VOLKSWAGEN GROUP

KIT Karlsruher Institut für Technologie

Optimizing Cost and Performance of European Sodium- and Lithium-Based Batteries

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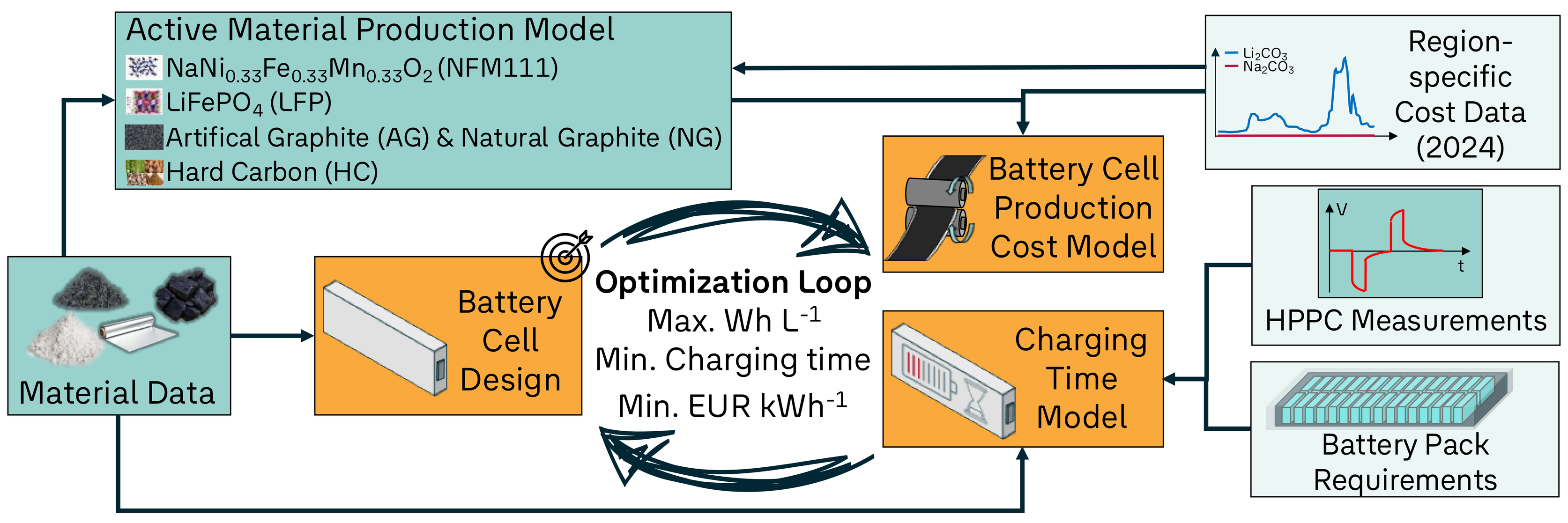
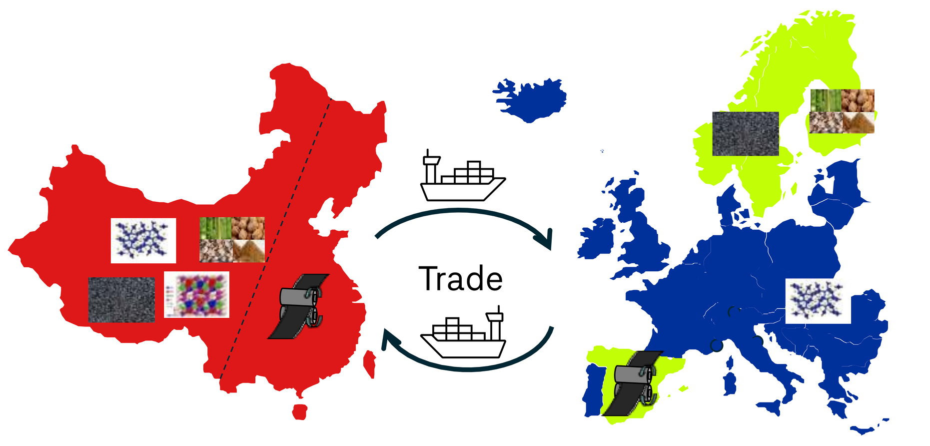
1. Motivation and Goal

- Currently, lithium-ion batteries (LIBs) dominate in battery electric vehicles (BEVs). Among them, $LiFePO_4$ (LFP) has gained significant attention for cost-sensitive applications.
- In parallel, Europe is increasingly focusing on building domestic manufacturing capacities and supply-chain robustness. That could open the door to onshore not just LIBs but also sodium-ion batteries (SIBs), which rely on more abundant raw materials.
- We use a multi-objective optimization framework that combines battery cell design with various cost models and fast-charging analysis to minimize cost and charging time while maximizing volumetric energy density (VED) across different materials, regions, and scenarios.
- **Goal of this study:** To optimize SIB and LFP cell designs to (i) compare the cost and performance across different solutions for Europe under varying value chain scenarios, and (ii) identify key innovation drivers for a representative SIB through sensitivity analysis.

