging time of NIB and LFP cell designs

Fig. 3 shows the optimized cell designs across the three production scenarios, revealing the fundamental trade-offs between VED, fast-charging, and manufacturing cost. The results indicate that NIB cell designs can be cost-competitive vs. LFP designs, albeit at lower VEDs and longer charging times.

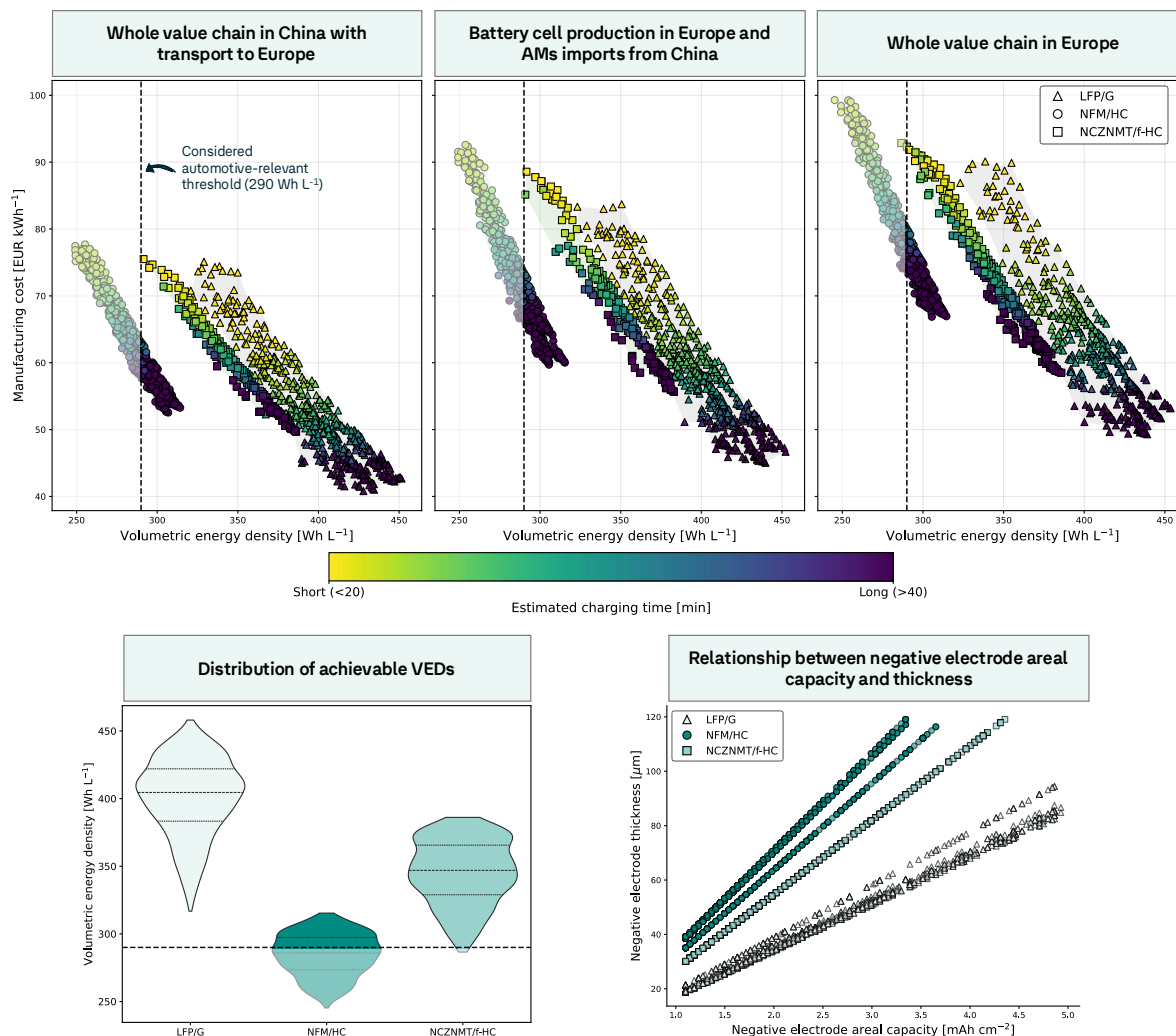


Fig. 3] Comparison of LFP/G, NFM/HC and NCZNMt/f-HC in terms of manufacturing cost, VED and charging time across three production locations: (top left) whole value chain in China; (top center) cell production in Europe (Spain) with AMs imported from China; (top right) whole value chain in Europe. The width of each area reflects the cost variation across the different modelled cell designs. The violin plots (bottom left) represent the density of feasible cell designs within the optimized design space, while the internal lines indicate the median and interquartile range. The scatter plot (bottom right) shows the relationship between negative electrode areal capacity and negative electrode thickness for all optimized cell designs.

