From Mine to Second Life: Comprehensive Life Cycle Assessment of Emerging Battery Chemistries

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ABSTRACT

As electric vehicle (EV) adoption accelerates, battery technology choices and end-of-life strategies play an increasingly important role in shaping the environmental footprint of transportation electrification. This study conducts a comparative life cycle assessment (LCA) of four battery chemistries—Lithium Iron Phosphate (LFP), Nickel Manganese Cobalt (NMC), Sodium-Ion (SIB), and Solid-State Batteries (SSB)—using a cradle-to-grave framework that incorporates production, transportation, recycling, and second-life energy storage applications. Two functional units are employed: 1 kWh of nominal battery capacity and 1 kWh of electricity delivered over the battery's full service life, enabling comparison across chemistries with differing durability and degradation characteristics. Environmental impacts are evaluated across multiple categories, including cumulative energy demand (CED), global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), and photochemical ozone creation potential (POCP), using data synthesized from recent peer-reviewed literature and established LCA databases. After excluding the use phase, which penalizes batteries for longer life, results show that production dominates environmental impacts across all chemistries in their first life as an EV, with cathode materials and associated processing representing the largest contributors. LFP batteries exhibit the lowest overall impacts under current conditions, driven by lower material intensity and strong recycling credits, while solid-state batteries show higher production impacts due to energy-intensive manufacturing. SIBs perform less favorably in the near term, reflecting immature recycling pathways and limited recovery of virgin material substitution. These findings, however, change when the lifetime of the battery is considered and SIBs become favorable due to their longevity and ability to defer impacts from production of new batteries. This effect is magnified when batteries are given second-life as energy storage, more than doubling the useful life of the battery. Overall, the findings highlight the critical role of manufacturing choices, recycling infrastructure, longevity, and second-life utilization in determining the environmental performance of current and emerging EV battery technologies.

EXECUTIVE SUMMARY

Electric vehicle batteries are rapidly evolving, with manufacturers pursuing a range of chemistries to balance cost, performance, safety, and supply-chain constraints. At the same time, the first large wave of EV batteries is approaching retirement, making questions about recycling and second-life use increasingly urgent. This study evaluates the environmental performance of four battery technologies—LFP, NMC, sodium-ion, and solid-state—across their full life cycle, including production, transportation, recycling, and repurposing for stationary energy storage.

Our analysis shows that battery production is the dominant driver of environmental impacts for all chemistries. Material processing and cell manufacturing account for the majority of cumulative energy demand and greenhouse gas emissions, far outweighing contributions from transportation. Among the technologies evaluated, LFP batteries consistently exhibit the lowest environmental impacts under current conditions. Their lower reliance on energy-intensive materials and strong recycling credits make them particularly favorable from a life-cycle perspective. NMC batteries show moderate impacts, reflecting higher material intensity but also benefiting from mature recycling pathways that partially offset production emissions.

Solid-state batteries display the highest production-related impacts in most categories, primarily due to energy-intensive manufacturing processes and the use of lithium metal anodes. While these technologies offer performance advantages and long-term potential, their environmental benefits depend on future improvements in manufacturing efficiency and recycling methods. Sodium-ion batteries, although attractive from a resource availability standpoint, initially perform less favorably when impacts are evaluated on a per-kWh-capacity basis. This reflects immature supply chains and the absence of established recycling infrastructure, which currently limit their ability to offset production impacts through material recovery.

Recycling and lifetime extension play a decisive role in shaping net environmental outcomes. Chemistries with established recycling pathways achieve substantial reductions in life-cycle impacts, while emerging technologies without mature recovery systems retain higher overall burdens. Second-life deployment in stationary energy storage further improves environmental performance by extending battery service life and increasing total energy delivered. When impacts are normalized over the full lifetime of the battery—including second-life use—technologies with high durability and long cycle life, particularly sodium-ion batteries, show substantially improved per-kWh-electricity environmental performance, narrowing or reversing differences observed under capacity-based comparisons.

Taken together, these results suggest that near-term environmental gains are most likely to come from improving manufacturing efficiency, durability improvements, and expanding recycling infrastructure for all battery chemistries. At the same time, evaluations that account for total lifetime energy delivery highlight the potential of emerging chemistries such as sodium-ion to achieve competitive environmental performance in applications where longevity and second-life utilization are prioritized. The sustainability advantages of next-generation batteries will therefore depend not only on materials and production processes, but also on system-level design choices that maximize lifetime use and enable effective end-of-life management.

1. INTRODUCTION

ELECTRIFICATION LANDSCAPE

The global electric vehicle (EV) market has grown exponentially since 2016, marking a transformative shift in the transportation sector. According to the International Energy Agency (IEA), more than 20% of new cars sold worldwide in 2024, approximately 17 million vehicles, were either battery electric vehicles (BEVs) or plug-in hybrid electric vehicles (PHEVs) (IEA, 2025). This momentum shows no sign of slowing as the two largest markets, China and the European Union (EU), intensify their commitments to zero-emission mobility targets (Blenkinsop, 2025). The EU, despite ongoing policy debates, remains firmly committed to achieving a fully zero-emission new vehicle fleet by 2035. Emerging regulatory measures, such as stricter corporate fleet purchasing requirements and financial incentives including tax reductions and carbon credit schemes, are designed to accelerate this transition. In parallel, China's EV market continues to expand at an extraordinary pace, supported by its 2060 carbon neutrality pledge and robust domestic manufacturing ecosystem. As a result, the global EV fleet continues to expand, dominated by battery electric vehicles, which now represent over 70% of total EV sales (IEA, 2025).

Despite these advancements, skepticism persists regarding the true environmental benefits of EVs. Critics argue that "zero-emission" claims overlook the substantial carbon footprint associated with battery production and electricity generation for charging. In response, life-cycle assessment (LCA) studies have emerged as a crucial tool to quantify and compare the total environmental impacts of ICE vehicles, PHEVs and BEVs. According to recent IEA data, the total life-cycle greenhouse gas emissions for ICE, PHEV, and BEV configurations are approximately 54.1, 36.9, and 25.0 tCO_2e per lifetime, respectively (IEA, 2025). These values, however, can vary significantly depending on factors such as the regional energy mix, manufacturing processes, and battery chemistry.

ELECTROCHEMICAL TECHNOLOGY

The battery serves as the primary energy source in electric vehicles, enabling propulsion without gasoline. The first EV batteries, developed nearly a century ago, were lead-acid batteries but were eventually surpassed by gasoline-powered vehicles due to their low energy density and limited driving range (Corrigan, 2022). Over the decades, energy density has remained a key driver in the development of battery chemistries. The advent of lithium-ion batteries, a type of nonaqueous electrolyte battery, marked a major breakthrough by providing the high energy density and performance necessary for the large-scale commercialization of electric vehicles (Yoshino, 2022).

Today, lithium-ion batteries dominate the EV market, while next-generation technologies such as solid-state, lithium-oxygen, lithium-sulfur, and sodium-ion batteries are actively being explored for future applications (Zhao et al., 2022). The global battery industry continues to evolve rapidly as demand accelerates and costs decline. In 2024, with electric car sales increasing by 25% to reach

17 million units, annual battery demand exceeded 1 terawatt-hour (TWh) (IEA, 2025). Currently, lithium iron phosphate (LFP) and nickel cobalt manganese (NMC) chemistries lead the EV battery market, together accounting for approximately 94% of global light vehicle production in 2024 (Ali & MacRae, 2024).

In the life cycle of a BEV, production is typically divided into three main units: the vehicle body (glider), the electric axle drive (e-drive), and the battery system. Among these, battery production generates a significant portion of the overall environmental impacts, shifting the burden from the use phase to the manufacturing phase (Koroma et al., 2022). Furthermore, for an average-configured EV, the battery pack is the single most expensive component, accounting for approximately 35%-45% of total manufacturing costs. Given its dominant role in both environmental and cost impact, our study will focus on the battery system as the primary unit for LCA and comparison across different chemistries.

Battery Life and Beyond

Over time and repeated charge-discharge cycles, the capacity and efficiency of traction batteries in EV gradually decline. When these batteries complete their first life in vehicles, they generally retain about 60-80% of their initial capacity (Koroma et al., 2022). Typically, a battery is regarded as no longer suitable for automotive use once its State of Health (SOH) drops to around 80%, indicating it can deliver only 80% of its original energy capacity when fully charged. After reaching this stage, used batteries can follow one of three main pathways: (i) disposal in landfills, (ii) recycling to recover valuable materials such as lithium, nickel, and cobalt or (iii) reuse in second-life applications that have lower energy and power demands (Colarullo & Thakur, 2022). While recycling is a well-established process and an essential part of resource recovery, growing attention has been directed toward extending battery lifespan through repurposing and reuse. Leveraging the remaining capacity of retired EV batteries in stationary energy storage systems (ESS) presents a promising opportunity to reduce overall storage costs, mitigate environmental impacts, and enhance the integration of renewable energy sources into the power grid (Zhu et al., 2021). Furthermore, optimizing End-of-Life (EoL) strategies is critical for minimizing the environmental footprint of the rapidly expanding EV industry and for improving circularity within the battery value chain. Reusing 50% of retired EV batteries for energy storage applications could provide an estimated capacity of 96 GWh by 2030, 3,000 GWh by 2040, and 12,000 GWh by 2050. Efficient recycling of EoL batteries, potentially following extended use in second-life applications, could also decrease the need for newly mined lithium, cobalt, nickel, and manganese by approximately 3% in 2030, 11% in 2040, and 28% in 2050 (Tankou, et al., 2023).

In light of these three EoL scenarios, our study will develop a scenario-based LCA framework to evaluate the environmental and resource implications of different EoL pathways for EV batteries. The outcomes will provide comprehensive life cycle inventories, inform decisions on second-life ESS deployment, guide the selection of efficient recycling technologies, and contribute to the sustainable lifecycle management of battery systems within the EV industry.

2. BACKGROUND

2.1. BATTERY TECHNOLOGIES

The advancement of efficient, high-performance EV batteries depends on optimizing key components, including the anode and cathode electrodes, separators, and electrolytes. For anodes, researchers are investigating carbon-based materials, metal composites, and polymer nanocomposites to achieve higher energy density and capacity. On the cathode side, significant progress has been made in lithium-ion systems, alongside exploration of novel materials for further improvement (Koech et al., 2024).

Within the lithium-ion battery (LIB) family, NMC and LFP chemistries currently dominate the EV market. Building on these established technologies, solid-state batteries (SSBs) are emerging as a promising next-generation solution to the safety issues and energy density limitations of state-of-the-art lithium-ion batteries (Boaretto et al., 2021). At the same time, sodium-ion batteries (SIBs) are attracting attention as a more abundant and potentially lower-cost alternative, offering competitive performance, particularly in cold environments, while reducing dependence on lithium resources.

EV batteries of different chemistries share a similar structure. A typical LIB pack consists of multiple cells, each containing a cathode (positive electrode) made of materials such as LFP, NMC, or LMO, and an anode (negative electrode), usually graphite, both connected to current collectors. A thin polymer separator, commonly polyethylene or polypropylene, insulates the electrodes and prevents short circuits. The cell is filled with a lithium-salt electrolyte, which allows lithium ions to move between the anode and cathode during charge and discharge (Fig. x). The anode and cathode account for most of the material demand. While all LIB cathode chemistries contain lithium, NMC and NCA are rich in nickel and cobalt, whereas LFP and LMFP primarily rely on iron and phosphate (IRENA, 2024).

SSBs differ primarily in that all components are solid. Instead of a liquid electrolyte, SSBs use a solid separator, generally ceramic or solid polymer, which also serves as the electrolyte. The cathode can be made from the same compounds as in LIBs (e.g., LFP, NMC, LMO), while the anode is typically pure lithium metal (Flash Battery, 2022). Due to the uneven global distribution of lithium resources, research has increasingly focused on alternative non-lithium insertion materials (Özsin, 2025). SIBs share a similar overall design but they utilize larger sodium ions as the charge carriers in place of lithium ions. A typical sodium-ion cell features a cathode composed of sodium-based compounds such as layered transition metal oxides, transition metal fluorophosphates, or Prussian blue, an anode often made from hard carbon, and a liquid electrolyte containing dissolved sodium salts in either polar protic or aprotic solvents (He et al., 2024).

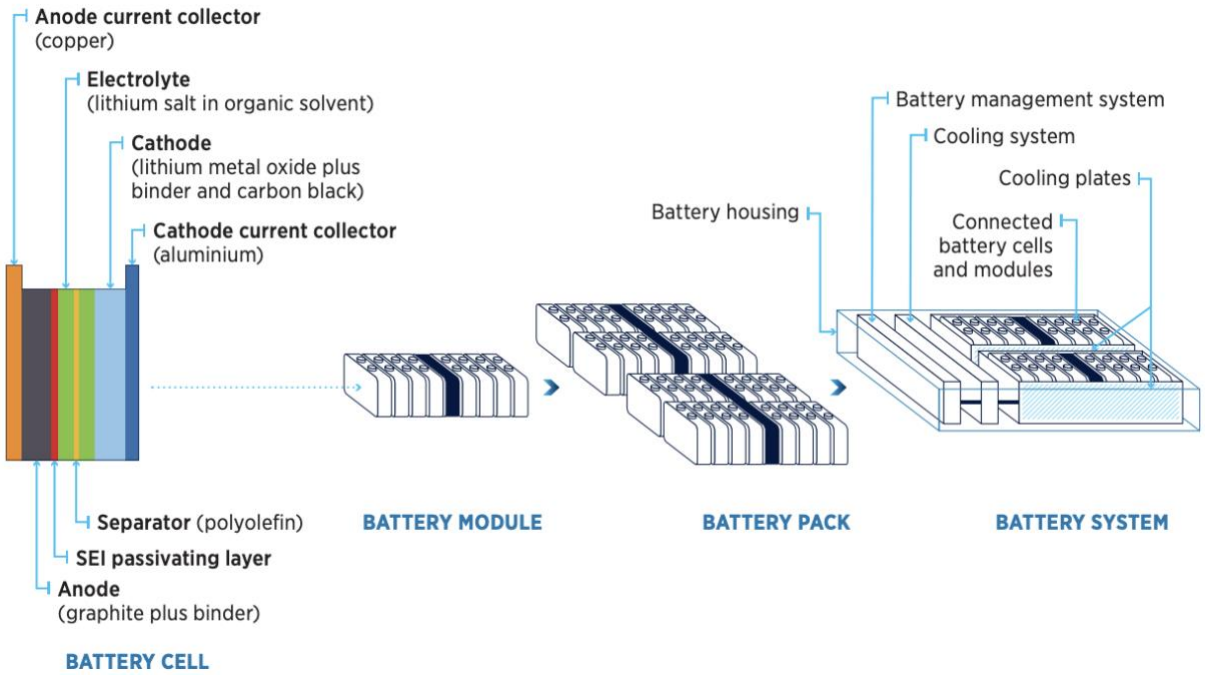


Fig. 1. System Components and Internal Components of a LIB Cell (Gaines et al., 2021)

Table. 1. Typical Cell Structures of Battery Types

	Cathode	Anode	Electrolyte	Distinguishing Features
NMC	$LiNi_xMn_\gamma Co\_zO_2$	Graphite	$LiPF_6$ (liquid)	high specific energy, and relatively high capacity
LFP	$LiFePO_4$	Graphite	$LiPF_6$ (liquid)	good thermal stability, good electrochemical performance, and long lifespan
SSBs	LFP / NMC / LMO	Lithium metal	Oxide/Polymer/ Sulfide/Halide -based (solid)	higher energy density, faster charging, and improved safety
SIBs	Na-layered transition metal oxides / polyanion	Hard carbon	$NaPF_6$ (liquid)	abundant cathode resources, cost savings, and long lifespan

2.1.1. NMC

NMC batteries integrate the advantages of their three key cathode components: nickel, manganese, and cobalt. Nickel contributes high specific energy, which increases the overall storage capacity and energy density at a relatively low cost, though it lacks stability when used alone ((Koech et al., 2024)). Manganese provides a high redox potential and enables two-electron transfer, resulting

in strong specific capacity and energy density. It also improves safety by allowing high current discharge at lower temperatures, which enhances thermal stability and cycle life despite its comparatively low specific energy (Li et al., 2021). Cobalt, on the other hand, are widely utilized in energy storage systems because they stabilize the layered crystal structure of the cathode and further increase energy density (Goudar et al., 2025). Together, these elements create a balanced chemistry that combines high energy density with strong structural stability. This layered oxide cathode supports high voltage and capacity, achieving pack-level energy densities typically between 150 and 250 Wh/kg (Evlithium, 2025), and often exceeding 200 Wh/kg (Greenwood et al., 2021).