2. Methodology





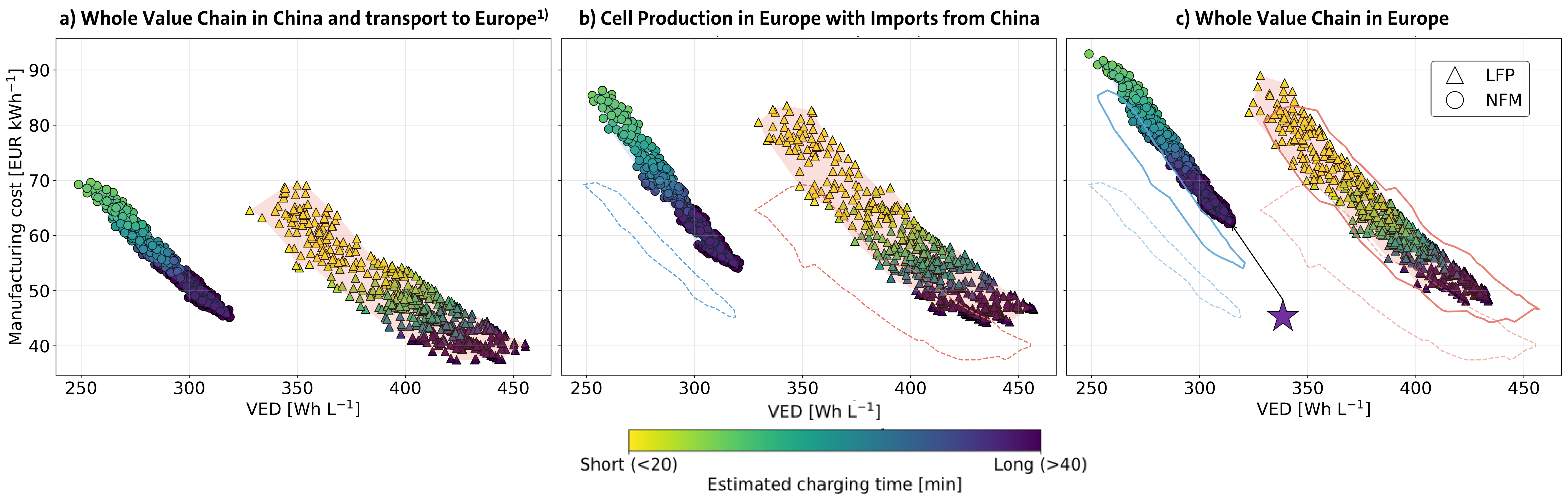
Material Availability in Value Chains

Grade*	High-end	Mid-end	Low-end
LFP	🇨🇳	🇨🇳 & 🇫🇮	
AG		🇨🇳 & 🇳🇴	
NG		🇨🇳 & 🇸🇪	
HC**		🇨🇳 & 🇫🇮	
NFM111	🇨🇳 & 🇭🇺 - no material grades		

*Classified according to compaction density, rev. capacity, etc. Cost models differentiate between grades, e.g., by omitting coating steps for low-end materials or by varying precursors and yields.