For most cell designs, increasing the VED leads to lower manufacturing costs. At a fixed cell volume, this is primarily achieved through thicker electrodes, which reduce inactive material intensity and processing effort per kWh. Under a fully China-based value chain with transport to Europe, LFP/G achieves the lowest modeled manufacturing cost (~41 EUR kWh⁻¹), outperforming NFM/HC (~53 EUR kWh⁻¹) and NCZNMt/f-HC (~50 EUR kWh⁻¹). The higher cost of both NIBs primarily stems from the higher AM costs (as shown in Fig. 2) and the lower VED of the cells. Moving cell production to Europe while importing AMs from China increases cost by ~10 % (LFP/G) and 12-14 % (NIBs). Fully relocating the entire value chain amplifies this penalty to +22 % and +18-27 %, respectively, dominated by higher upstream material costs and elevated labor and energy expenditures in Europe.

The highest modelled VED for NFM/HC is at 315 Wh L⁻¹ and for NCZNMT/f-HC at 386 Wh L⁻¹, which is significantly lower compared to the 453 Wh L⁻¹ of LFP/G. The lower VED of both NIBs primarily results from the lower volumetric capacity of HCs compared to graphite (Δ 155-312 mAh cm⁻³), which leads to thick negative electrodes reaching processing limits at relatively low areal capacities (< 3.5 mAh cm⁻²). Consequently, as shown in Fig. 3, NFM/HC offers limited design flexibility if automotive-relevant VEDs of ~ 290 Wh L⁻¹ are to be achieved. Moreover, the thick and porous HC negative electrode largely confines NFM/HC to high-energy cell architectures, as fast-charging designs require substantially thinner electrodes. Through improved AMs, NCZNMT/f-HC shows greater design flexibility, allowing the realization of fast-charging NIB designs.

These observations also translate into the charging behavior of the modeled cells. On average, both NIBs exhibit longer charging times than LFP/G. While fast-charging is inherently complex and influenced by factors beyond the scope of the present model - such as the overall lack of NIB-specific fast-charging profiles - the longer charging times of the NIB designs can primarily be attributed to two fundamental principles. Firstly, while the characteristic plateau region in the voltage profile of HCs provides high capacity, it is also characterized by sluggish kinetics due to constrained ion transport in the porous structure [4]. Especially at high charging rates, this leads to severe polarization, limiting the allowable charging current and prolonging the charging time. Secondly, increasing electrode thickness amplifies ionic transport limitations, leading to stronger concentration gradients, electrolyte depletion in inner regions, and increased ionic and ohmic resistance. These limitations are more pronounced in NIBs due to the structural differences of the negative electrode [27]. While the modeled LFP cells maintain a high AM fraction even at larger electrode thicknesses, NIBs exhibit a lower AM fraction and the intrinsically lower electronic conductivity of HC compared to graphite. As a result, ohmic losses and polarization increase disproportionately with electrode thickness significantly limiting the fast-charging capability.

Deep dive on cost-optimized battery cells

Fig. 4 compares the cost-optimized battery cell designs for production in China with transport to Europe and for the full value-chain localization in Europe. We focus on these two cases, as they capture the essential regional cost differences, while the scenario with imported AMs adds little explanatory value.