The cost of NMC batteries generally ranges from USD 100 to 130 per kWh, with an average cycle life of approximately 1,000 to 2,000 cycles. According to the International Energy Agency (IEA, 2024), NMC chemistries continue to dominate battery markets in Europe and North America, particularly for premium and long-range electric vehicles. However, their dependence on cobalt and nickel contributes to higher production costs and exposes manufacturers to supply chain risks (Phogat et al., 2025). To mitigate these challenges, current research is directed toward developing high-nickel and cobalt-free formulations that maintain performance while reducing reliance on critical materials. The progression of NMC technology illustrates this transition. Early generations, such as NMC 111, used equal parts nickel, manganese, and cobalt. As performance requirements grew, improved formulations like NMC 532 and NMC 622 were introduced (Lee, 2025). The most recent advancement, NMC 811, features a substantially higher nickel concentration, can deliver high capacities of 195 mAh/g, which is integral to achieving the range of around 500 km, satisfying consumers' driving demand (Tran et al., 2023).

However, the primary drawback of nickel-rich NMC batteries lies in their structural instability, which leads to capacity fading during repeated charge and discharge cycles. Such instability can result in the formation of oxygen vacancies, microcracks, and phase transformations that progressively deteriorate performance. While density functional theory (DFT) and experimental studies have explored these degradation pathways, a comprehensive understanding of the phase stability mechanisms is still lacking (Tran et al., 2023). Moreover, high-nickel cathodes are thermally less stable (Greenwood et al., 2021), posing safety concerns such as thermal runaway. When exposed to elevated temperatures (above 150 °C), internal heat accumulation triggered by mechanical stress, overcharging, or electrolyte reactions can initiate exothermic decomposition of the cathode material, separator collapse, and even combustion (Cui & Manthiram, 2023).

2.1.2. LFP

Unlike NMC batteries, which rely on nickel-manganese-cobalt oxides, LFP batteries use a lithium-phosphate compound as the cathode (Wikipedia, 2025). Compared with other lithium-ion chemistries, LFP benefits from the abundance and low cost of its primary elements, iron and phosphorus, which are readily available natural resources. LFP cells are more than 20% cheaper than NMC cells, with the average price of an LFP cell just below $60 per kWh in 2024 (S&P Global Mobility, 2025). Also, this chemistry is well regarded for its superior thermal stability, long cycle life, low toxicity, and consistent performance across a wide range of temperatures (Zhao et al., 2024). The strong Fe-O and P-O bonds within its olivine crystal structure provide exceptional structural stability, ensuring safety and durability during cycling (Wang et al., 2022). In contrast

to layered oxide cathodes like NMC, where polar TM-O bonds can break and release oxygen, LFP's stable framework prevents such degradation.

However, the phospho-olivine structure has inherent drawbacks, most notably its poor electronic conductivity, which restricts electrochemical performance (El Moutchou et al., 2022). LFP batteries typically exhibit an energy density of about 140–160 Wh/kg and operate at voltages below 3.4V. They are also prone to higher self-discharge rates, particularly at elevated temperatures or when electrolyte additives are insufficient (Buechele et al., 2023). In most recent advancements, LFP systems could be enabled to reach specific energies of up to approximately 200 Wh/kg while maintaining cycle lives of 4,000-5,000 cycles (Chen et al., 2024).

Owing to these characteristics, LFP batteries are commonly used in low- to medium-range EVs, where durability and environmental performance are prioritized. While their energy density is generally lower than that of NMC batteries, limiting suitability for long-range or cold-climate applications, recent improvements have made LFP technology sufficient for most EV applications, further strengthening its competitiveness (IEA, 2025). By 2024, LFP accounted for over 40% of global EV battery capacity (IEA, 2024), making it one of the most widely adopted technologies, although NMC batteries remain dominant in the United States and Europe.

2.1.3. SOLID-STATE

SSBs are attracting global attention as a promising advancement in both safety and performance. Unlike conventional lithium-ion batteries that rely on flammable liquid electrolytes, SSBs employ solid ionic conductors, such as sulfide or oxide materials, to transport lithium ions (Joshi et al., 2025). Coating the cathode surface with a solid electrolyte that has a high ionic conductivity has been shown to hold potential for solving the intrinsic oxygen-released problem of oxide cathode materials (Yu et al., 2023). Also, this design enables the use of lithium-metal anodes, which can achieve energy densities typically in the range of 350-400 Wh/kg (Melançon, 2024), significantly higher than traditional lithium-ion cells. According to the IEA (2024), current SSB prototypes reach 200-300 Wh/kg and are anticipated to enter limited commercial production between 2028 and 2030. SSBs have demonstrated proven durability, with large-format cells achieving over 1,000 charge cycles while retaining more than 80% of their capacity, validating the technology's potential for commercialization (ION Storage Systems, 2025).

Despite these advantages, SSBs face challenges related to manufacturing complexity, stringent material purity requirements, and interface resistance, which make them currently two to three times more expensive than conventional lithium-ion systems (Phogat et al., 2025). Nevertheless, ongoing improvements in solid electrolyte conductivity and interface engineering are gradually bridging this gap. Presently, solid-state batteries cost between $400 and $600 per kWh (ViBMS, 2025), with projected reductions to $150-200 per kWh by 2030 as production scales up.

2.1.4. SODIUM-ION

SIBs operate through similar intercalation mechanisms as lithium-ion batteries, but use layered oxide or polyanionic compounds as cathodes and hard carbon as the anode (Yao et al., 2024). Owing to the abundance and low cost of sodium resources, along with their strong recyclability, SIB technology presents a cost-effective alternative in applications where affordability is

prioritized over achieving the highest energy density (Abdolrasol et al., 2025). According to the IEA (2024), pack-level costs for Na-ion batteries could fall below 60 USD per kilowatt-hour by 2030, representing nearly a 40 percent reduction compared with lithium-ion systems. And that makes them highly competitive for short-range EVs and stationary energy storage. In addition, Na-ion batteries eliminate dependence on critical minerals such as lithium, nickel, and cobalt, which contributes to a 30 percent lower supply-chain greenhouse gas intensity (IEA, 2025).

Based on the reversible capacities of different sodium-intercalating metal oxide and metal phosphate cathode materials, it is estimated that sodium-ion cells employing these cathodes in combination with hard-carbon anodes can achieve specific energies of up to approximately 150 Wh/kg, comparable to lithium-ion cells that use $LiFePO_4$ cathodes. (Abraham, 2020). Recent studies have also demonstrated that solid-state Na-ion systems can achieve high ionic conductivity and stable interfacial performance, improving both safety and durability (Song et al., 2025). With these advantages, sodium-ion batteries are emerging as a viable and environmentally responsible option for the next generation of affordable energy storage technologies (Phogat et al., 2025).

Table. 2. Key Performance Metrics for Different Battery Technologies

	Output Voltage (V)	**Pack-level Specific Energy (Wh/kg)**	**Cycle Life (cycles)**	**Cost (USD/kWh)**	**Limitations**
NMC	3.0-4.2 (usually 3.7)	150-250	1,000-2,000	90-120	structural instability; thermal runaway risk; high material cost
LFP	<3.4	140-160	3,000-5,000	~60-100	low energy density and voltage limitation
SSBs	>4.5	350-400 (current prototypes)	1,000+ (prototype)	400-600 (current)	manufacturing complexity; interfacial instability
SIBs	3-3.6	100–160	3,000-4,000	<60 (projected)	low energy density and voltage limitation

2.2. End of Life Management

Over a lifespan of 5-10 years operating within an electric vehicle, batteries often experience more than 1,000 partial charge and discharge cycles, endure wide temperature variations from -20°C to 70°C, and face demanding conditions such as deep discharge levels and high charging/discharging rates (Zhu et al., 2021). Once an EV battery pack can no longer meet the vehicle's performance requirements, it is typically removed, signaling the end of its service life in automotive use. The U.S. Advanced Battery Consortium (USABC) introduced a widely accepted retirement criterion in 1996, recommending replacement when the battery's capacity drops by 20% from its original value. However, this threshold has become increasingly debatable as modern batteries achieve

significantly higher capacities, and because optimal retirement criteria may vary across different battery chemistries (Zhu et al., 2021).

By 2030, around 1.2 million batteries from light- and heavy-duty BEVs and PHEVs are expected to reach end-of-life globally, increasing to 14 million by 2040 and 50 million by 2050 (Tankou, et al., 2023). Potential options for retired EV batteries (REVB) after reaching EoL include disposal, recycling, and repurposing. If REVBs are discarded directly, they enter municipal solid waste (MSW) streams, contributing significant undesirable waste to landfills. Improper disposal can pose serious environmental risks, as these batteries contain heavy metals and hazardous chemicals. Leakage or soil infiltration of battery toxins can contaminate land and water, threatening the habitats of countless organisms (Al-Alawi et al., 2022). A more sustainable alternative is recycling, which focuses on recovering valuable materials, particularly from the battery electrodes, for use in new battery production. One study projected that 1.3 million metric tons of LIB waste from EVs could generate approximately three billion USD in commodity value, assuming full collection and recovery of metals such as aluminum, copper, nickel, cobalt, iron, and steel (Richa et al., 2014). Recycling is essential for conserving critical resources, and has increasingly become the preferred option for managing batteries at the EoL stage. The European Commission's updated 2025 regulations on Mandatory Recycling Efficiency Targets require that all REVB be processed through certified channels. By 2025, at least 65% of lithium and 70% of nickel and cobalt must be recovered from battery waste (Welter, 2025). In the United States, battery recycling is governed by federal frameworks such as the Resource Conservation and Recovery Act and the Universal Waste Rule, with significant variation across states, alongside federal research initiatives such as the ReCell Center developing improved recycling technologies. California has adopted stricter requirements, including producer take-back programs and financial incentives for recycling (Machín et al., 2024). Another viable EoL route for REVB is repurposing, where battery modules are reconfigured to serve less demanding applications, such as stationary energy storage. These energy storage systems (ESS) improve the flexibility and reliability of renewable energy systems by mitigating the intermittency between energy generation and consumption over time (Guo et al., 2020).

2.2.1. RECYCLING

The industrial recycling of LIBs generally involves several key steps: collection, sorting, handling, processing, and distribution. Spent LIBs, whether sourced directly from EoL EVs or from second-life applications, are typically processed using three main approaches: pyrometallurgy, hydrometallurgy, and direct recycling (Beaudet et al., 2020). Pyrometallurgy involves heating batteries to very high temperatures (around 1500 °C) to melt them and burn all carbon-based materials. This process yields a Co-, Ni-, and Mn-rich alloy that can subsequently be processed hydrometallurgically to recover individual metals. A key advantage of pyrometallurgy is that it reduces the need for extensive battery handling, eliminating crushing and other pre-treatment steps (Larouche et al., 2018). However, other battery components, such as electrolytes, graphite, steel, aluminum, and lithium, are lost as slag or emissions. In addition, costly gas treatment systems are required to prevent the release of toxic compounds.

Hydrometallurgical recycling focuses on extracting metals from batteries by dissolving them in acidic solutions. To enable this, batteries are first dismantled and crushed, with materials like steel, aluminum, and copper foil separated for recovery. One of the main strengths of hydrometallurgy

is its efficiency in reclaiming lithium, often through precipitating lithium carbonate after purifying the leachate. Because of its ability to recover lithium and other valuable metals with relatively high efficiency, hydrometallurgy is increasingly seen as a leading approach for sustainable battery recycling (Beaudet et al., 2020). In contrast, direct recycling of LIBs is a process that regenerates and reuses battery components like the cathode material without breaking down their chemical structure, but the potential for fully restoring the initial cathode capacity is yet to be proven.

Table. 3. Comparison of main recycling methods (Beaudet et al., 2020)

Recycling Method	Advantages	Disadvantages
Pyrometallurgy	● Flexible; applicable to any battery chemistry and configuration ● No sorting or other mechanical pre-treatment necessary ● High recovery of metals (e.g., Co, Ni, and Cu) ● Proven technology	● Cannot recycle Li, Al, or organics ● Cannot treat LFP batteries ● Expensive gas clean-up is required to avoid toxic air emissions ● Energy and capital intensive ● Further refinement is necessary to produce elemental metals
Hydrometallurgy	● Applicable to any battery chemistry and configuration ● Flexible in separation and recovery processes to target specific metals ● High recovery rates for lithium ● High purity of products ● Energy efficient ● No air emissions	● Battery cells must be crushed ● Acid breaks down cathode structure ● High volume of process effluents to be treated or disposed ● Not economical for LFP batteries ● Anode materials are not recovered ● High operating cost
Direct recycling	● Retains valuable cathode structure ● Practically all battery materials can be recovered, including anode, electrolyte, and foils ● Suitable for LFP batteries ● Energy efficient ● Convenient for recycling manufacturing scraps	● Complex mechanical pre-treatment and separations are required ● Recovered material may not perform as well as virgin material ● Regeneration processes yet to be developed ● Not scaled up to industrial level

Large-scale recycling of lithium-ion batteries is still an emerging industry, lacking the established supply chains, standardized products, and safety protocols needed to handle the increasing volume of EV batteries approaching EoL. A key issue with LIBs recycling is that there is substantial variation in the cathode materials used in commercial LIBs, with at least five major chemistries in circulation and many EV cells incorporating blended cathodes that combine multiple materials. Ongoing innovation in cathode design will only expand this diversity, creating a highly heterogeneous waste stream for recyclers. Because the supply chain for recyclers fluctuates

significantly and includes LIBs with many different cathode (and other) materials, if a recycler cannot recover pure and consistent material, the resulting market value of the recovered products becomes lower and more uncertain (Chen et al., 2019). Nevertheless, the sector is expanding rapidly, with companies like Redwood Materials scaling up to meet the anticipated demand from over five million EVs currently on the road (Redwood Materials, 2025). While rare earth metals are expected to achieve near-complete recycling rates, other battery materials may still be lost through incineration or disposal during the recycling process.

Although SSBs and SIBs are still in early stages of commercialization, it is important to implement recycling-friendly design strategies from the outset. For SSBs, the main differences from conventional LIBs lie in their anode structures and the use of solid rather than liquid electrolytes. Many SSB designs use lithium metal anodes, which provide high energy density but are highly reactive, creating added challenges for recycling. Because SSBs often use cathode materials similar to those in LIBs, existing recycling, resynthesis, and reconditioning processes can still be applied to recover cathode active materials (Ahuis et al., 2024). However, unlike LIBs, solid electrolytes in SSBs cannot be easily separated from electrode materials, resulting in complex material mixtures that complicate recycling. One proposed approach is to mechanically process batteries into a homogeneous black mass, which can then be treated using existing LIB recycling methods. At the same time, the recoverability of solid electrolytes depends on their chemistry. Oxide- and, to some extent, polymer-based electrolytes are more compatible with conventional hydrometallurgical processes, while sulfide- and halide-based electrolytes are better suited to direct recycling approaches, such as dissolution and recrystallization (Jacob et al., 2024).

