EV Li-Ion Battery Lifecycle Environmental Tradeoffs – NMC vs. LFP

ESENG 503 Project Report

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Executive Summary

Problem Statement

As electric vehicles (EVs) scale globally, selecting the appropriate battery chemistry is critical to balancing environmental, economic, and social goals. This study compares the full lifecycle impacts of two leading lithium-ion chemistries – Nickel Manganese Cobalt (NMC) and Lithium Iron Phosphate (LFP) – to guide more sustainable EV design decisions. The analysis quantifies tradeoffs in energy use, greenhouse gas (GHG) emissions, local pollutants, and water consumption across all major lifecycle stages.

Approach

Using Argonne National Lab's GREET 2024 model, this study evaluates five NMC variants and one LFP chemistry assuming a 300-mile range SUV and 2030 U.S. grid projections. The four lifecycle stages analyzed are: raw material extraction & processing (RME&P), manufacturing & distribution (M&D), use, and end-of-life (EOL). Literature sources supplement GREET data to assess modeling gaps and contextualize results.

Major Findings

- Raw material extraction & processing (RME&P): LFP has the lowest impacts due to low emissions per kg, despite higher total mass. High Ni NMC chemistries reduce most impacts but increase sulfur oxide (SO_x) emissions.
- Manufacturing & distribution (M&D): Minimal difference in impact between chemistries; minor efficiency gains possible with NMC's higher specific energy.
- Use: NMC outperforms LFP across all metrics due to improved energy efficiency resulting from reduced mass.
- End-of-life (EOL): NMC chemistries have greater impact reduction from implementing recycling than LFP. GREET does not capture the superior second-life potential of LFP.

Full lifecycle comparison (exchanging LFP for NMC955 chemistry)				
-6% Energy	-3% GHGs	-10% Water	-4% Organic Carbon	+158% SO_x

Estimated Benefit

Shifting 50% of 2023 U.S. BEV sales (625,000 units) from low- to high- Ni content NMC could reduce GHG emissions by 582 kt and water consumption by 2 kt – equivalent to the total lifecycle impact of 21,700 and 41,200 vehicles, respectively. SO_x emissions would increase by 14 kt (192,500 vehicles), highlighting the need for site-specific mitigation.

Recommendations

1. Avoid low-Ni NMC chemistries, which raise SO_x with minimal benefit.
2. Prefer high-Ni NMC over LFP due to its use-phase efficiency and greater recyclability. Localized SO_x emissions can be mitigated more feasibly than LFP's distributed use-phase impacts.

Chemistry choice should align with vehicle design, grid conditions, and the recycling policy landscape. The magnitude of environmental benefits of NMC is generally small, so LFP remains viable for some applications, particularly when it is certain a battery will enter a second life. Additionally, it is critical that economic and social factors be included to attain a holistic view of the impacts of chemistry choice – these effects may outweigh the environmental impacts analyzed here.

1. Introduction and Current State

Electrification is a key strategy to decarbonize transportation and accelerating the transition from internal combustion engine vehicles (ICEVs) to electric vehicles (EVs) is critical to achieve state, national, and international climate goals. Due to the relative novelty of advanced EV technology, significant uncertainty lies in its technological, environmental, economic, and social future. Understanding these uncertainties enables smarter decisions to mitigate negative externalities, maximize electrification benefits, and promote sustainable EV battery life cycle management. Without holistic guidance on the EV lifecycle, it is likely that unintended tradeoffs will occur that result in suboptimal solutions. This report evaluates key tradeoffs specific to the EV battery life cycle, through a framework developed by the University of Michigan's Center for Sustainable Systems (UM CSS). Specifically, the report compares the life cycle impacts of two commonly used chemistries - Lithium Iron Phosphate (LFP) and Nickel Manganese Cobalt oxide (NMC) - to inform chemistry selection in EV battery design.

1.1 Project Overview

The global, interconnected nature of the EV battery supply chain renders it a complex system to study, due to evolving chemistries, dispersed material sourcing and processing, variable consumer demands, and shifting government policies. The battery supply chain begins with the sourcing and refining of critical materials – such as lithium, nickel, cobalt, and graphite – which are then transported to manufacturing stages. These materials are assembled into cells, which are typically grouped into modules, and then integrated into full packs. Simultaneously, manufacturers must develop manufacturing technologies and processes to ensure reliability, performance, and scalability. EV battery design is influenced by a wide range of design and engineering considerations, including evaluating consumer preferences and requirements, material and labor costs, regulatory compliance, and environmental impacts. Even after a battery's primary use in a vehicle ends, early design decisions shape its end-of-life pathways – whether it enters second-life applications, is recycled, or becomes waste.

Throughout the battery lifecycle, different stakeholders hold both common and conflicting interests. A mining company will aim to provide minerals at the lowest possible cost, while the local community will desire safe employment and minimal local pollution. Consumers may prioritize longer ranges and higher performance, goals that often align with an original equipment manufacturer's (OEM)'s pursuit of the highest profit margin product. Considering the overarching consequences of the life cycle's individual processes will allow stakeholders from all levels to work together to avoid, or at least understand, negative environmental, economic, and social outcomes.