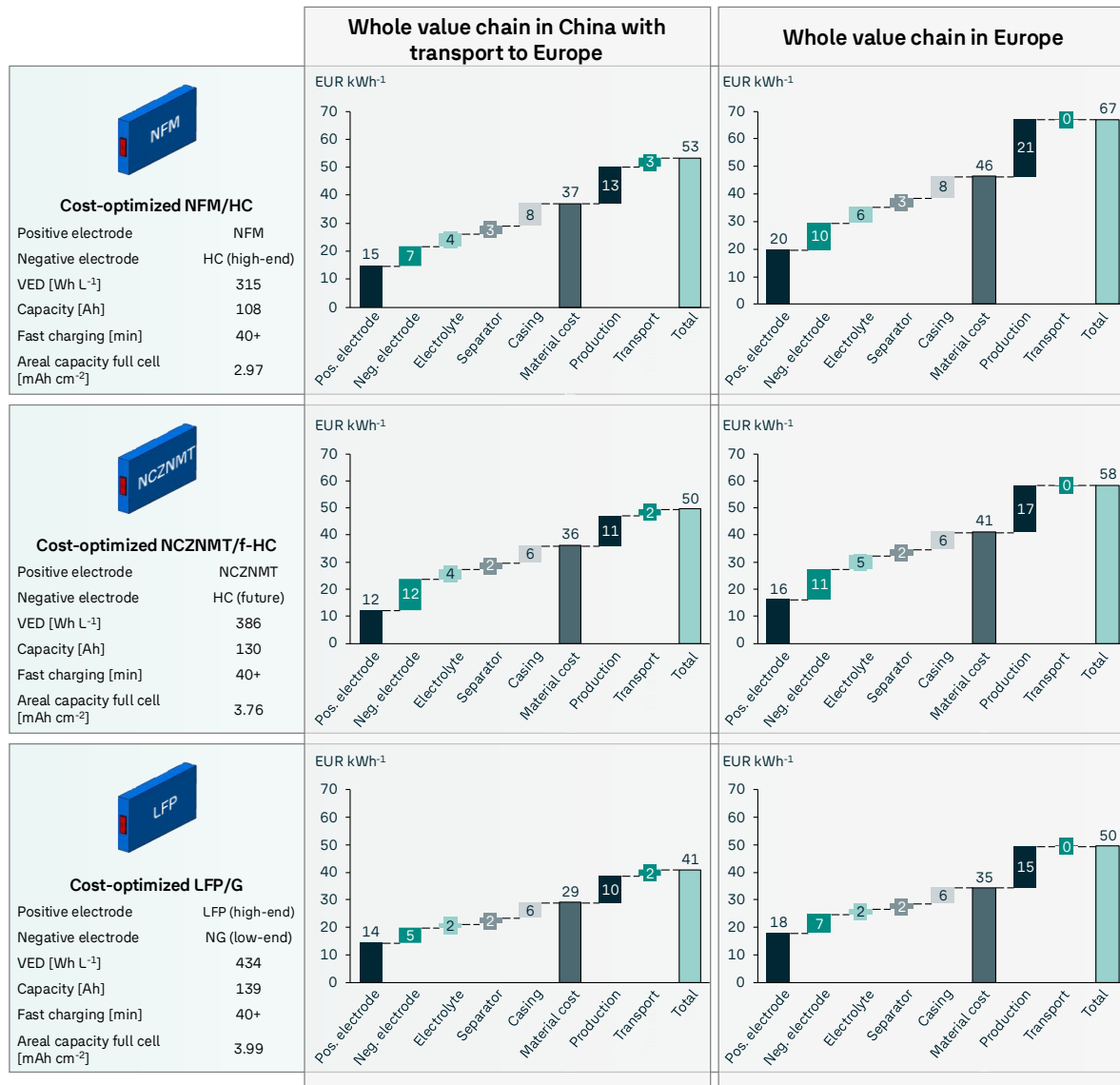


Fig. 4 | Analysis of the cost-optimized NFM/HC, NCZNMt/f-HC and LFP/G cells produced in China vs. in Europe

The cost-optimized designs for both NIBs exhibit a clear structural pattern: maximally thick electrodes and minimally thick CCs. For NFM/HC produced in China, total material cost reaches 37 EUR kWh⁻¹, dominated the positive electrode. The HC electrode contributes 7 EUR kWh⁻¹, with the coconut-shell precursor, purification, and coating steps being the most expensive aspects. Moreover, the thick and highly porous HC electrodes also increase the pore volume within the cell, which in turn necessitates significantly larger electrolyte quantities (3-4 mL Ah⁻¹ in NFM/HC vs. < 2 mL Ah⁻¹ in LFP/G), further adding to cost. Producing NFM/HC cells entirely in Europe elevates the total cost to 67 EUR kWh⁻¹, reflecting the cumulative impact of higher raw material prices, energy costs, higher wages and lower annual working hours, as well as equipment expenses through the entire European value chain. NCZNMt/f-HC illustrates the trade-off between higher material costs and lower costs per unit of energy. Although a higher Ni-content in the positive electrode and resin-based HC increase material costs, the higher specific capacity and VED reduce material demand and manufacturing effort per kWh. As a result, NCZNMt/f-HC achieves only a marginal cost advantage in China but a substantially larger benefit in Europe, demonstrating that increases in VED have a disproportionately strong impact in high-cost production environments.