For SIBs, although SIBs have an economic value about 30-40% lower than that of LIBs, they still contain valuable metals like nickel, copper, manganese, and fluorine, making recycling a more environmentally favorable alternative to mining and remain potentially economically viable. Pyrometallurgical processes are generally more suitable for SIBs than for LIBs because sodium is less prone to volatilization during high-temperature treatment and is less critical to recover given its natural abundance. SIBs also allow easier physical separation, since the current collectors, casing, and tabs contain only aluminum, whereas LIBs include copper, aluminum, and nickel. (Zhao et al., 2023).

2.2.2. SECOND-LIFE ESS

Reusing batteries before recycling them extends the lifespan of materials much more effectively than recycling alone, and current evidence suggests that recycling lithium-ion batteries is often not economically viable. Typically, batteries entering their second life retain about 80% of their original capacity. According to the Energy Storage World Forum, second-life batteries (SLBs) can be integrated into energy storage systems (ESS) serving a wide range of applications for both grid operators and behind-the-meter users. As a result, many Original Equipment Manufacturers (OEMs) have started their own second-life programs or partnered with companies like Spiers New Technology to repurpose retired batteries for use in ESSs (Horesh et al., 2021). At the grid level, ESS can provide services such as energy arbitrage, flexible peaking, frequency regulation, reserve capacity, and transmission deferral. Behind the meter, they can support time-of-use energy management, increased solar self-consumption, demand charge reduction, and backup power supply (Haram et al., 2021).

Before retired EV batteries can be deployed in energy storage applications, they typically undergo several processes, like a reconditioning process. One emerging approach of reconditioning is the Heterogeneous Unifying Battery (HUB) system, which improves SOH uniformity across cells within a battery module without requiring the module to be dismantled (Horesh et al., 2021). Therefore, repurposing retired EV batteries for ESS also entails additional environmental and operational impacts, including those associated with transportation, performance testing, and the extra hardware needed for grid integration — such as inverters (Cusenza et al., 2019).

Studies indicate that SLBs can operate for up to six years in ancillary services and as long as fifteen years in network deferral applications (Strickland et al., 2014). However, the optimal residual capacity defining the end of a battery's second life remains under debate. Extending the EoL threshold has been shown to substantially increase SLB lifespan, while reducing the depth of discharge (DOD) can further enhance longevity. For instance, batteries cycled at 50% DOD with a 60% EoL threshold remained functional for up to sixteen years, compared to only four years under 80% DOD and 70% EoL conditions (Mathews et al., 2020).

2.3. LCA Framework of EV Batteries

Life Cycle Assessment provides a systematic and quantitative framework for evaluating the environmental impacts of EV batteries across all life-cycle stages under a cradle-to-grave perspective. According to ISO 14040 and 14044 standards, the four-phase LCA framework outlined below enables a comprehensive assessment of environmental impacts and opportunities for improvement throughout the EV battery life cycle:

(1) Goal and scope definition, which establishes the purpose, boundaries, and functional unit of the study;

(2) Life cycle inventory (LCI), which quantifies all relevant energy and material inputs and environmental releases;

(3) Life cycle impact assessment (LCIA), which translates inventory data into potential environmental impacts such as global warming potential, resource depletion, and human toxicity;

(4) Interpretation, where results are analyzed to derive insights, evaluate uncertainty, and support decision-making.

2.4. Available LCA Studies of EV Batteries

Dai et al. (2019) conducted a cradle-to-gate LCA of NMC111 lithium-ion batteries, integrating multiple updates to LCI data that reflect the latest industry information. Their system boundary spanned from raw material extraction to the final production of the battery pack at the factory. All upstream processes, such as mineral extraction, refining to battery-grade materials, and component manufacturing, were modeled through GREET's cradle-to-gate inventories. Using the GREET 2018 model, the study assumed battery manufacturing occurred in the United States and relied on the 2017 national electricity grid mix. To cross-compare emission intensities, the authors also referenced Ecoinvent 2.2 and 3.1 for selected battery materials. Argonne's BatPaC model was employed to define the bill of materials at the cell, module, and pack levels. The functional unit was 1 kWh of battery capacity, though per-kilogram results were also reported to account for variability in pack design and configuration. Environmental metrics evaluated include total energy

demand, greenhouse gas emissions, and criteria air pollutants such as NO_x, SO_x, and particulate matter.

Their findings showed that the extraction and processing of battery materials account for a larger share of total energy use and environmental impacts than the stages of cell manufacturing or pack assembly. In particular, the production of active cathode materials, the use of aluminum, and the electricity consumed during cell fabrication emerged as the dominant drivers of cradle-to-gate impacts for NMC111 batteries. In contrast, module and pack assembly which were assumed to be manual, contributed negligible environmental burdens, consistent with findings from Ellingsen et al. and Kim et al.

Quan et al. (2022) examined a comparative cradle-to-grave LCA of LFP and NMC batteries. The analysis used a functional unit of a 1 kWh nominal-capacity battery pack and included five major phases: production, first use, repurposing, secondary use, and recycling. Transport between phases was excluded. The production phase encompassed material extraction and processing, such as cathode fabrication and lithium mining and refining. The first-use phase modeled battery operation in electric vehicles, accounting for charging inefficiencies and the increased vehicle energy demand associated with battery weight. In the repurposing phase, the authors assumed that only selected components, not entire modules or cells, would be replaced or refurbished. During the secondary-use phase, retired batteries were modeled as serving in stationary energy storage systems, specifically communication base stations, consistent with China's cascade-utilization policy. Background data for the assessment were sourced from the Ecoinvent, GREET, and GaBi databases, while foreground parameters were derived from published literature and industry reports. All life cycle stages were assumed to take place in China under the 2016 national electricity mix.

They found that LFP batteries exhibit higher resource depletion and environmental emissions than NMC chemistries. Their results also indicated that hydrometallurgical recycling offers superior environmental performance compared with direct physical recycling. Across the entire life cycle, the production, first use, and secondary use stages were identified as the dominant contributors to environmental impacts, and improvements in charge-discharge efficiency were shown to substantially mitigate these burdens.

SSBs are still in early development, and existing prototypes differ widely in electrolyte and cathode chemistry. Keshavarzmohammadian et al. (2018) examines the environmental impacts associated with manufacturing a laboratory-scale pyrite-based SSB. Because this technology remains experimental, reliable data on in-use performance and end-of-life management are not yet available. As a result, their analysis incorporates several assumptions about operational characteristics, including battery lifetime. Due to the lack of established durability data, the pyrite battery is assumed to last for the full service life of an electric vehicle, requiring only one 80-kWh battery pack (rated at 100 kW power) over the vehicle lifetime. In the modeled design, the cell uses pyrite (FeS_2) as the cathode material, a lithium metal anode, and a Li_2S-P_2S_5 solid electrolyte. The assessment was performed in SimaPro (version 8.4) using the US-EI 2.2 life cycle inventory database. Environmental impacts were characterized using the TRACI v1.02 methodology

They suggest that contributions from upstream raw material extraction can be relatively modest for SSB chemistries, with mining of pyrite having a negligible contribution to the impacts of cathode paste, while the majority of embodied energy and environmental impact tends to originate

from cell production processes and the electricity mix supplying the manufacturing facility. The major processes in cell manufacturing with considerable energy consumption include cathode and electrolyte preparations, coating and calendering, pouch forming, and the operation of the clean dry-room. Similar to conventional LIBs, clean dry room operation is a major energy driver, but the stricter moisture requirements for solid electrolytes make this even more critical for SSBs. As a result, the dry-room can account for 96% direct energy consumption during manufacturing.

Degen et al. (2025) present a comparative cradle-to-gate LCA of the four battery chemistries examined in our study, including multiple NMC variants, focusing exclusively on the production phase and using a functional unit of 1 kWh of battery cell capacity. Their assessment draws on primary data from a commercial battery cell factory, teardown analyses, established LCA databases, and published literature. For sodium-ion batteries (SIBs), the authors model NaNFM442 as the representative cathode chemistry due to its favorable energy density characteristics and relatively low nickel content. For solid-state batteries (SSBs), they use an NMC900 cathode paired with an oxide-based solid electrolyte, reflecting one of the more mature SSB design pathways currently under development. The impact assessment is performed using the ReCiPe 2016 methodology.

Across chemistries, NMC cells with higher nickel content showed lower overall environmental burdens due to reduced cobalt content and improved energy density, while LFP exhibited lower material toxicity but higher per-kWh impacts when energy density penalties were included. The examined SIB cell demonstrated competitive or lower impacts in several categories because it avoids cobalt, copper, and graphite, although its climate-change impact fell between mid- and high-nickel NMC chemistries. The assessed SSB cells had impacts comparable to or slightly higher than conventional LIBs, primarily driven by lithium-metal anodes rather than the solid electrolyte itself. The study also underscored that often-overlooked components, such as copper foil and NMP solvent, are major contributors to environmental damage and are not consistently accounted for in existing LCAs.

Table. 4. Summary of existing LCA studies for the EV battery chemistries evaluated in this study.

Reference	Battery Chemistry	System Boundary and Regional Scope	Battery Size	Specific energy (Wh/kg)	Method of impact assessment	Functional Unit

Dai et al. (2019)	NMC111	Cradle-to-Gate; U.S.-based battery production with a global upstream supply chain	165 kg	197 Wh/kg at the cell level; 143 Wh/kg at the pack level	N.A. (midpoint only)	1 kWh capacity (also results per kg)
Accardo et al. (2021)	NMC111	Cradle-to-Grave including recycling; Production modeled mostly with global averages, electricity mix China for manufacturing and EU for use and recycling	226 kg	155Wh/kg	CML v4.7	1 kWh capacity (also results per kg)
Quan et al. (2022)	LFP; NMC111	Cradle-to-Grave including repurposing, secondary use (ESS), and recycling; Entire lifecycle assumed to occur in China using China grid mix	203 kg (LFP) 165 kg (NCM)	116Wh/kg (LFP) 143 Wh/kg (NMC)	CML 2001	1 kWh capacity
Keshavarzmohammadian et al. (2018)	SSB (FeS_2+TiS_2-Li metal)	Only production stage included; Prospective U.S.-based battery production	440 kg	182 Wh/kg	TRACI v1.02	1 kWh capacity
Pell et al. (2021)	SSB (NMC811/ LFP-Li metal)	Cradle-to-Gate; EU-based production with a global upstream supply chain (transportation excluded)	300 kg	400 Wh/kg (NMC811 cathode) 250 Wh/kg (LFP cathode)	Minviro internal model	1 kWh capacity
Guo et al. (2023)	SIB (Na-layered transition metal oxides-hard carbon); LFP	Cradle-to-Grave including repurposing, secondary use (CBS), and recycling; Entire lifecycle assumed to occur in	558 kg (SIB) 600 kg (LFP)	102Wh/kg (SIB) 95Wh/kg (LFP)	ReCiPe 2016	1 kWh capacity

		China using China grid mix				
Degen et al. (2025)	SIB (NaNFM442-hard carbon); SSB (NMC900-Li metal); NMC532; NMC622; NMC811; NMC900; LFP	Cradle-to-Gate; Not specific for supply chain and electricity scenarios	N.A.	170Wh/kg (SIB); 430Wh/kg (SSB); 230Wh/kg (NMC532) 240Wh/kg (NMC622); 290Wh/kg (NMC811); 330Wh/kg (NMC900); 200Wh/kg (LFP)	ReCiPe 2016	1 kWh capacity
Lai et al. (2023)	SIB (NaMMO/NaNMC/NaNMMT/NaPBA/NaMVP-hard carbon); NMC532; NMC622; NMC811; NMC111; LFP	Cradle-to-Gate; Not specific for supply chain, electricity scenarios modeled for China, US, Japan, Germany and Switzerland	N.A.	133.5Wh/kg (NaMMO); 115.9Wh/kg (NaNMC); 146.1Wh/kg (NaNMMT); 105.5Wh/kg (NaPBA); 129.6Wh/kg (NaMVP); 170Wh/kg (NMC532); 180Wh/kg (NMC622); 200Wh/kg (NMC811); 160Wh/kg (NMC111); 140Wh/kg (LFP)	ReCiPe	1 kWh capacity (also results per kg)

2.5. Identified Literature Gaps

Despite the growing body of research on battery environmental performance, several important gaps remain. First, there is still limited life-cycle assessment work for emerging chemistries such as sodium-ion and solid-state batteries. Most existing studies rely on partial datasets or proxy materials, meaning that environmental impacts for these technologies are not yet well understood. In addition, the rapid pace of innovation in cell design, manufacturing methods, and material

sourcing means that many published LCAs become outdated quickly, even when they are methodologically sound.

A second gap concerns consistency. Studies often use different system boundaries, functional units, electricity mixes, and end-of-life assumptions, making it difficult to compare results across chemistries in an “apples-to-apples” way. This is compounded by the limited availability of real-world data from retired EV batteries. Because large EV fleets have only recently begun aging into retirement, we still know relatively little about actual degradation patterns, second-life suitability, or realistic recycling outcomes.

There is also substantial uncertainty in many lifecycle assumptions. Battery lifetime, degradation rates, charging behavior, and operating conditions vary widely across users and climates, yet many LCAs must rely on simplified or generalized parameters. Finally, most existing work treats EV applications and stationary energy-storage applications separately, even though many batteries will move from one to the other. Few studies model the full combined first-life and second-life environmental footprint in a unified framework, leaving a gap in understanding the true long-term impacts of battery technologies.

3. GOAL

3.1. PROBLEM STATEMENT

As electric vehicle adoption accelerates and the first major wave of EV batteries approaches retirement, understanding the full environmental implications of different battery technologies has become increasingly urgent. The rapid pace of technological change along with inconsistent system boundaries, limited end-of-life data, and scarce cradle-to-grave assessments for emerging chemistries has created substantial uncertainty in the literature. At the same time, automakers continue to explore new battery designs that promise lower costs, higher performance, faster charging, and improved safety. Because each battery chemistry carries distinct trade-offs, the future EV market is unlikely to converge on a single dominant technology; instead, it will likely diversify, with different chemistries serving different applications.

This study aims to address several of the most pressing gaps in the existing research. Specifically, we evaluate the cradle-to-grave environmental impacts of two widely commercialized lithium-ion chemistries—Lithium Iron Phosphate (LFP) and Nickel Manganese Cobalt (NMC)—alongside two emerging alternatives: Solid-State Batteries (SSB) and Sodium-Ion Batteries (SIB). We also assess two major end-of-life pathways, direct recycling and second-life reuse in stationary energy storage, both of which are understudied but increasingly relevant as EV batteries reach retirement age.

The goals of this study are threefold: (1) to construct complete life cycle inventories (LCIs) for four representative EV battery chemistries across production, use, and end-of-life stages; (2) to compare their environmental performance across multiple impact categories using a consistent, cradle-to-grave framework; and (3) to evaluate the environmental implications of alternative end-of-life strategies and offer guidance for selecting scalable, sustainable recycling or repurposing pathways.

By filling gaps related to emerging chemistries, inconsistent boundaries, and limited end-of-life data, this study provides evidence that can inform policy design, manufacturing practices, supply-chain decisions, and future investment in EV and second-life battery technologies.

3.2. QUESTIONS TO ANSWER

1) How do the environmental impacts (Global Warming Potential, Toxicity, Land and Water Use) compare across four battery chemistries: Lithium Iron Phosphate (LFP), Nickel Manganese Cobalt (NMC, NCM), Solid State, and Sodium Ion?
2) To what extent does the choice of end-of-life strategy (recycling, or second-life applications) alter the overall environmental profile of each battery type?
3) How do unique characteristics of each chemistry such as materials availability, energy density, or durability over time impact the lifetime environmental impacts of EV batteries?