**High-end: biomass-based (as of 2025), mid-end: biomass-based, low-end: pitch-based

3. Results



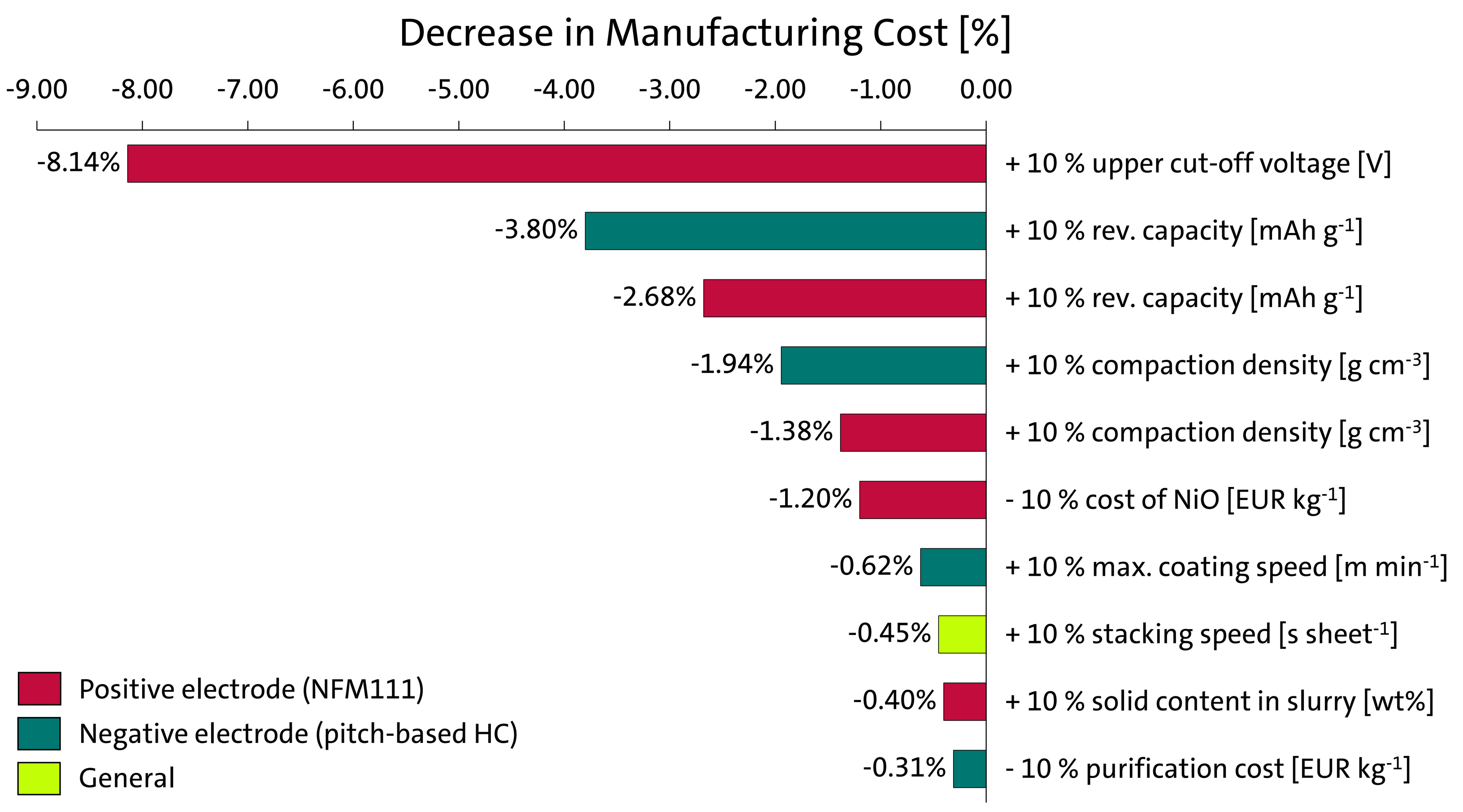
- State-of-the-art NFM is not competitive with LFP in terms of cost, VED, or charging time:
  - ↘ Higher cost due to larger material intensity per kWh and higher active material cost (2024 raw material cost values). Main cost drivers include nickel oxide in the pos. electrode and the precursor and purification for HC.
  - ↘ Lower VED largely from lower volumetric capacity of HC vs. graphite (Δ ~270-300 mAh cm^{-3}).
  - ↘ Longer charging times mainly due to high polarization losses at low SoC levels (10-40 %), restricting the maximum allowable current.

1) It is assumed that the transportation cost of the battery cells is comparable in cost to the transportation cost for active materials.

- Battery cell production in Europe (Spain) with Chinese active material imports increases cost by ~20 % for NFM and ~16 % for LFP.
  - ↘ Cost increases mainly driven by higher costs for energy, labor, and infrastructure.
- Under a fully European battery value chain, costs increase by ~35 % for NFM and ~26 % for LFP compared to a fully China-based production.
  - ↘ LFP cell performance would suffer greatly, with a VED loss of ~26 Wh L^{-1} and a ~3 min[2)] increase in charging time due to the lack of high-end LFP, NG, and AG.
  - ↘ NFM cells shows smaller VED losses of <10 Wh L^{-1} mainly due to consistent positive electrode performance despite the unavailability of high-end HC.

2) The implications for cycle life should also be rigorously investigated.

★ Sensitivity Analysis of Cost-Optimized European NFM



- More than 40 parameters were systematically varied by ± 10 % to identify the ten most influential levers for cost reduction.
- Increasing the accessible upper cut-off voltage of NFM seems straightforward but poses significant challenges such as irreversible phase transitions and electrolyte degradation.

4. Key Messages

- First LFP vs. SIB study to consider charging time as a dimension of cell designs. Even when a given SIB design is cost-competitive against a given LFP design, it charges slower, meaning it is not price-competitive in front of customers. Significant innovations are thus required to improve the competitiveness of SIBs.
- Europe faces a structural trade-off between cost competitiveness and strategic autonomy: the lowest-cost supply relies on cell imports from China, while a full value chain localization increases costs (26-35 %) and reduces performance due to the current absence of a high-end value chain.
- If a high-end LFP and AG value chain cannot be established in the near term, more advanced NFM-based SIBs could gain enhanced strategic relevance for BEVs. A declining industrial focus on NFM in the Chinese SIB market[3)] may even open a strategic window for Europe to leverage existing NCM[4)] expertise and establish leadership in NFM-based SIBs to increase supply-chain robustness.

3) The Chinese SIB market is currently undergoing a transition from NFM towards polyanionic $Na_4Fe_3(PO_4)_2P_2O_7$ (NFPP), which is primarily driven by the evolving safety regulations and growing demand from the stationary battery sector.
4) $LiNi_xCo_yMn_zO_2$

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