Cost-optimized LFP/G designs follow a different strategy, relying primarily on low-cost materials rather than maximizing VED. Given the assumptions considered, low-end NG has the most favorable cost-to-capacity ratio and substantially contributes to the lowest cell costs. However, since cycle life

and safety are not considered in the optimization, the suitability of such designs for automotive applications must be carefully evaluated. Nevertheless, the results suggest that reducing material costs is a more effective way to reduce costs for LFP/G cells than increasing VED.

Sensitivity analysis

As outlined in the previous chapter, raw materials strongly influence battery cell costs and, consequently, their economic competitiveness. Given the high volatility of raw material prices, we evaluate the cost sensitivity to Li_2CO_3 , the dominant cost driver for LFP/G cells. Specifically, we determine the material intensity (including the indirect effect of Li-prices on LiPF_6 costs), group NIB and LFP/G cell designs by charging time and calculate the mean Li_2CO_3 break-even price at which each NFM/HC and NCZNMT/f-HC cluster becomes cost-competitive with the corresponding LFP/G cluster.

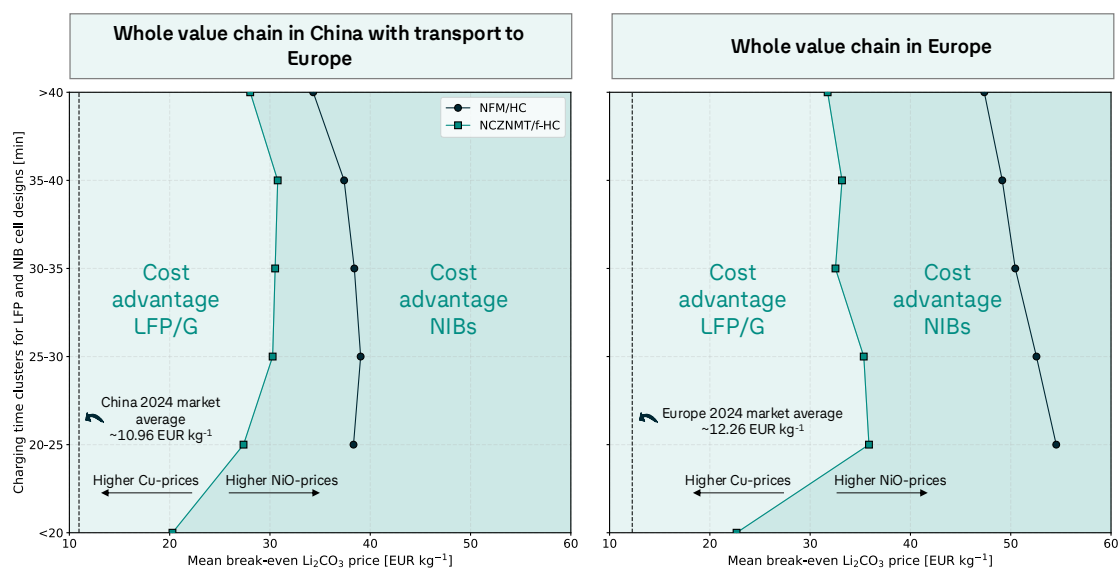


Fig. 5 Sensitivity analysis for NFM/HC and NCZNMT/f-HC versus LFP/G for: (left) whole value chain in China and (right) whole value chain in Europe. The light green area shows the range where LFP/G maintains a cost advantage - the dark green area shows the range where NIBs become economically favorable. It should be noted that, for NFM/HC, no cell design achieved a charging time of less than 20 min.

Fig. 5 shows that the Li_2CO_3 break-even price as a function of charging time in China ranges from 34–39 EUR kg^{-1} for NFM/HC and 20–31 EUR kg^{-1} for NCZNMT/f-HC, whereas in Europe it ranges from 22–36 EUR kg^{-1} and 47–55 EUR kg^{-1} , respectively. Technological improvements and further cost reductions in NIBs would shift the break-even point to lower Li-prices, thereby narrowing the cost gap on cell level to LFP, if such breakthroughs cannot be replicated in LIBs.

Furthermore, the break-even curves show significant differences. In China, both NIBs display a characteristic "banana shape." Shortening the fast-charging time reduces the VED for both NIBs and LFP/G, which increases costs for both technologies, especially for NIBs due to the previously described phenomenon, causing the break-even point to initially rise. However, a turning point occurs at around 25–30 minutes, beyond which the break-even point decreases again. This effect is driven by the increasing share of copper in LFP/G cell designs, which raises costs more than it does for NIBs, as NIBs rely exclusively on Al-CCs in this study. A similar inflection point is observed for European production but only for NCZNMT/f-HC. For NFM/HC, the "copper effect" is continuously offset by the European cost structure. Consequently, we suggest that future fast-charging NIB designs could have an advantage over LFP/G fast-charging designs, particularly since the latter are subject not only to volatile Li-prices but increasingly also to Cu-prices.