4) How does local energy mix affect the Global Warming Potential of each battery chemistry and lifecycle stage?
5) Do newer technologies (Solid State, Sodium Ion) offer environmental benefits over established technologies (LFP, NMC)?

4. SCOPE

4.1. LIFE CYCLE PHASE

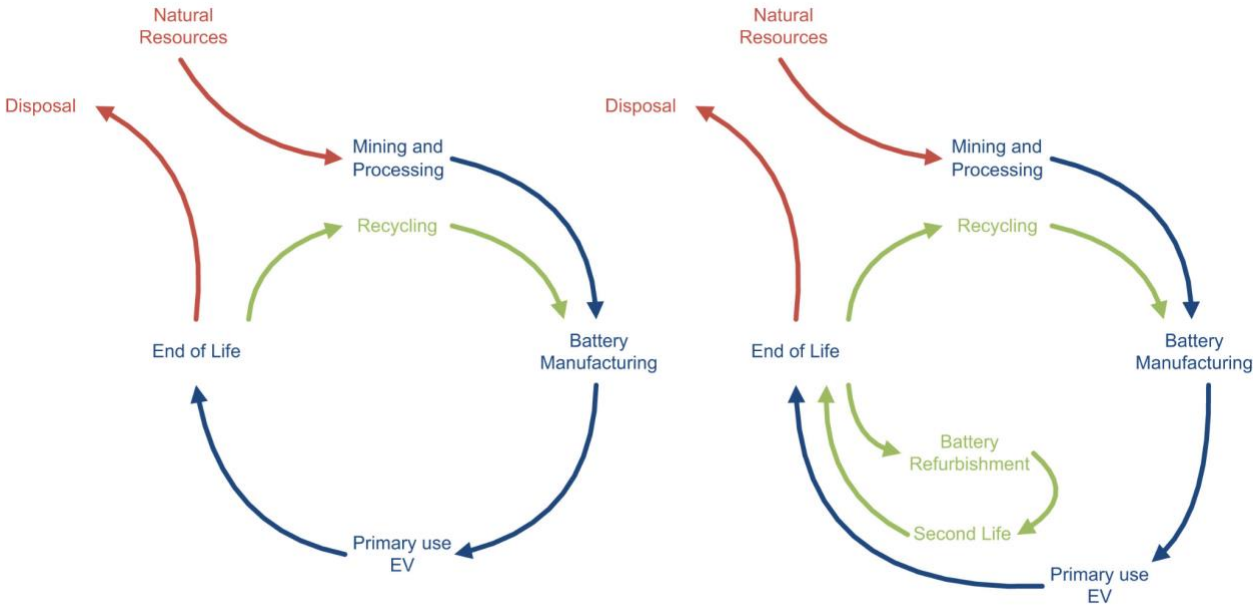


Fig. 2. Diagram of Life Cycle of EV Batteries (Ambrose, 2020)

4.1.1. BATTERY MANUFACTURING

Mining: The first stage in the EV battery life cycle involves the extraction of raw minerals and metals, most notably lithium, nickel, cobalt, and graphite. Although these elements are relatively abundant in the Earth's crust, their availability is constrained by geographic concentration and current mining capacity, which has not yet scaled to match rapidly growing battery demand. Lithium demand has risen sharply in the past decade due to its essential role in cathode and electrolyte materials, far exceeding traditional uses such as ceramics and lubricants. Cobalt requirements have also expanded historically because of its role in stabilizing layered cathode chemistries, though industry trends toward nickel-rich cathodes have gradually reduced cobalt intensity. Nickel has become a dominant cathode metal, but EV batteries require high-purity "class-1" nickel, which involves additional processing and faces supply risks due to geopolitical factors. Graphite, primarily sourced and processed in China, remains the key anode material, and demand has risen in parallel with cathode materials (Barman et al., 2023). As part of the upstream supply chain, mining and extraction activities are highly energy- and resource-intensive, often associated with significant greenhouse gas emissions, land disturbance, and water consumption.

Processing: Following the extraction of raw minerals, the material processing and refining stage transforms natural ores into high-purity, battery-grade materials suitable for cell manufacturing. This process involves a combination of mechanical, chemical, and thermal steps to concentrate, purify, and synthesize key compounds, ensuring the requirements for battery production are met.

Manufacturing & Assembly: Refined materials are processed into cell components through a series of energy-intensive electrode and electrolyte manufacturing steps that vary by chemistry. For NMC lithium-ion batteries, nickel-rich cathode active materials are synthesized via coprecipitation and high-temperature calcination, then mixed with conductive additives and binders into slurry, coated on aluminum foil, dried, calendared, and paired with a graphite anode coated on copper foil; a liquid electrolyte ($LiPF_6$ in organic solvent) is later injected in a moisture-controlled dry-room environment. LFP cells follow largely the same assembly processes but use an olivine-structured iron-phosphate cathode that requires different precursor synthesis and results in lower binder and solvent demand (Liu et al., 2021). SIBs share similar manufacturing steps to LIBs, but replace graphite with hard carbon anodes and use sodium-based salts (e.g., $NaPF_6$) and aluminum foil current collectors on both electrodes; material preparation for layered oxide cathodes like NaMMO or NaNMC differs, yet cell assembly remains comparable. In contrast, solid-state batteries introduce additional complexity: graphite anodes are often replaced by lithium-metal foil or anode-free designs, a solid electrolyte layer replaces the polymer separator, and powder-based solid electrolytes require high-temperature sintering or precision cold-pressing. Moreover, SSBs demand stricter humidity control, and reports show dry-room operations dominate manufacturing energy (>90% in early SSB designs) (Keshavarzmohammadian et al., 2018). Across all chemistries, subsequent stacking, welding, electrolyte filling (if used), formation cycling, and pack integration contribute additional electricity consumption, making the production stage one of the largest contributors to life-cycle environmental impacts — especially for chemistries requiring nickel/cobalt refining or sensitive solid-electrolyte fabrication.

4.1.2. PRIMARY USE IN EV

During the use phase, batteries operate to deliver power through repeated charging and discharging cycles. The environmental impact associated with this phase is strongly influenced by the electricity generation mix used to charge the vehicle. In addition, battery-specific characteristics such as capacity, energy consumption per kilometer, and degradation rate play important roles in determining the cumulative energy demand over the vehicle's lifetime.

4.1.3. END-OF-LIFE

Recycle: Recycling is a baseline EoL pathway for electric vehicle batteries, aiming to recover valuable materials such as lithium, nickel, cobalt, and copper while reducing environmental impacts. Once collected, spent batteries are discharged, disassembled, and processed using techniques such as pyrometallurgy, hydrometallurgy, or direct recycling to extract reusable metals and compounds. These recovered materials can then be reintroduced into the battery manufacturing supply chain, helping to reduce the demand for virgin mineral extraction and lower the overall carbon footprint of battery production. Although large-scale recycling infrastructure is still developing, increasing policy support and technological innovation are accelerating the growth of a circular battery economy.

Second Life: After their initial use in electric vehicles, batteries that retain sufficient capacity, typically around 70-80% of their original performance, can be repurposed for less demanding applications. In second-life use, these batteries are reconfigured into ESS that support functions such as grid stabilization, renewable energy integration, and backup power. Following this

extended use phase, the batteries can still be routed to recycling. This approach extends the overall lifespan of battery materials, delays recycling or disposal, and enhances resource efficiency within the battery value chain.

4.1.4. TRANSPORTATION

Transportation impacts include emissions from moving extracted raw materials to refineries and from refineries to component assembly facilities. These stages are already accounted for in the literature data used for the production phase. In our calculations, the transportation emissions we add specifically cover the movement of battery packs from the battery manufacturing facility to the vehicle manufacturing plant, after which the completed vehicle enters the market. For the EoL scenarios—both recycling and second-life applications—we also include the transportation emissions associated with moving battery packs from the point of sale (car market) to the appropriate refurbishing or recycling facilities. This ensures that all transport-related impacts beyond the production stage are consistently captured.

4.2. SYSTEM DESCRIPTION

The system boundary of the study is cradle-to-grave. This includes raw material extraction and processing, battery materials manufacturing, battery assembly, use of the battery over the lifetime of the vehicle and second-of-life application and EoL treatment.

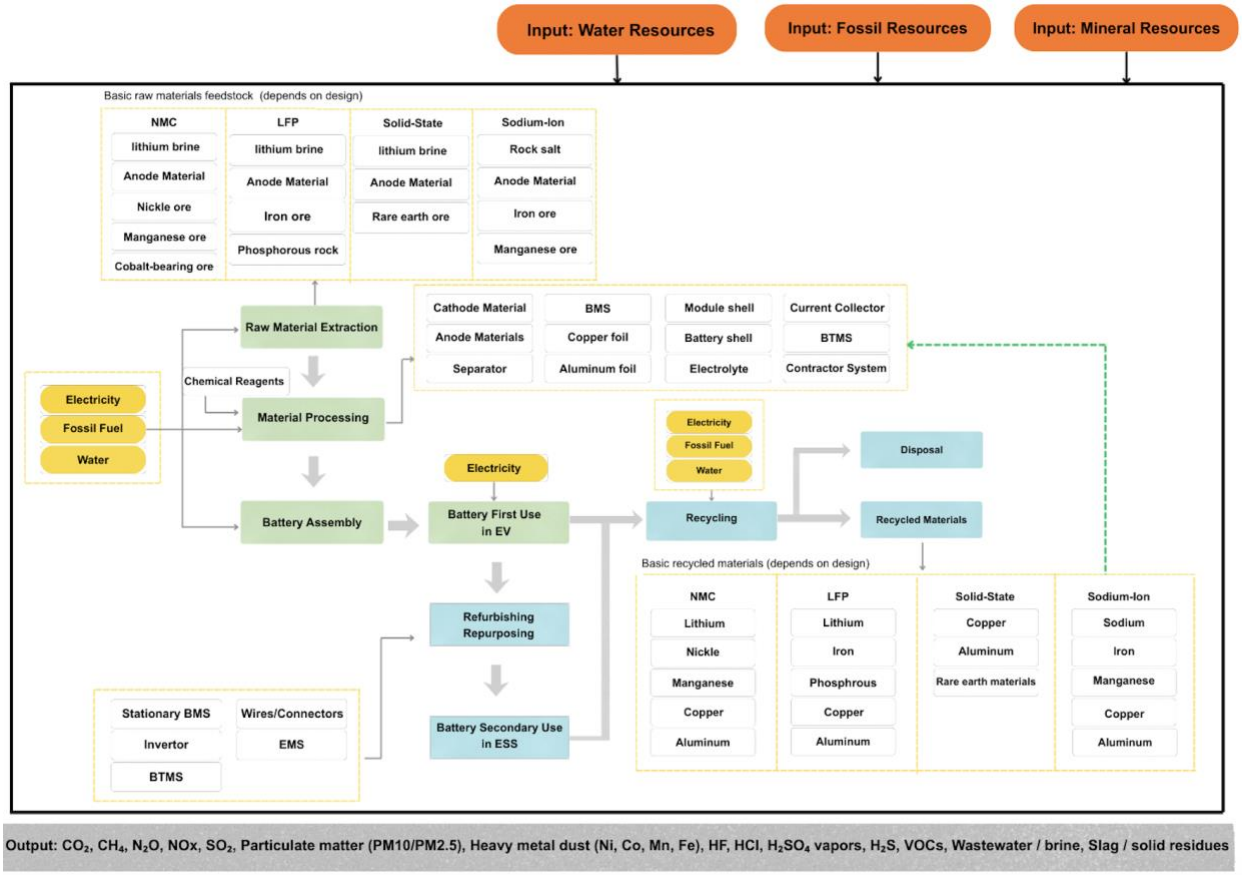


Fig. 3. Defined System Boundaries of EV Batteries.

5. Modeling Approach and Data

This study applies the standardized Life Cycle Assessment (LCA) framework as defined by ISO 14040 and ISO 14044. We perform a comparative cradle-to-grave assessment of four EV battery chemistries—NMC111, LFP, Sodium-Ion (SIB), and Solid-State (SSB), under two end-of-life scenarios: 1)Direct recycling and 2) Repurposing for stationary energy storage ("second life").

The assessment uses a combination of existing peer-reviewed LCAs and assumptions informed by technical literature on battery materials, manufacturing processes, and degradation characteristics. Where direct data are unavailable, especially for emerging chemistries (SIB and SSB), we model processes by analogy and normalization to ensure comparability across systems.

5.1. Functional unit

We employ two functional units in this study:

(1) **1 kWh of nominal battery-pack capacity** to evaluate cradle-to-grave impacts in a first-life EV-only scenario, and

(2) **1 kWh of electricity delivered over the battery's full service life** to evaluate cradle-to-grave performance when a second-life stationary storage stage is added before recycling.

This dual-unit framework enables consistent comparison across chemistries while capturing the influence of durability, degradation, and second-life deployment on overall environmental outcomes.

Cycle life is quantified using Full-Cycle Equivalents (FCE), defined as the cumulative energy discharged over the battery's lifetime divided by its nominal capacity. All impact results are normalized to the primary functional unit—1 kWh of electricity delivered—to ensure comparability across scenarios and to align with established LCA practice.

5.2. Assumptions

5.2.1. Battery Chemistry Sub-type

Because comprehensive cradle-to-grave LCAs are not yet available for all battery chemistries in our study, we draw on multiple literature sources to assemble phase-specific data. For emerging technologies such as SSBs and SIBs, published LCAs typically exclude end-of-life recycling, so we develop recycling assumptions by combining production-phase inventories with existing LCA studies of recycling processes. For the second-life stage, no chemistry-specific assumptions are needed: the analysis simply allocates additional full cycle equivalents to reflect extended service life, independent of the underlying battery subtype.

Table. 5. Assumptions of Battery Chemistry Sub-type for Production Phase (Quan et al., 2022 & Degen et al., 2025)

		Cathode	Anode	Electrolyte	Energy density (Wh/kg)
Production Phase	**NMC**	NMC811	graphite	$LiPF_6$	290
	LFP	LFP	graphite	$LiPF_6$	200
	SSB	NMC900	Li metal	$Li_{1.3}Al_{0.3}Ti_{1.7}(PO_4)_3$	430
	SIB	NaNFM442	hard carbon	$NaPF_6$	270
Primary Use Phase	**NMC**	NMC 111	graphite	$LiPF_6$	142.4
	LFP	LFP	graphite	$LiPF_6$	115.8
	SSB	N.A	N.A	N.A	N.A
	SIB	N.A	N.A	N.A	N.A
Recycling Phase	**NMC**	NMC 111	graphite	$LiPF_6$	142.4
	LFP	LFP	graphite	$LiPF_6$	115.8
	SSB	NMC900	Li metal	$Li_{1.3}Al_{0.3}Ti_{1.7}(PO_4)_3$	430
	SIB	NaNFM442	hard carbon	$NaPF_6$	270

5.2.2. TRANSPORTATION

For this study, we assume a consistent transportation pathway for all battery chemistries:

Table. 6. Assumptions of Transportation Pathway

Stage	Start Point	Transport Mode / Facility	End Point
Manufacturing → Port	Ningde, China	Dry Van – Single (LTL)	Shanghai, China
Export Shipping	Shanghai, China	Container Ship	Oakland, CA
Import → Vehicle Assembly	Oakland, CA	Dry Van – Single (LTL)	Reno, NV
Assembly → EV Use Phase	Reno, NV	Specialty Auto Bin	San Francisco, CA
EV End-of-Life → Refurbishment	San Francisco, CA	Dry Van – Single (LTL)	Reno, NV
Refurbishment → ESS Deployment	Reno, NV	Dry Van – Single (LTL)	San Francisco, CA
ESS End-of-Life → Recycling	San Francisco, CA	Dry Van – Single (LTL)	Reno, NV

Transport emissions for each mode were calculated using published emission factors (tons CO_2 per kg·km) from Horvath (2025). All transport impacts were computed on a per-kilogram basis and subsequently normalized to both per kWh of nominal battery capacity and per kWh of electricity delivered. Battery mass and energy density for each chemistry was used to parameterize emissions throughout the logistics chain.