Discussion

This study used a multi-objective optimization framework to evaluate the competitiveness of Ni-based NIBs compared to LFP cells. A total of ~4,500 cell designs were modeled across three production

scenarios and evaluated based on manufacturing cost, VED, and fast-charging capability. The results show that NFM/HC and advanced NCZNMT/f-HC cell designs can achieve cost parity with LFP/G at the cell level across all scenarios. However, this comes at the expense of lower VEDs and longer charging times, which may reduce their competitiveness from an OEM perspective. To be competitive with LFP, NIBs therefore require further reductions in material costs, improved VED, and/or faster charging performance.

NIBs are often praised for using abundant and potentially low-cost materials. However, this does not apply to any of the cell compositions investigated across the three considered scenarios. Due to the use of nickel, both NFM and NCZNMT have no clear cost advantage over LFP at the positive electrode level. While a higher nickel content in NIBs enables increased VEDs and thus lower cell-level costs, it simultaneously introduces greater exposure to raw material price volatility. In this respect, nickel in NIBs plays a role like lithium in LFP cells by shifting cost sensitivity from one critical commodity to another.

As demonstrated by the shift from NFM to NCZNMT, one way to increase VED in NIBs is to raise the upper cutoff voltage (from 4.0 V to 4.3 V, for example). Unlocking the latent capacity potential at higher voltages is a promising way to improve overall cell performance and reduce costs. However, while this may seem straightforward in theory, increasing the upper cutoff voltage poses significant technical challenges, such as irreversible phase transitions and electrolyte degradation. Both of these issues reduce cycle life [21]. Therefore, volumetric capacity requires further improvement independent of voltage, for example, by blending PC and SC materials or increasing compaction density via particle size optimization. Ideally, these strategies are pursued in combination to maximize VED gains.

Furthermore, our modeling confirms the findings of previous studies that HCs are the primary obstacle to large-scale industrialization and significant performance improvements in Na-ion technology. Although HC is often highlighted for its substantial cost potential, current industrial realities suggest otherwise. The high cost of imported feedstocks (such as coconut shells) from Southeast Asia, combined with batch-to-batch inconsistency, extensive purification requirements, fluctuating demand, and the absence of a mature, integrated supply chain, has prevented HC from achieving the anticipated cost advantage over AG or NG thus far [28]. To reduce costs, establishing domestic, biomass-based HC production independent of imported precursors in China or Europe could play a decisive role. In China, bamboo is frequently discussed as a promising alternative [28], whereas in Europe, lignin is considered a viable feedstock [24]. However, neither has achieved large-scale production at the time of writing, and it remains uncertain whether comparable or superior electrochemical performance can be achieved at an equal or lower cost than coconut-shell-derived HCs. Additionally, it is of paramount importance to increase the volumetric capacity and first cycle efficiency of HCs, especially given the significant performance gap compared to graphite. As demonstrated by f-HC, improvements can initially come at higher material costs without undermining competitiveness overall, since the net effect on a EUR kWh⁻¹ basis remains largely positive. In addition to improving capacity and cost, it is also essential to enhance charging performance by reducing polarization through material optimization [4, 28]. However, if the cost and performance issues of HCs remain unresolved, it follows that a growing number of research and industry concepts will shift toward zero-excess ("anode-free") configurations [29].

From a European perspective, the results reveal a trade-off between cost competitiveness and strategic autonomy. The lowest-cost option is to import battery cells from China. Establishing cell production in Europe while continuing to import AMs increases costs by 10-14 %. Full localization of the value chain, however, raises costs by 18-27 %, due to higher labor, energy, and machinery costs, which disproportionately affect NIBs. Consequently, from a cost and performance perspective alone, a European battery value chain centered on LFP, and graphite remains the most competitive option. However, if establishing such a value chain proves difficult in the near term, Ni-based NIBs could become strategically relevant despite their current limitations. NIBs are often promoted as a resilient alternative to LIBs because of their abundant raw materials. However, our results show that this advantage is only meaningful if NIBs can also be manufactured at competitive cost levels. Currently, their economic viability is limited by the combination of low VEDs and comparatively high European production costs, which has likely contributed to the absence of a competitive European NIB value

chain. Overcoming these disadvantages will require lower production costs, for example, through reduced energy prices, higher levels of automation, or continued improvements in cell performance.