5.2.3. Lifetime (in Full-Cycle Equivalents) of battery types

We express battery lifetime in terms of full-cycle equivalents (FCEs), which convert partial charge-discharge events into an equivalent number of full 100% cycles. Battery degradation is modeled using an exponential decay curve, calibrated to the most recent cycle-life data reported by major manufacturers such as CATL and BYD. These sources typically provide verified cycle counts at the 80% state-of-health (SOH) threshold, which we use as anchor points when generating degradation curves.

For the first-life EV stage, we use the 80% SOH cutoff, which is widely applied in the literature and industry practice as the point at which most EV batteries no longer meet performance requirements for automotive use. For second-life stationary storage, many studies traditionally assume end-of-life at around 60% SOH, though this value is often based on technical criteria rather than economic optimality. More recent analyses show that batteries can continue providing meaningful value in ESS applications even well below 50% SOH, because stationary duty cycles are far less demanding and round-trip efficiency remains acceptable (Business Insider, 2025). In this study, we adopt a 50% SOH cutoff for the second-life stage. This also reflects emerging evidence that battery degradation often transitions from exponential to more linear behavior below this threshold (Montes et al., 2022), reducing the economic value of further use and indicating that recycling becomes preferable.

Figure. 4. Battery Degradation in First- and Second-Life Across Four Battery Chemistries

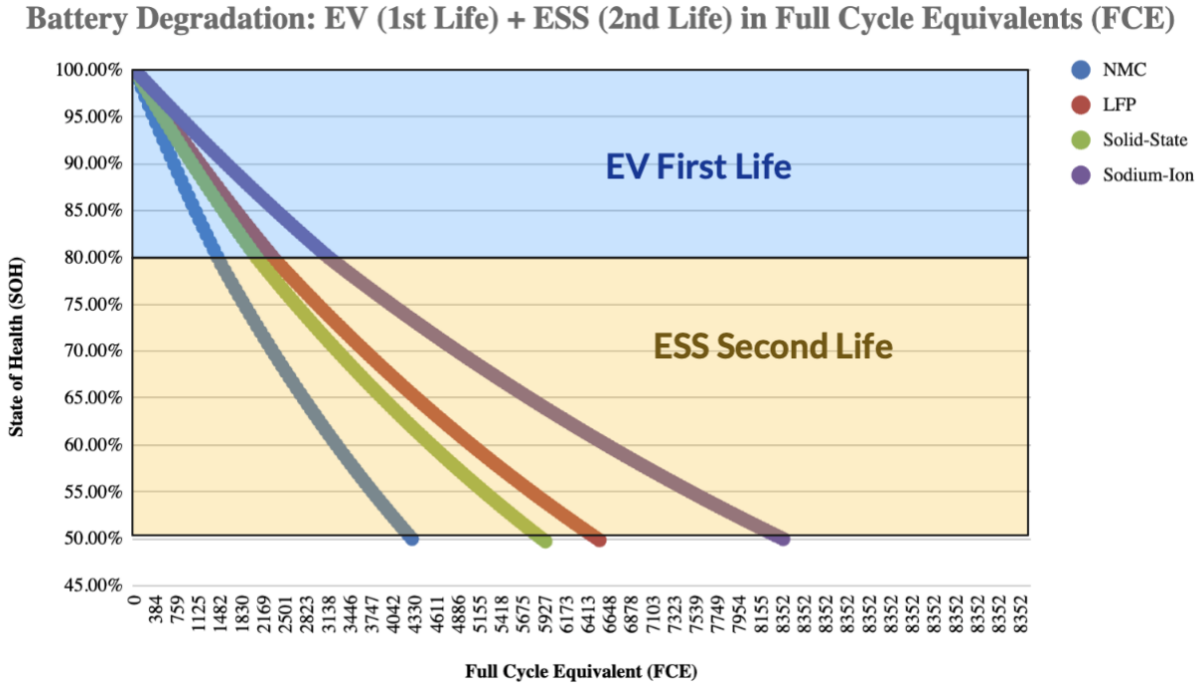
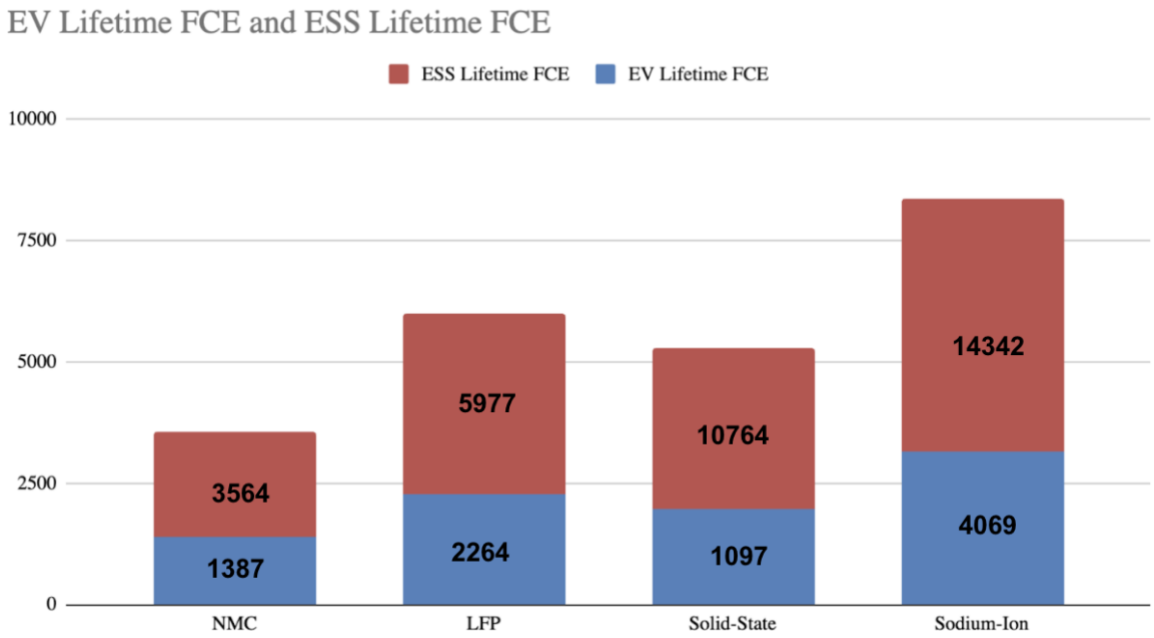


Figure. 5. Lifetime FCE by Life Stage Across Four Battery Chemistries



It is important to note, however, that cycle-life claims in the current EV battery market span a very wide range. Reported values can differ by an order of magnitude depending on testing protocols, charge rates, depth of discharge, temperature, and commercial incentives. Because of this variability, we rely on values that are most consistently supported across published literature and manufacturer disclosures

5.2.4. Primary Use Phase Impact

To quantify the environmental impacts associated with the primary-use phase, we evaluate the electricity losses incurred during each charging-discharging cycle. This provides a consistent and comparable metric for assessing how efficiently different battery chemistries utilize energy. For simplicity, the literature we use assumes that charge-discharge efficiency remains constant over the battery's lifetime, even though in practice it may decline as the battery degrades.

However, we do not integrate the full use-phase impacts into our primary results. At present, reliable use-phase data are available only for NMC and LFP batteries, and incorporating these values would risk overshadowing production-phase impacts while creating inconsistencies across chemistries. Instead, we treat the use phase as a sensitivity analysis, allowing us to explore its influence without compromising comparability among the four battery types. This approach ensures that differences in production and end-of-life processes remain the primary drivers in our comparative assessment.

5.2.5. Recycling Approaches

NMC batteries can be recycled using either hydrometallurgical or pyrometallurgical processes, whereas LFP batteries are more commonly treated through hydrometallurgy or direct physical recycling. For this study, we adopt hydrometallurgical recycling for both NMC and LFP as a

consistent upper-bound estimate of recycling benefits. Hydrometallurgy generally requires less energy and achieves higher recovery rates for critical materials, leading to larger environmental credits from avoided virgin material production.

For emerging technologies solid-state batteries (SSB) and sodium-ion batteries (SIB), commercial recycling routes have not yet been established. To represent these systems in a comparable framework, we apply scaled analogs of Li-ion hydrometallurgical recycling. In this approach, SSB and SIB recycling is modeled as following similar mechanical dismantling, material separation, and hydrometallurgical recovery steps as conventional LIBs, with adjustments to reflect solid electrolytes, alternative electrode chemistries, and sodium-based materials. Because no empirical recovery data exist for SSBs or SIBs, we estimate recycling impacts by using LCA results from hydrometallurgical processes applied to each battery's material composition. Assumed recovery rates are combined with production-phase impact factors to calculate the environmental credits associated with recycling.

Metals with mature and well-established recycling pathways, such as aluminum, copper, nickel, manganese, and cobalt, are assumed to be recoverable at very high rates in our analysis. Hydrometallurgical processes commonly achieve recovery efficiencies above 90%, and in optimized industrial settings, metal-salt recovery for NMC cathode materials can exceed 95-99%. To remain consistent with the upper bound of documented recycling yields and to avoid undervaluing the material-recovery benefits of these chemistries, we adopt high recovery rates for these transition metals. (Fang et al., 2022). Lithium metal poses a unique challenge in the recycling of solid-state batteries, and unlike the recovery of nickel, cobalt, manganese, or aluminum, its recovery yields are currently very low. Because lithium metal is extremely reactive, it readily converts into lithium oxides, hydroxides, and carbonates during dismantling and preprocessing. As a result, much of the lithium is lost before it ever reaches hydrometallurgical treatment (Ahuis et al., 2024).

For SSBs, we assume that the solid electrolyte is currently little recovered, consistent with the limited technical literature, though its small mass fraction makes this omission minor in overall environmental terms. For SIBs, sodium-containing electrolytes are assumed to be zero recovered, while major metals in cathode and current collectors remain recoverable. Finally, casing materials (typically steel or aluminum) are assumed to be nearly fully recyclable due to their established recovery markets.

Table.7. Recycling Fate of Battery Components in SSB and SIB Systems

Components	**Assumed Recycling Fate**	
	SSB	**SIB**
Current collector (Al)	90%	90%
Carbon black	0%	0%
Binder (PVdF)	0%	0%
Solvent (NMP)	20%	20%

NMC/NFM active material	99.4%	Ni/Mn/Fe: 95% Na: 20%
Current collector (Cu)	90%	N.A
Hard Carbon	N.A	0%
Lithium metal	50%	N.A
Binder (CMC-SBR)	N.A	0%
Separator	0%	0%
Electrolyte (Na)	N.A	0%
Electrolyte (SE)	2%	N.A
Casing	98%	98%

5.2.6. ESS Refurbishment Impacts and repurposing

We assume that the additional material and energy inputs required for battery testing, minor repairs, and preparation prior to ESS deployment are negligible. These activities typically involve diagnostic procedures, module-level inspection, and limited component replacement, all of which contribute only a small fraction of the overall environmental burden compared to original battery manufacturing and ESS operation.

5.3. Battery Cell Production

A cradle-to-gate LCA was conducted by Degen et al. (2025), providing a detailed evaluation of the environmental impacts of four battery types of interest. The study assessed cell designs, material recipes, and associated material flows. Cell recipe data were derived from battery teardowns and meta-studies, upstream material inventories were taken from established databases and peer-reviewed literature, and primary production data were sourced directly from industrial battery cell manufacturing facilities. Environmental impacts were characterized and assessed across the following categories: cumulative energy demand (CED), global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), and photochemical ozone creation potential (POCP).

5.4. Transportation

The study limits its transportation analysis to global warming potential (GWP) because GWP is the dominant environmental impact category associated with logistics and long-distance freight movement. Other midpoint indicators, such as acidification, eutrophication, or photochemical ozone formation, tend to contribute far less to total impacts from transport. By focusing on GWP,

the assessment captures the most consequential and policy-relevant effect of transportation while maintaining methodological consistency with the broader LCA.

5.5. Primary Use in EV

The assumptions used for the primary use phase in this study follow the framework established in Quan et al. (2022) to ensure methodological consistency. Specifically, EV energy consumption was assumed to be 13.1 kWh per 100 km, with a total driving distance of 200,000 km over the battery's automotive lifetime.

5.6. Secondary ESS

In order to measure the impact of the secondary ESS stage, we first considered the alternative. We assumed for every kWh of capacity placed in secondary storage, the retired EV battery displaced a battery that would have been manufactured from raw materials. In this scenario, extending the lifetime of the battery impacts all environmental impact categories equally, aside from transportation. If a battery lasts twice as long, the entire system requires half the battery manufacturing, and so its environmental impact is halved. We chose to exclude any secondary effects this may have on the broader battery market, as the error of these assumptions would grow exponentially with each assertion.

We then modeled the transition from a more demanding life as an EV battery to a gentler retirement as stationary storage by reducing the degradation rate by 10%. We modeled the continued degradation to 50% and measured the lifetime FCE achieved for each battery chemistry. After 50%, the batteries are assumed to be removed from storage and recycled. As these numbers were already normalized to 1 kWh of nominal battery capacity, we were able to divide each of the impact categories by the lifetime FCE to provide a per kWh impact assessment of the battery, after accounting for the extra transportation leg required for refurbishment. This method allowed us to appropriately account for the extended lifetime of each battery chemistry, measured per kWh delivered.

*Comprehensive LCIA results and methodological details are presented in the appendix.

6. RESULTS AND FINDINGS

This study evaluates the environmental impacts of lithium-ion batteries across different lifecycle stages, focusing on understanding the impacts within each phase, identifying the main contributing factors, and exploring the underlying reasons for these impacts. Specifically, four analyses are conducted:

- Environmental impacts at Production Phase
- Environmental Impacts Across Primary Use Phases
- Environmental Impacts Across Three Critical Phases (Production, Transportation, Recycling)
- Impact of ESS on Environmental Impacts compared to Direct Recycling

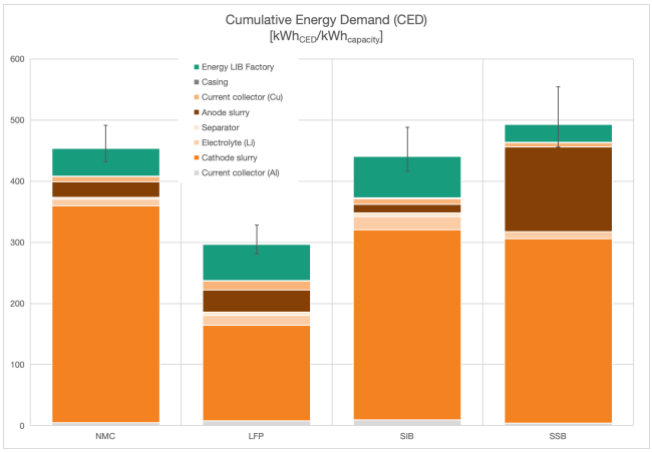
6.1. ENVIRONMENTAL IMPACTS AT PRODUCTION PHASE

All data presented in this section were extracted from Degen et al. (2025). Specifically, values were obtained from the "LCIA" tab, using the High Energy category for each battery chemistry (NMC811, LFP, NaNFM422 (SIB) and NMC900 Li (SSB)).