Meanwhile, the decreasing industrial focus on LTMO-based NIBs and the prospect of slower progress in China could present an opportunity for Europe to gain a competitive edge in this technology. Europe could accelerate the development of a domestic NIB value chain by leveraging its existing expertise, infrastructure, and supply chains for NCM production and expanding them to NFM. Advanced compositions such as NCZNMT/f-HC could be a viable alternative if LFP supply is limited. Nevertheless, localization of NIBs would (like for LFP/G) require substantial investment and the onshoring of key production steps. Therefore, the implementation of pilot or lighthouse projects will be essential to demonstrate the technological feasibility and industrial maturity of this path. Looking ahead, it appears that NIBs with HC can only remain relevant for automotive applications if either significant cost and performance improvements are achieved or development will move toward higher-risk cell designs, such as zero-excess (“anode-free”) concepts. It remains to be seen which of these paths will ultimately prevail. Independent of this, NIBs remain a technology worth pursuing.

Methods

Process-based cost modelling

Active material production

Each AM model was implemented as a PBCM, including region-specific inputs for feedstock, energy and labor demand as well as cost parameters for equipment and other production factors. As a baseline for the PBCMs, we primarily rely on material supplier flowcharts, as these comprehensively represent all the relevant synthesis steps. However, due to confidentiality reasons, equipment specifications and process throughput times of these suppliers were not used and are therefore derived from the literature below. To reflect industrial practice, we incorporated adjustments in our PBCMs that allow differentiation between high-end, mid-end and low-end material grades such as omitting coating steps for low-end materials or by varying feedstock quality across grades. For the production of AG and NG, we utilize information provided in [30]. For HC, we developed a model that combines individual processing steps derived from [30] with further process steps, information and assumptions based on [28, 31, 32]. Data from [33, 34, 34, 35] served as input for the LFP, NFM, and NCZNMT models.

Battery cell production

The battery cell production model requires among various other parameters such as equipment, labor or energy cost, the respective bill-of-materials of every cell as inputs and is primarily based on the equations provided in [17]. The model calculates for every cell design the respective process time (mostly s cell⁻¹ or s sheet⁻¹) for every process step and covers electrode manufacturing, cell assembly, cell finishing and further auxiliary steps. Based on industry insights, we adjusted the model to account for specific process differences between LIBs and NIBs in battery cell production that influence cost, such as different dry-room requirements, as well as variations in the electrode drying protocols, tab welding, formation procedures and further process steps that cannot be disclosed.

Transport

The transport model captures the cost associated with shipping of the AMs. We assume that other battery components - including the casing, the electrolyte, the binders and additives - are not transported between regions and are always produced domestically. In the scenario with AM imports from China to Europe, the model compares the cost of domestic production with the cost of the imported supply and selects the minimum for each traded component, thereby determining the least-cost configuration for each cell production location. In our analysis, domestic production refers to manufacturing located within either Europe or China, respectively. Intra-regional transport costs are excluded, as they were found to be negligible (< 1 EUR kWh⁻¹).

Region-specific parametrization

All cost models are parameterized on a region-specific basis regarding raw material, labor, energy, and equipment cost. Raw material cost data are region-specific and based on publicly available sources, including data from the Shanghai Metals Market [18], and Fastmarkets [19]. Historical cost data were analyzed to quantify regional differences between Europe and China in key materials such as nickel, lithium, or copper, ensuring that the model reflects realistic regional cost structures. Based on the analysis of these key raw materials, it was found that raw material costs in Europe are on average approx. 10 % higher than in China. Based on this observation, the same percentage markup was applied to other raw materials for which no European cost data were available. Labor and energy costs were derived from numerous publicly available sources, with further details provided in the supplementary information (SI). All data used refers to the year 2024 to ensure consistency and enable a robust comparison. Within China and Europe, further spatial differentiation is applied, as illustrated in Fig. 1. In China, AM production is assumed to take place in provinces west of the Heihe-Tengchong line to reflect the common utilization of regional cost advantages, particularly with respect to renewable energy and labor. Battery cell production is assumed to occur in a representative region east of the line. In Europe, Spain is considered as the location for battery cell production due to its favorable manufacturing conditions. The remaining value chain in Europe includes AM production in countries with existing or announced production capacities, such as Norway, Sweden, Finland, and Hungary [36]. The model structures, the adjustments made, and further details are given in the SI.