Across all impact categories examined, a consistent pattern emerges regarding the environmental drivers of battery production. As shown in the figures, the cumulative energy demand (CED) of lithium-ion batteries is dominated by the cathode slurry, which accounts for roughly 78-92% of total energy use, yielding a CED range of 296.3-493.1 kWh per kWh of capacity. LFP batteries exhibit the lowest energy demand, while solid-state batteries are the most energy-intensive to manufacture. A similar trend appears for global warming potential (GWP), where the cathode slurry is again the primary contributor, although the anode slurry becomes equally significant for solid-state batteries; here, LFP displays the lowest GWP, with solid-state batteries showing substantially higher impacts. Acidification potential (AP) is likewise driven mainly by the cathode slurry, with the current collector and anode slurry contributing next; sodium-ion batteries show lower AP due to less energy-intensive materials and reduced sulfur-related emissions. Eutrophication potential (EP) follows the same general structure, with cathode slurry as the dominant contributor and lower EP values observed for sodium-ion batteries, whose simpler material processing reduces nutrient-related emissions. Finally, photochemical ozone creation potential (POCP) is also shaped primarily by the cathode slurry, though in solid-state batteries the anode slurry slightly exceeds the cathode contribution due to higher energy and chemical processing requirements, resulting in increased VOC and NO_x emissions. Overall, across CED, GWP, AP, EP, and POCP, solid-state batteries consistently exhibit the highest impacts, while LFP and SIB chemistries generally perform more favorably.

Figure.6. Environmental Impact Comparisons Across Five LCIA Categories

a)



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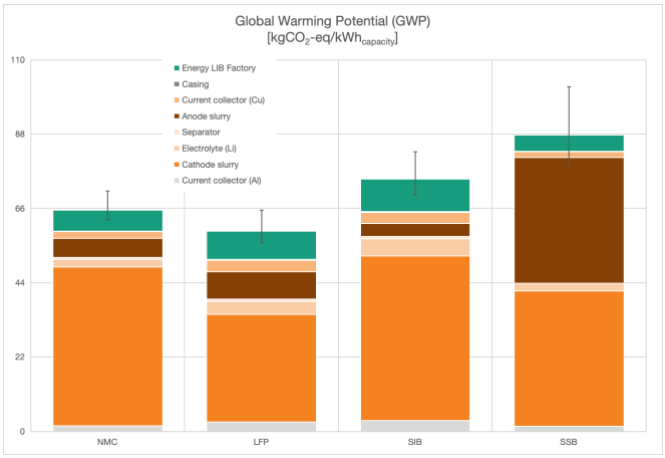

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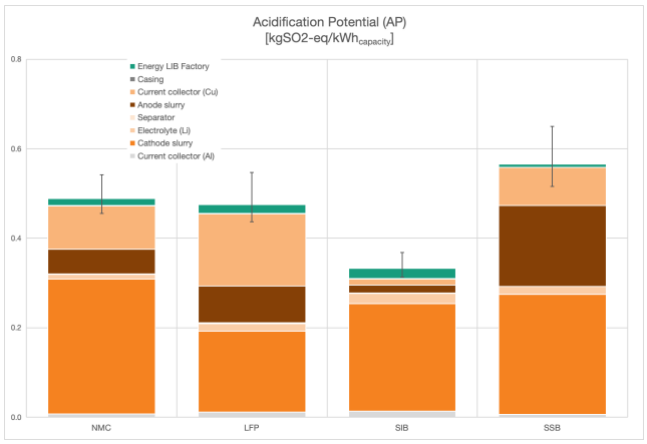

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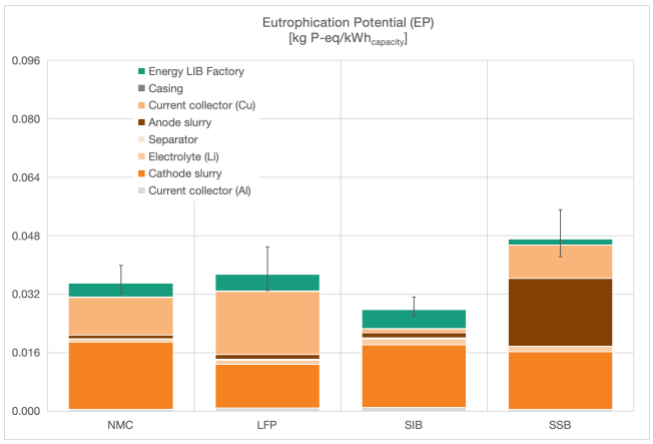

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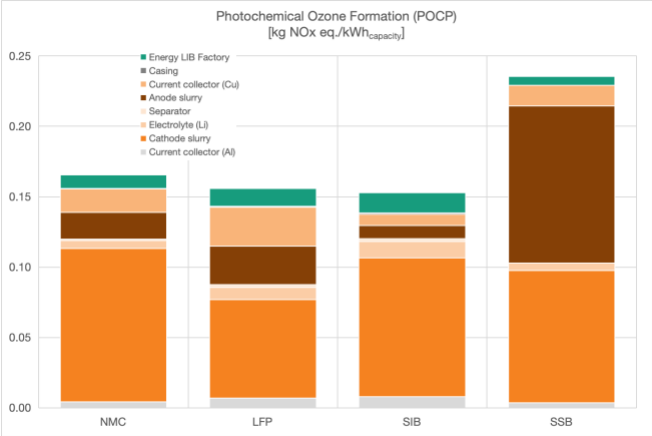

6.2. ENVIRONMENTAL IMPACTS AT USE PHASES

The use phase of batteries, encompassing both first-life and second-life applications, represents a critical stage in the lifecycle due to its substantial contribution to GWP. This phase accounts for charging and discharging losses as well as the cycle life of batteries in electric vehicles and ESS. To maintain consistency with our study scenario, the GWP values reported by Quan et al. (2022) are used here, as we adopt the same assumptions regarding battery operation and cycle life.

Importantly, only NMC and LFP chemistries are included in this portion of the analysis. Sodium-ion (SIB) and solid-state batteries (SSB) remain in early stages of development, and the literature does not yet provide reliable data on use-phase electricity losses, battery-carrying energy demand, or charge–discharge efficiency patterns. Due to the absence of these parameters, use-phase GWP cannot be estimated for SIB or SSB at this time.

Table. 8. GWP of NMC and LFP Batteries During Primary Life Use Phases (Quan et al., 2022)

Global Warming Potential (GWP) [kgCO_2-eq/kWh Capacity]		
Battery Chemistry	First Life	Second Life
NMC	137.29	181
LFP	152.11	441

At first glance, LFP batteries appear to have higher environmental impacts, but this is a consequence of the way the use-phase results are expressed. Quan et al. report impacts per kWh of battery capacity, not per kWh of electricity actually delivered over the battery's lifetime. Therefore, the results in some degree punish LFP for degrading more slowly and having a longer cycle life. When impacts are instead normalized by electricity delivered over the full service life, LFP would not necessarily exhibit higher use-phase emissions. In other words, the apparent disadvantage arises from the functional unit used, not from an inherently higher environmental

burden of LFP chemistry.

6.3. Environmental Impacts Across Three Critical Phases

This assessment focuses on the production, transportation, and recycling phases because they represent the most critical stages for understanding the environmental impacts of the battery lifecycle. The production phase is included because it consistently represents one of the dominant contributors to environmental burden across battery chemistries in all the literature, driven by energy-intensive material mining and extraction, cathode and anode processing, and cell manufacturing.

Transportation is analyzed to ensure that results better reflect real-world supply chain conditions and align with a U.S. context, which is the primary focus of this study. Battery materials and finished cells often travel long distances, frequently across continents, before reaching U.S. markets, and these logistics pathways contribute meaningful emissions. Including transportation enables a more realistic assessment of environmental impacts.

Recycling is incorporated because it constitutes the baseline end-of-life process with both environmental costs and potential benefits through material recovery. Recycling outcomes influence the overall lifecycle performance of batteries by offsetting primary material extraction and reducing long-term waste burdens.

Use phase impacts are intentionally not included in this three-phase comparison. The use phase accounts for a substantial share of total environmental impact, especially GWP, to the extent that it can dominate and overshadow the contributions of other lifecycle stages. Including the use phase here would make it difficult to isolate and interpret the relative impacts of production, transportation, and recycling. Therefore, the use phase is addressed separately through sensitivity analysis, where its influence can be evaluated more transparently and without diminishing the visibility of other critical phases.

As shown in Figure 7, across the production, transportation, and recycling phases, solid-state batteries exhibit the highest production GWP, driven by energy-intensive material processing and cell fabrication, though these impacts are partly offset by relatively low transportation emissions. This reinforces earlier findings that production overwhelmingly dominates total life-cycle emissions. By contrast, LFP shows the lowest production-related emissions and receives the largest recycling credit, making it the most environmentally advantageous chemistry in this assessment. NMC demonstrates moderate impacts during production and transportation and benefits from recycling, though not enough to outperform LFP.

Across all chemistries, recycling plays a decisive role in shaping net GWP outcomes. Technologies with mature and efficient recycling pathways, such as LFP and NMC, and to a lesser extent solid-state batteries, receive substantial offsets from avoided virgin material production. In contrast, sodium-ion batteries receive no net recycling credit, as the impacts of the assumed recycling process exceed the benefits from recovered materials. This reflects their early-stage supply chains and the current absence of established end-of-life recovery pathways.

Transportation contributes only a small share of overall GWP relative to production and recycling and does not meaningfully affect the comparative ranking across chemistries.

Overall, current conditions position LFP as the lowest-GWP option, while the long-term performance of solid-state and sodium-ion batteries will depend on future advances in manufacturing efficiency, logistics, and recyclability.

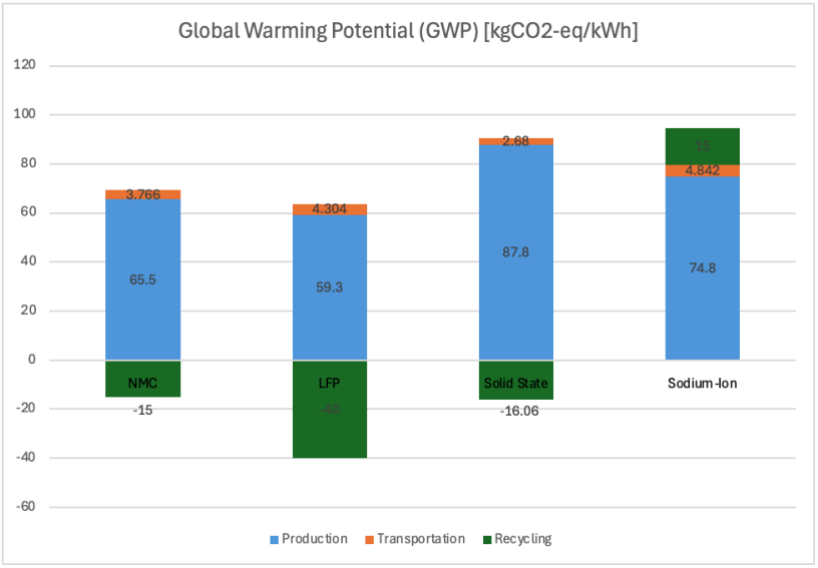

Figure. 7. GWP of Different Battery Chemistries for Three Critical Phases

For the remaining four environmental impact categories, transportation data are not available. Based on the GWP assessment above where transportation contributes only a minor share relative to production and recycling, its exclusion is unlikely to alter comparative results. Therefore, due to limited data availability, transportation is omitted from the following assessments.

Production dominates cumulative energy demand (CED) for all battery types. LFP exhibits the lowest production CED (296.3 MJ), while solid-state batteries show the highest (493.1 MJ). Recycling contributes relatively little to CED except for Sodium-Ion batteries, where recycling phase CED (241.21 MJ) represents a substantial share of total impacts.

Acidification potential (AP) from production is similar across chemistries (~0.3-0.6 kg SO_2-eq.), but recycling reduces AP for all battery types. Solid-state batteries show the largest reduction (-0.477 kg SO_2-eq.), suggesting that recycling provides meaningful offsetting benefits for this chemistry.

Eutrophication potential (EP) is low across all chemistries, with Sodium-Ion batteries showing the lowest production impact (0.028 kg PO_4^{3-}-eq.). Recycling effects are modest and vary by chemistry: NMC and LFP show slight increases, while solid-state and Sodium-Ion show small reductions, indicating that recycling contributes minimally to nutrient-related emissions.

Photochemical ozone creation potential (POCP) is highest for solid-state batteries during production (0.236 kg NMVOC-eq.), while other chemistries cluster around 0.15-0.17 kg NMVOC-eq. Recycling reduces POCP for all chemistries, with LFP and NMC showing the largest reductions (-0.020 and -0.015 kg NMVOC-eq., respectively).

Across all categories, recycling generally reduces environmental impacts, especially AP and POCP, though the magnitude of these reductions varies depending on the battery chemistry and technological maturity. Sodium-ion batteries remain a notable exception in CED, unlike NMC or solid-state chemistries, which recover valuable metals such as nickel, cobalt, or lithium, SIBs contain fewer recyclable high-impact materials to offset the energy used during recycling.

Overall, LFP batteries consistently exhibit lower environmental impacts across most categories, particularly in production CED and POCP, indicating strong environmental performance. Solid-state batteries tend to show the highest production impacts, highlighting the trade-offs associated with next-generation chemistries. Across all systems, production remains the dominant contributor to life-cycle impacts, underscoring the importance of upstream material choices and manufacturing processes. Recycling offers meaningful mitigation potential but remains highly chemistry-dependent.

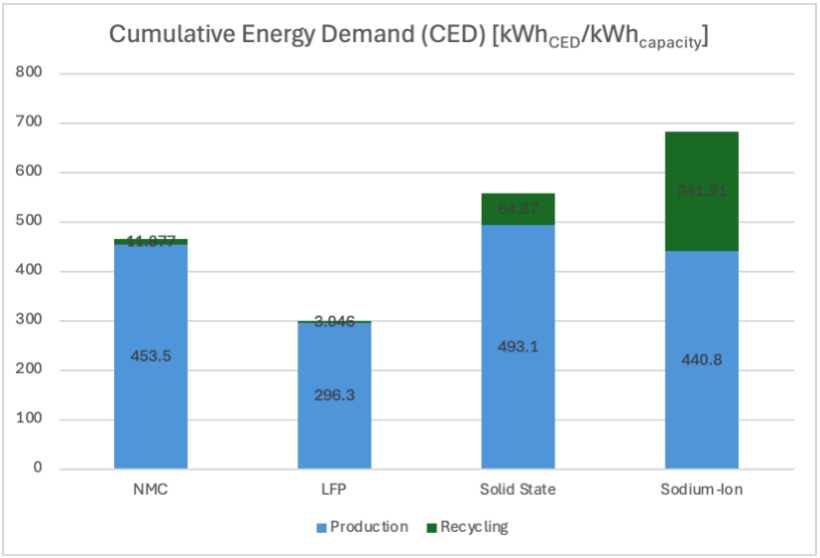

Figure. 8. CED of Different Battery Chemistries for Three Critical Phases

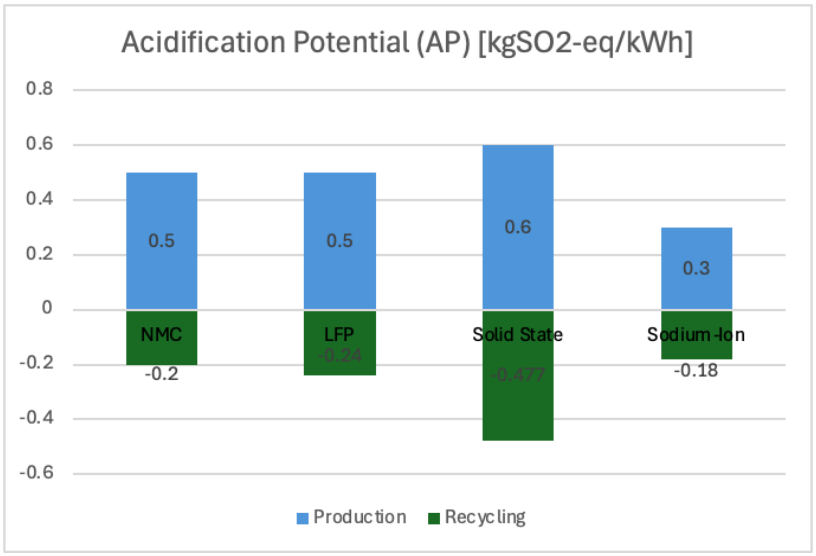

Figure. 9. AP of Different Battery Chemistries for Three Critical Phases

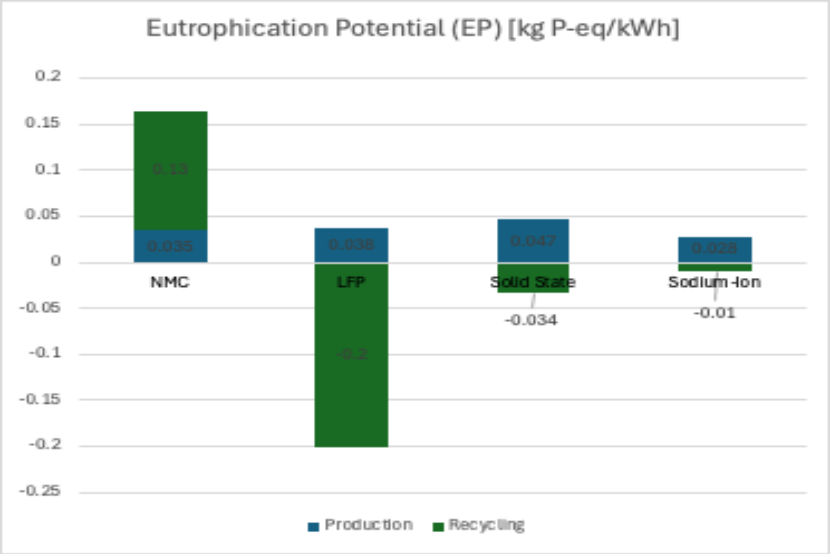

Figure. 10. EP of Different Battery Chemistries for Three Critical Phases

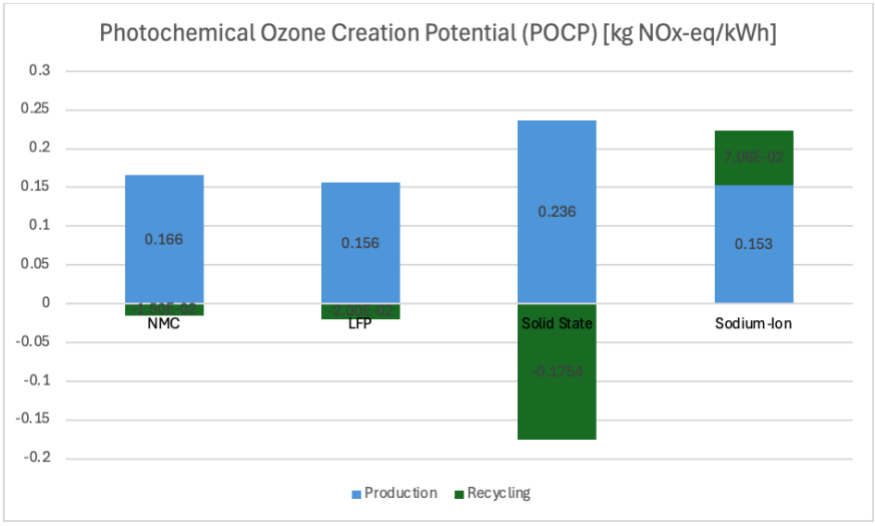

Figure. 11. POCP of Different Battery Chemistries for Three Critical Phases

6.4. Second Life: Energy Stationary Storage (ESS)

We found that incorporating a secondary ESS stage typically increases the lifetime (measured in FCE converted to kWh) by an average of 163% and reduces the per-kWh environmental impact of the battery system by an average of 62% across all chemistries. SIBs and SSBs had a slight advantage, but all chemistries showed similar results. However, the advantage is sensitive to factors such as first life cycle counts and degradation rates, highlighting the importance of context-specific LCA modeling.

Table. 9. % Lifetime Extension and % Impact Reduction of ESS relative to EV first life

Metric	NMC	LFP	Solid-State	Sodium-Ion
% Lifetime Extension	157%	164%	165%	165%
% Impact Reduction	61%	62%	62%	62%

By accounting for the extended life and dividing the per kWh capacity environmental impact assessment from the first life, we are able to produce an impact assessment that represents the full extended-life impact of each battery chemistry normalized to 1 kWh of electricity. We also account for the additional transportation leg.

Table. 10. Lifecycle Impact Assessment with Direct Recycling

LCIA Per kWh electricity w/ Direct Recycling (no ESS)								
	NMC		LFP		Solid State		Sodium-Ion	
CED	0.336	kWh	0.132	kWh	0.509	kWh	0.168	kWh
GWP	0.0386	kgCO2-eq	0.0100	kgCO2-eq	0.0673	kgCO2-eq	0.0230	kgCO2-eq
AP (SO2, NOx)	0.0002163	kgSO2-eq	0.0001148	kgSO2-eq	0.0001121	kgSO2-eq	0.0000302	kgSO2-eq
EP	0.0001190	kg P-eq	-0.0000716	kg P-eq	0.0000119	kg P-eq	0.0000041	kg P-eq
POCP	0.0001089	kg NOx-eq	0.0000601	kg NOx-eq	0.0000552	kg NOx-eq	0.0000550	kg NOx-eq

Table. 11. Lifecycle Impact Assessment with Secondary Life as ESS

LCIA Per kWh electricity w/ ESS								
	NMC		LFP		SSB		SIB	
CED	0.131	kWh	0.1047	kWh	0.1951	kWh	0.0634	kWh
GWP	0.0152	kgCO2-eq	0.00809	kgCO2-eq	0.02602	kgCO2-eq	0.0088	kgCO2-eq
AP (SO2, NOx)	0.0000842	kgSO2-eq	0.0000909	kgSO2-eq	0.0000430	kgSO2-eq	0.0000114	kgSO2-eq
EP	0.0000463	kg P-eq	-0.0000566	kg P-eq	0.0000045 5	kg P-eq	0.0000015 5	kg P-eq
POCP	0.0000424	kg NOx-eq	0.0000476	kg NOx-eq	0.0000211 9	kg NOx-eq	0.0000208	kg NOx-eq

As shown above there are meaningful reductions to the lifecycle impact across all categories. The additional impact of transportation is included, although negligible compared to the benefits of prolonging the life of these batteries. SIBs perform better across nearly all impact categories when second life is considered, due to their longevity.

It is important to note that our production and recycling estimates for NMC and LFP are drawn from different literature sources, each using distinct assumptions, system boundaries, and chemistry-specific process data. Because of these methodological differences, the recycling credits for LFP exceed its production impacts in certain environmental categories.

7. Sensitivity Analysis

7.1. Battery Lifetime Assumptions

While all battery chemistries are evolving quickly, SIBs and SSBs are more nascent than their more mature NMC and LFP technologies and longevity claims vary widely. As we have shown, the environmental impact of a battery can be significantly reduced by increasing its lifespan. As a sensitivity analysis, we measured the impact of SIBs and SSBs achieving significantly higher lifespans, achieving 6000 and 4500 cycles before reaching 80% SOH.

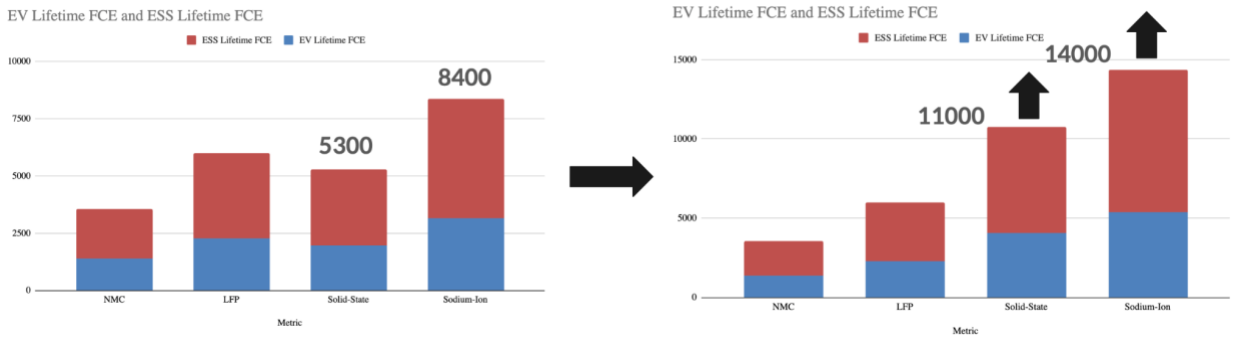

Figure. 12. Lifetime Increase of SSB and SIB Technologies

As evidenced in the visuals above and the table below, if SSBs and SIBs are able to achieve lifespans of 4500 and 6000 FCE respectively, they will become favorable across nearly every impact category. These results demonstrate the importance of lifespan on the environmental impact of all battery types and can inform future efforts to invest in battery longevity.

Table. 12. Lifecycle Impact Assessment with Increased SSB and SIB Lifetimes

LCIA w/ ESS and Increased SSB and SIB Lifetimes								
	NMC		LFP		SSB		SIB	
CED	0.131	kWh	0.1047	kWh	0.0518	kWh	0.0476	kWh
GWP	0.0152	kgCO2-eq	0.00809	kgCO2-eq	0.00691	kgCO2-eq	0.0066	kgCO2-eq
AP (SO2, NOx)	0.0000842	kgSO2-eq	0.0000909	kgSO2-eq	0.0000114	kgSO2-eq	0.0000086	kgSO2-eq
EP	0.0000463	kg P-eq	-0.0000566	kg P-eq	0.00000121	kg P-eq	0.00000116	kg P-eq
POCP	0.0000424	kg NOx-eq	0.0000476	kg NOx-eq	0.00000563	kg NOx-eq	0.0000156	kg NOx-eq

7.2. Impact of Electricity Carbon Intensity

Consistent with the findings of Quan et al. (2022), the use phases represent the largest contributors to the GWP of EV batteries, accounting for approximately 80% of total lifecycle impacts. In this

study, electricity consumption was the sole impact source during the use phases, meaning that the environmental burdens are primarily determined by the composition of the electricity grid.

Our analysis shows that under the 2016 China grid mix (0.656 kg CO_2-eq/kWh; Li et al., 2023), the GWP of NMC batteries increased by 101% and LFP batteries by 53% relative to the baseline scenario, which includes production, transportation, and recycling phases. In contrast, under the 2022 California grid mix (497.4 lb CO_2/MWh; EPA, 2024a), the GWP increases were 34.7% for NMC and 18.2% for LFP batteries, reflecting the greater share of low-carbon electricity in California.

Table. 13. Global Warming Potential of NMC and LFP Batteries During Use Phase Under China and California Grid Mixes

	NMC	LFP
Total GWP contribution across 3 critical phases (Baseline)	315.14 kg	1119.31 kg
2016 China power mix	318.29 kg	593.11 kg
GWP increase	**101.0 %**	**53.0 %**
2022 California power mix	109.45 kg	203.95 kg
GWP increase	**34.7 %**	**18.2 %**

These results underscore the critical influence of power generation on the environmental impact of EV batteries. As the use phase dominates total GWP, analyzing it separately allows for a more precise evaluation of mitigation strategies. In particular, transitioning to a cleaner electricity grid with a higher share of renewables, can substantially reduce the lifecycle environmental footprint of EV batteries.

8. UNCERTAINTY ASSESSMENT AND MANAGEMENT

It is essential to acknowledge and systematically evaluate the uncertainties inherent in the assessments to ensure the robustness and reliability of the life-cycle results and to provide a better understanding of the magnitude and extent of their potential impacts. A data quality assessment was conducted across the various life-cycle phases, taking into account factors such as the data acquisition method, as well as temporal, geographical, and technological representativeness.

Following the data quality assessment ("pedigree") framework developed by Junnila and Horvath (2003), the recommended scoring system was applied to evaluate the reliability of the data. A data quality assessment was conducted for each life-cycle phase, considering factors such as the data acquisition method, as well as temporal, geographical, and technological representativeness.

8.1. DATA QUALITY ASSESSMENT

Data quality	Acquisition method	Temporal correlation	Geographical correlation	Technical correlation
Production	2	3	4	3
Transportation	1	1	2	2
First life	2	1	3	2
Second life	3	3	4	2
Recycling	3	1	3	3

Using a five-point scale in which 1 represents the highest data quality and 5 the lowest, the overall quality of the data employed in this study is assessed as moderate to high. Most indicators score between 2 and 3, reflecting generally reliable inputs. All data are drawn from reputable peer-reviewed literature, established databases and modeling frameworks, large-sample empirical datasets, or well-documented industry sources.

The temporal representativeness of the dataset is strong. The analysis relies primarily on recent studies, with most sources published within the last ten years and a substantial share appearing in the past three years. This ensures that the data reflect current battery technologies, manufacturing practices, and energy-system conditions.

By contrast, geographical representativeness is comparatively weaker. The dataset combines information from Europe, China, and the United States. Differences in material supply chains, production processes, regulatory environments, and electricity mixes across regions introduce uncertainty when applying these data to a single geographic context, such as California, which is the primary focus of this study.

Finally, technical representativeness is generally robust for mature battery technologies, as most data are based on commercially deployed cell designs and manufacturing methods. However, for emerging technologies such as solid-state and sodium-ion batteries, available information remains

limited and, in many cases, proprietary. As a result, these data may not fully capture real-world performance and production conditions.

8.2. Sources of Data Gaps and Variability

The reliability of the environmental assessment is constrained by the limited availability and heterogeneity of life cycle data across battery technologies. Variation in reported results stems from differences in modeling approaches, system boundaries, and underlying assumptions, as well as practical constraints such as proprietary data, restricted data sharing, and the early development stage of certain battery chemistries. Differences in material sourcing, production processes, and methodological choices further contribute to uncertainty and complicate cross-study comparison.

Upstream impacts associated with raw material extraction and refining represent a major source of variability. Mining practices, ore grades, processing routes, and refining locations differ substantially across regions, leading to wide variation in reported environmental burdens. Traceability of materials is often limited, and several preprocessing steps are commercially sensitive, restricting transparency in published inventories. Similarly, differences in material sourcing and supply-chain structure—including the proportion of recycled versus virgin inputs, feedstock origins, and transportation distances—significantly influence environmental outcomes and limit the comparability of results across geographic contexts.

Uncertainty is further amplified in the manufacturing stage, where detailed information on energy use, bills of materials, process yields, and recovery efficiencies is frequently proprietary. As a result, many studies rely on averaged values, pilot-scale data, or engineering estimates that may not fully reflect current large-scale industrial practices. This limitation is particularly pronounced for emerging battery chemistries such as sodium-ion and solid-state batteries, for which industrial-scale production data remain scarce. Laboratory- and pilot-scale studies tend to overestimate energy use and material losses relative to mature manufacturing systems, potentially biasing life cycle impact estimates upward.

Use-phase impacts introduce additional uncertainty due to variation in battery lifetime, degradation behavior, charging patterns, and regional electricity mixes. Differences in data resolution, reporting formats, and geographic assumptions complicate the adaptation of use-phase results to specific contexts, such as U.S.-based electricity systems. End-of-life and recycling stages also contribute to uncertainty, as recycling technologies, material recovery efficiencies, and assumptions regarding reuse or second-life applications vary widely across studies. Simplified or optimistic recovery assumptions, as well as inconsistent treatment of partial reuse pathways, can lead to divergent conclusions regarding net environmental benefits.