Setting up the cell designs

Cell design tool

The in-house developed cell design tool is a spreadsheet-based framework for modeling different battery cell architectures, including prismatic, cylindrical, and pouch formats. The tool enables the systematic definition of geometric, mechanical, and electrochemical design parameters, such as cell dimensions, tab configuration, electrode stacking or winding strategies, layer-specific properties (e.g., electrode overhangs, separator margins, and housing thickness) and so on. The tool integrates detailed inputs on material composition and electrode design, including CC materials and thicknesses, separator properties, and AM formulations with possible blends of active components, conductive additives, and binders. The inputs originate from an embedded material database, which provides the required properties (such as stoichiometry, compaction density, average voltage, and further) from industrial suppliers, ensuring comparability through uniform testing conditions (e.g., reversible capacity measured at a certain C-rate). Additionally, an electrolyte database enables the selection of application-specific electrolyte systems. Overall, the tool allows for the optimization of the VED by systematically adjusting design parameters and maximizing cell can utilization.

We explicitly exclude certain emerging cell concepts - such as zero-excess (“anode-free”) designs and solid-state electrolytes - despite their high potential regarding cost and performance, particularly in the context of NIB systems. While these technologies are highly promising, we exclude them from our analysis due to their low technological maturity and the corresponding lack of reliable data on cell design and fast-charging performance. We acknowledge this limitation and refer readers to the work of Yao et al. [8], who have explored these next-generation approaches in greater depth.

LIB and NIB specific cell design premises

All cells considered are large-format prismatic cells with a volume of 1.03 L, comprising AMs, a separator, an electrolyte, CCs and additional foils and adhesives. The cells are modeled such that up to two electrode stacks can be accommodated within a single cell, each arranged in a Z-stacked configuration to maximize volume utilization in the cell can.

Al-foils are assumed as CCs on both the positive and negative sides for NIBs and on the positive side for LIB cells. For the negative CCs in LFP cells, Cu-foils are modeled. Cu-foil thicknesses of 4.5, 6, and 10 μm are considered, while Al-foils are evaluated at 10, 12, 13, and 15 μm . Although Al-foils thinner than 13 μm are currently uncommon in large-scale industrial production due to the increased risk of foil tearing and web breaks, they are nevertheless considered to capture potential future developments. In general, the different foil thicknesses are included to increase design variability and capture their impact on cost, VED, and charging performance. For all cell configurations, the positive

electrode composition is modeled as > 97 wt% AM, < 2 wt% conductive additive, and < 3 wt% binder. Carbon black is taken as the main conductive additive, and polyvinylidene fluoride (PVDF) dissolved in N-methyl-2-pyrrolidone (NMP) as the binder. Additionally, all positive electrode sheets include an additional boehmite coating at the electrode edges acting as an insulating layer. The negative electrode composition is set to > 96 wt% AM, < 2 wt% conductive additive, and < 4 wt% binder. As the binder we consider a blend of styrene-butadiene rubber (SBR) and sodium carboxymethyl cellulose (CMC), combined with different carbon additives. The cell configurations described reflect commonly adopted designs in current commercial cells.

We account for differences between NIBs and LFP-based LIBs in cell design. In particular, the carbon additive content in the electrodes is guided by the percolation threshold, which depends on the intrinsic electronic conductivity of the AMs, as described in [37]. Consequently, the type and content of the additives differ between both technologies. Furthermore, we employ a dual salt electrolyte system for the NIBs, consisting of sodium hexafluorophosphate (NaPF_6) and sodium bis(fluorosulfonyl)imide (NaFSI) as the conductive salts, as this combination has been shown to improve battery performance [38]. The salts are dissolved in various carbonate-based solvents including propylene carbonate (PC) to ensure the low-temperature performance of the battery. For the LIBs, we employ a lithium hexafluorophosphate (LiPF_6)-based electrolyte also blended in carbonate-based solvents. Regarding the separator, all LFP cells are modelled with a ~ 11 μm separator consisting of polyethylene (PE) as the base film coated with ceramics and polymers on both sides. For the NIBs, a similar separator is considered. However, due to the different electrolyte properties, enhanced wettability is required to ensure uniform and rapid wetting comparable to LIBs. Consequently, we chose a separator that differs in pore size, porosity (which affects the electrolyte volume in the cell), and other related structural properties. Owing to confidentiality constraints, further details on the specific cell design differences between NIBs and LIBs cannot be disclosed. A fixed negative-to-positive (N/P) capacity ratio of 1.1 and an electrolyte filling corresponding to a certain percentage of the pore volume are applied uniformly across all configurations. The variation in areal capacity is subject to optimization (see below), with electrode thickness x being constrained by the upper and lower limits of the slot-die coating process ($15 \mu\text{m} \leq x \leq 120 \mu\text{m}$, after coating and drying).