Finally, methodological and database limitations play a significant role in shaping reported results. This study synthesizes data from multiple life cycle assessments that differ in system boundaries, functional units, and the inclusion of supporting infrastructure. In addition, commonly used life cycle inventory databases often aggregate or generalize industrial data to protect proprietary information, which can mask variability and introduce further uncertainty. Temporal and geographic differences in electricity mixes, manufacturing efficiency, and policy environments further complicate direct comparison across studies conducted in different regions or time periods.

9. Interpretation and Discussion of Results

9.1. Manufacturing Phase

Across all four battery chemistries examined, the manufacturing phase constitutes the dominant share of cradle-to-gate environmental impacts. This outcome reflects the high electricity demand associated with precursor synthesis, cathode slurry preparation, and cell assembly. Production-phase results vary substantially by chemistry, with cumulative energy demand (CED) ranging from 296.3 kWh per kWh of capacity for LFP batteries to 493.1 kWh for solid-state batteries, while global warming potential (GWP) spans from 59.3 kg CO_2-eq (LFP) to 87.8 kg CO_2-eq (solid-state). These differences are primarily driven by material composition and the intensity of processing required for each battery system.

Because electricity consumption is the dominant contributor to manufacturing impacts, regional differences in grid carbon intensity would significantly affect absolute GWP outcomes across all chemistries. As a result, the local electricity mix plays a central role in determining production-related emissions, regardless of battery design. Taken together, these findings indicate that no single chemistry exhibits uniformly superior environmental performance; rather, environmental outcomes emerge from trade-offs among material selection, processing requirements, and design characteristics.

The contrast between NMC and LFP batteries illustrates how cathode composition directly shapes environmental burdens. NMC batteries, despite their higher energy density, exhibit higher production impacts, with a CED of 453.5 kWh and a GWP of 65.5 kg CO_2-eq. These elevated impacts are driven by the extraction, refining, and processing of nickel and cobalt, both of which involve energy-intensive and environmentally burdensome upstream steps. In contrast, LFP batteries rely on more abundant materials such as iron and phosphate, which require less energy-intensive processing. As a result, LFP batteries display the lowest cradle-to-gate impacts across most categories, with a CED of 296.3 kWh and a GWP of 59.3 kg CO_2-eq. This comparison highlights how material availability and processing intensity, alongside energy density as a key performance metric, influence life-cycle environmental outcomes.

Solid-state batteries exhibit the highest production-phase impacts among all chemistries evaluated, with a CED of 493.1 kWh and a GWP of 87.8 kg CO_2-eq. These results are consistent with their current manufacturing requirements. The synthesis of solid electrolytes typically involves high-temperature sintering processes, while lithium-metal anode fabrication is also energy intensive. Together, these steps substantially increase electricity consumption during cell production. As a consequence, solid-state batteries show consistently higher burdens across multiple impact categories, including photochemical ozone creation potential (POCP), which is linked to upstream NO_x emissions from electricity generation. These findings suggest that, in their current developmental state, solid-state batteries do not yet offer clear environmental advantages over conventional lithium-ion technologies.

Sodium-ion batteries present an intermediate environmental profile in the manufacturing stage, with a CED of 440.8 kWh and a GWP of 74.8 kg CO_2-eq. Although sodium-ion systems avoid critical metals such as nickel and cobalt, the production of layered oxide cathodes and hard-carbon anodes still requires substantial processing energy. Notably, sodium-ion batteries exhibit

the lowest acidification potential (0.3 kg SO_2-eq) and eutrophication potential (0.028 kg P-eq) among the chemistries analyzed. This outcome reflects their reduced reliance on sulfur-intensive precursors and lower nutrient-related emissions during material processing. These results indicate that sodium-ion technology offers advantages in specific environmental dimensions, even if it does not outperform other chemistries across all impact categories.

9.2. Transportation

Transportation contributes only a minor share of total life-cycle impacts across all battery chemistries. The total global warming potential associated with battery transport ranges from approximately 2.69 to 4.84 kg CO_2-eq, which is negligible relative to production-phase emissions. Because transportation burdens are uniformly low and similar across chemistries, they do not affect the comparative ranking of battery technologies in this assessment. While included for completeness and realism, transportation plays a limited role in shaping overall environmental outcomes.

9.3. Recycling Phase

In contrast, recycling outcomes vary substantially by battery chemistry and play a decisive role in determining net life-cycle impacts. NMC and LFP batteries benefit significantly from the recovery of high-value metals, resulting in net negative recycling-related GWP of approximately –15 kg CO_2-eq for NMC and –40 kg CO_2-eq for LFP. Solid-state batteries also receive moderate recycling credits (–16.1 kg CO_2-eq), reflecting partial recoverability of valuable materials despite higher production complexity. Sodium-ion batteries, however, exhibit a net positive recycling GWP of approximately +15 kg CO_2-eq. This outcome reflects their lower recoverable metal content, primarily iron and manganese, and the limited economic and environmental offsets available from avoided virgin material production.

Recycling substantially improves the environmental performance of battery chemistries with established recovery pathways and valuable material streams, while offering limited or even adverse benefits for chemistries with lower recovery potential. As a result, end-of-life management emerges as a key determinant of total life-cycle impacts, particularly for conventional lithium-ion technologies, whereas emerging chemistries will require further development of recycling infrastructure to achieve comparable benefits.

9.4. Repurposing Phase

Including the repurposing phase substantially alters the life-cycle interpretation of all battery chemistries. Second-life deployment increases total service life by approximately 157% for NMC and 164-165% for LFP, solid-state, and sodium-ion batteries, effectively more than doubling the functional lifetime of battery materials. When impacts are normalized over this extended service life, total environmental burdens are reduced by 61-62% across all chemistries, demonstrating that repurposing is a highly effective strategy for mitigating production-dominated impacts. These reductions highlight that the primary benefit of second-life use arises from improved utilization of embodied energy and materials rather than chemistry-specific performance differences. Nevertheless, the absolute benefits of repurposing remain contingent on battery durability, degradation behavior, and the carbon intensity of electricity used during second-life operation. Overall, the results reinforce that integrating repurposing with eventual

recycling provides a robust pathway to improve environmental performance across both mature and emerging battery technologies, while emphasizing that policy and system design should prioritize lifetime extension alongside advances in recycling infrastructure.

9.5. FUNDAMENTAL CONCLUSIONS

Across all analyses, several consistent themes emerge that clarify how battery chemistry, production processes, and end-of-life strategies jointly determine environmental performance. First, no single battery chemistry is environmentally superior across all impact categories. Each system exhibits trade-offs, with advantages in certain metrics offset by disadvantages in others. This underscores the importance of moving beyond simplified comparisons and instead evaluating batteries through a multi-impact, life-cycle perspective.

Material availability plays a meaningful role in shaping upstream environmental burdens. Chemistries relying on more abundant elements, such as iron and phosphate in LFP or sodium, iron, and manganese in sodium-ion batteries, generally avoid some of the resource and toxicity concerns associated with nickel- and cobalt-intensive systems. However, reduced material scarcity does not automatically translate into lower overall impacts, as processing requirements and energy use remain critical determinants.

Energy density and manufacturing complexity emerge as dominant drivers of environmental differences among chemistries. High-nickel NMC systems benefit from higher energy density but incur greater production impacts due to energy-intensive refining and processing steps. Solid-state batteries, while promising from a performance and safety perspective, currently exhibit the highest manufacturing burdens because of complex solid-electrolyte synthesis and lithium-metal anode fabrication.

Electricity mix is another decisive factor, particularly for energy-intensive chemistries such as NMC and solid-state batteries. Because manufacturing electricity dominates cradle-to-gate emissions, regional grid carbon intensity can significantly alter comparative GWP results. As grids decarbonize, production-phase impacts may decline substantially, improving the relative performance of currently energy-intensive technologies.

End-of-life strategies further modify environmental profiles, but their benefits depend strongly on material recoverability. Chemistries with established recycling pathways and high-value metals, such as NMC and LFP, achieve meaningful environmental offsets through recycling and repurposing. In contrast, sodium-ion batteries currently offer limited recycling benefits due to lower recoverable metal value and immature recovery processes.

Overall, sodium-ion and solid-state batteries provide targeted improvements in specific impact categories and address important concerns such as material scarcity and safety. However, under current production and recycling conditions, they do not consistently outperform established lithium-ion systems across the full life cycle. Collectively, these results directly address the guiding research questions and demonstrate that environmental outcomes are shaped by the interaction of chemistry choice, manufacturing intensity, electricity mix, and end-of-life pathways rather than by chemistry alone.

9.6. Recommendations and Future Research directions

Based on the results, several recommendations and areas for further research emerge.

9.6.1. Recommendations

1. **Reduce electricity intensity and decarbonize manufacturing energy.**

   Reducing the electricity intensity of manufacturing processes and increasing the share of low-carbon electricity would likely yield the most substantial reductions in overall impacts. Chemistry selection also appears to interact with regional grid conditions, as lower-processing chemistries may perform more favorably in carbon-intensive electricity systems, while energy-dense or processing-intensive technologies may benefit more from cleaner grids, although the feasibility of such changes depends on regional energy systems and industrial practices

2. **Enhance recycling efficiency and material recovery.**

   Recycling can meaningfully offset life-cycle impacts for chemistries with recoverable, high-value materials, such as NMC and LFP, but its effectiveness is chemistry-dependent. For sodium-ion batteries in particular, current recycling pathways offer limited environmental benefits, suggesting that improvements in material recovery would be necessary for recycling to play a comparable role.

3. **Increase the share of batteries entering a second life.**

   Battery repurposing and second-life deployment can meaningfully extend service life and reduce per-unit environmental impacts, but only if paired with clear standards for performance, safety, and eventual recycling. Without such safeguards, second-life applications risk delaying rather than improving end-of-life outcomes.

9.6.2. Future Research Directions

- **Improving manufacturing methods for emerging chemistries.**
  Reducing the processing temperature of solid electrolytes and improving the efficiency of lithium-metal fabrication could help lower the manufacturing impacts of solid-state batteries.

- **Advancing recycling processes for sodium-ion batteries.**
  Sodium-ion systems would benefit from recycling approaches that more effectively recover materials such as iron and manganese, which are not well captured in current processes.

- **Incorporating regional or time-specific electricity mixes in future LCAs.**
  Since electricity use is the primary driver of manufacturing impacts, future assessments should reflect variations in grid carbon intensity across regions and over time.

- **Integrating battery degradation and second-life use into lifecycle models.**
  Including realistic aging behavior and potential second-life applications would provide a more complete understanding of overall lifetime environmental impacts.

- **Reassessing new cathode and anode materials as technologies evolve.**
  As battery materials and manufacturing techniques continue to change, updated LCAs will be necessary to evaluate how these developments influence resource use, energy demand, and recyclability.

10. APPENDIX

*Production Phase data could be found in the attached excel.

10.1. APPENDIX A: INVENTORY DATA FOR THE FIRST USE OF THE LFP BATTERY (QUAN ET AL., 2022)

Type		Parameter	Amount	Unit
Input	Material	LFP battery	1	kg
	Energy	Electricity	26.83	kWh
Output	Product	Retired LFP battery	1	kg

10.2. APPENDIX B: INVENTORY DATA FOR THE FIRST USE OF THE NMC BATTERY (QUAN ET AL., 2022)

Type		Parameter	Amount	Unit
Input	Material	NCM battery	1	kg
	Energy	Electricity	29.81	kWh
Output	Product	Retired NCM battery	1	kg

10.3. APPENDIX C: INVENTORY DATA OF THE HYDROMETALLURGY FOR EOL NCM BATTERY (QUAN ET AL., 2022)

Type		Parameter	Amount	Unit
Input	Material	EoL NMC battery	1.00E+00	kg
		HCl (30%)	4.00E-02	kg
		H_2SO_4 (98%)	1.10E+00	kg
		$NaNO_3$	2.10E-02	kg
		NaOH (30%)	1.87E+00	kg
		Ammonia(20%)	1.12E-01	kg
		P507 extractant	2.00E-03	kg
		Kerosene	4.89E-03	kg
		H_2O_2	3.66E-01	kg
		Li_2CO_3	1.21E-01	kg
		Water for industry	1.40E+01	kg
	Energy	**Natural Gas**	**2.33E+00**	**kWh**
		Electricity	**2.80E-01**	**m³**
Output	Products	NMC cathode material	3.00E-01	kg
		Plastic Scrap	4.00E-02	kg
		Copper Scrap	9.99E-02	kg
		Aluminum Scrap	5.99E-02	kg
		Steel Scrap	1.80E-01	kg

	Atmospheric pollutants	Ni	4.00E-03	kg
		CO_2	6.73E-02	kg
	Solid waste	Residue and Ashes	3.51E-01	kg
	Water pollutants	Waste water	9.99E+00	kg
		Ammonia Nitrogen	5.99E-02	kg

10.4. APPENDIX D: INVENTORY DATA OF THE HYDROMETALLURGY FOR EOL LFP BATTERIES (QUAN ET AL., 2022)

Type		Parameter	Amount	Unit
Input	Material	EoL LFP battery	1.00E+00	kg
		HCl (30%)	3.43E-02	kg
		H_2O_2 (7.5%)	9.54E-02	kg
		NaOH (32%)	8.73E-02	kg
		CaCl	3.57E-01	kg
		Fresh water	5.31E-01	kg
	Energy	**Electricity**	**4.85E-01**	**kWh**
Output	Products	LiCl (Solid)	3.57E-01	kg
	Atmospheric pollutants	Dust	1.76E-04	kg
		Hydrogen fluoride	2.39E-06	kg
		VOC	1.32E-04	kg
		Hydrochloric acid mist	4.01E-06	kg
	Solid waste	Plastic casing scrap	2.00E-01	kg
		Separator scrap	5.00E-02	kg
		Waste BMS	3.00E-02	kg
		Copper scrap	1.00E-01	kg
		Aluminium scrap	6.00E-02	kg
		Waste graphite	1.50E-01	kg
		Other solid waste	5.93E-01	kg

10.5. APPENDIX E: CALCULATIONS OF EMISSIONS FROM TRANSPORTATION

Stage	Leg	Distance (km)	Method	NMC kgCO2*kW	LFP kgCO2*kW	SS kgCO2*kWh	SIB kgCO2*kWh-1
First Life (Manufacture + Delivery)	---Factory to Port (Ningde, Fujian, China) (Battery Only)	700	Class 8b - Dry Van - Single (Heavy-Bulk)	0.686	0.784	0.49	0.882
	---China to Oakland, CA, USA (Battery Only)	10,000	Cargo Ship	1.12	1.28	0.8	1.44
	---Oakland to Reno, NV, USA (Battery Only)	400	Class 8b - Dry Van - Single (Heavy-Bulk)	0.392	0.448	0.28	0.504
	---Reno to San Francisco, CA, USA (Full Vehicle)	400	Class 8b - Specialty (Auto Bin)	0.392	0.448	0.28	0.504
				2.59	**2.96**	**1.85**	**3.33**
Energy Storage Solution (ESS)	---SF to Reno, NV, USA (Battery Only)	400	Class 8b - Dry Van - Single (Heavy-Bulk)	0.392	0.448	0.28	0.504
	---Reno to San Francisco, CA, USA (Battery Only)	400	Class 8b - Dry Van - Single (Heavy-Bulk)	0.392	0.448	0.28	0.504
				0.784	**0.896**	**0.56**	**1.008**
Recycling	---SF to Reno, NV, USA (Battery Only)	400	Class 8b - Dry Van - Single (Heavy-Bulk)	0.392	0.448	0.28	0.504
				0.392	**0.448**	**0.28**	**0.504**
Total				**3.766**	**4.304**	**2.69**	**4.842**

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