Modelling of fast-charging

Methodology

The approach used to calculate the fast-charging time for every cell design is based on the methodology developed in [39, 40], which is also implemented in the BatPaC tool developed by Argonne National Laboratory (ANL) [41]. This method enables the positive electrode thickness to be tailored to a target charging time using the area-specific impedance (ASI) and other relevant parameters derived from a reference cell. The charging time for each new cell design and material combination is then calculated via a simplified recalculation of the ASI. We adapted and validated the equations from the BatPaC Tool (version 5.2) [41] such that the charging time is no longer specified as an input parameter but is instead calculated as an output based on the required parameters. Additionally, we define specifications at the pack level for peak power, usable capacity, and minimum state of charge (SoC) based on representative requirements for entry-level BEVs, where NIB systems are expected to be most competitive.

The simplified methodology was chosen primarily for two reasons. First, it represents a balanced approach, weighing model complexity, parameterization effort, and computational cost against achievable accuracy. This was particularly important, as approx. 4,500 designs were modeled in this study. Second, the opening of cells is often not permitted for legal reasons, especially in the case of prototypes, preventing the parameterization of detailed electrochemical models. Such models would be required to monitor the negative electrode potential and temperature evolution during fast-charging to determine the exact charging time as well as the corresponding charging protocol. Consequently, given the inherent complexity of fast-charging, the approach and the derived values should be interpreted as indicative for a given cell design rather than as exact predictions.

Used Data

Regarding the input data required for the methodology, we use own test data from prismatic, automotive-grade NFM/HC and LFP/G cells as references. We employ the measured open-circuit

voltage (OCV) profiles and ASI values, obtained from Hybrid Pulse Power Characterization (HPPC) tests conducted at 25 °C with two distinct pulse durations, as the key input parameters. Since no large-format prismatic cells were available for the NCZNMT/f-HC system, we used the ASI values of the NFM/HC cell as a reference, too. This introduces an inherent uncertainty for the technology, as improvements in material properties, electrode engineering or electrolyte optimization, could result in lower ASI values for the technology. Conversely, based on supplier feedback, an increase in the upper cut-off voltage for NIBs may lead to a higher charge-transfer resistance, which could partially or fully offset these possible improvements. Given the limited availability of experimental data, we accepted this uncertainty.

Multi-objective optimization

For the optimization of the overall system and the coupled tools, we employed the Siemens HEEDS 2210.0 software using a multi-objective trade-off (pareto) optimization approach. For each composition (NFM/HC, NCZNMT/f-HC and LFP/G) across the three scenarios, 500 designs were evaluated, resulting in overall ~ 4,500 simulated cell designs (slightly fewer due to constraint violations rendering some designs invalid). Within this design space, the previously described possible variations in AM combinations, CC thicknesses, and other design parameters lead to further diversity and covered millions of possible cell design combinations. The optimization objectives were defined as maximizing VED while simultaneously minimizing cost and charging time. Key simulation constraints included upper and lower bounds for both positive and negative electrode thicknesses, derived from coating process limitations. The resulting cell designs were then subsequently analyzed, clustered, and visualized.

Disclaimer on the use of AI in the writing process

During the preparation of this work the authors used Microsoft Copilot and ChatGPT for individual sections to improve language and readability. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRedit authorship contribution statement

Jonas Sprengelmeyer: Writing – review & editing, Writing – original draft, Visualization, Conceptualization, Methodology. **Soeren Lukas Dreyer:** Writing – review & editing, Validation. **Marcel Weil:** Writing – review & editing, Validation, Supervision. **Werner Bauer:** Writing – review & editing, Validation, Supervision. **Helmut Ehrenberg:** Validation, Supervision, Project Administration.

Competing Interests Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Disclaimer

The results, model assumptions, parameters, opinions and conclusions expressed in this publication are not necessarily those of Volkswagen Aktiengesellschaft. Specifically, this work aims to contribute to

academic discourse and is therefore deliberately built exclusively on publicly available information. Neither costs nor specifications are those of current and future products and components of Volkswagen Group, its subsidiaries and respective suppliers and partner companies.

Data Availability

The data used in this work can be found in the supplementary information file.

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