The UM CSS's sustainable EV battery management framework helps stakeholders align their decisions with environmental, economic, and social sustainability goals. This report applies the framework in a case study comparing LFP and NMC chemistries to evaluate associated tradeoffs. The case study integrates GREET-based analysis with findings from existing literature to validate, update, and extend prior research. LFP and NMC are selected for comparison because they are two of the most common[1,2] EV chemistries used today. Key differences between the chemistries include LFP's lower cost, inferior gravimetric and volumetric energy density, superior flammability safety, enhanced cycle life, and reduced use of critical minerals.[3, 4]

1.2 Review of Current State Design / Literature Review

This project draws from two main areas of literature: (1) frameworks for evaluating the sustainability of EV batteries, and (2) life cycle assessments (LCA) comparing LFP and NMC chemistries. In the first area, a prior literature analysis[5] identified the need for development of a robust evaluation framework integrating tradeoff analysis[6]. The UM CSS's sustainable battery management framework addresses this gap.

For the second area, some existing literature is applicable, but much is outdated, focus on non-EV applications, do not consider the cradle-to-grave lifecycle, or do not analyze LFP and NMC chemistries simultaneously. Among the applicable studies, the following are noted: Almeida et al.[7] use the GREET model to analyze emissions and energy usage across 8 battery types, 13 electricity generation mixes, and 4 vehicle segments. The cause of these impact differences is explored by Dai & Kelly[8], who analyze cradle-to-gate GHG emissions and break them down by cell component. Evro et al.[4] compare LFP and NMC chemistries by focusing on technological, environmental, and market characteristics. Bouter & Guichet[9] conduct a statistical review of LCA studies on EV battery GHG emissions and highlight substantial variability in reported outcomes. They recommend methodological harmonization to improve cross-study comparability. The present report consolidates insights from these studies and others to support a clear, comparative understanding of the environmental tradeoffs between LFP and NMC chemistries.

1.3 Stakeholders

The life cycle of EV batteries involves global sourcing, manufacturing, use, and end-of-life management, encompassing a wide variety of stakeholders. Because stakeholder roles differ across life cycle stages, they are organized below according to each stage.

1) Raw material extraction & processing

a) Local communities

b) Extraction and processing companies

c) Cell manufacturers

d) Policymakers

2) Manufacturing and distribution

a) Manufacturing companies

b) Original Equipment Manufacturers (OEMs)

c) Local communities

d) Policymakers

3) Use

a) Drivers

b) OEMs

c) Policymakers

4) End-of-Life (EOL)

a) Municipalities and waste managers

b) OEMs

c) Battery manufacturers

d) Policymakers

1.4 Scope

This project is part of a larger effort to implement the UM CSS's EV sustainable battery framework, including metrics, principles, and drivers, to guide the advancement of life cycle management for EV batteries. A case study of the environmental tradeoffs between Lithium Iron Phosphate (LFP) and Nickel Manganese Cobalt oxide (NMC) chemistries is presented. NMC chemistries include several subtypes based on varying elemental ratios. These subtypes are referred to in the format of NMCXYZ, where X, Y, and Z indicate the proportion of the elements in the material, denoted in subscript. An example of this is NMC622, with a composition of $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$. Included for analysis in GREET 2024 are NMC111, NMC532, NMC622, NMC811, and NMC955.

The UM CSS framework applies an LCA across four key stages of an EV battery's life:

1) Raw material extraction & processing (RME&P)
2) Manufacturing and distribution (M&D)
3) Use
4) End-of-Life (EOL)

Specific impact metrics are evaluated in each of these stages to encourage understanding and analysis of the tradeoffs. The UM CSS framework evaluates additional environmental, economic, and social factors; only those which are available for analysis through GREET are listed here. The impact categories (numeric listing) and impacts (alphabetic listing) are as follows:

1) Energy usage and GHG emissions
    a) Energy
    b) GHG emissions (as CO2e, containing CO_2, CH_4, and N_2O)
2) Local environmental pollutants
    a) VOC - Volatile organic compounds
    b) CO - Carbon monoxide
    c) NO_x - Nitrous oxides
    d) PM10 - Particulate matter from 2.5-10 microns
    e) PM2.5 - Particulate matter smaller than 2.5 microns
    f) SO_x - Sulphur oxides
    g) BC - Black carbon
    h) OC - Organic carbon
3) Water consumption

ANL's GREET model is the primary driver for the recommendations of this report. Although GREET supports analysis of passenger cars, SUVs, and pickup trucks, this study focuses solely on SUVs due to their market importance in the U.S.[1] Previous literature indicates that SUVs have mid-range outcomes relative to other vehicle classes.[7] The

differences in cycle life between LFP and NMC are not accounted for in this analysis. The analysis assumes a 300 mi achievable range under one full battery discharge. NMC and LFP are estimated to exceed 1,000 cycles[10] before reaching their EOL 80% capacity – equivalent to 300,000 miles. Since GREET assumes an SUV lifetime of 183,363 miles, the battery is expected to significantly outlast the rest of the vehicle. The 64% margin for error means calendar aging effects are unlikely to play a part in changing this conclusion. Thus, cycle life differences would only be relevant in a second life application, which is beyond the scope of GREET.

The analysis assumes technology and grid conditions projected for 2030 – a year chosen as a compromise between near-term certainty and long-term relevance, despite the inherent uncertainty in such forecasts. Note that GREET uses a 5-year delay between the actual year and the average model year. Thus, a grid/use year of 2030 results in a Vehicle Model Year of 2025, and the associated vehicle efficiency for that year.

In addition, the following are outside the scope of this report:

1) Market volatility
2) Technological obsolescence
3) Impacts of near-term policy and regulatory changes

1.5 Project Deliverables

The primary deliverables of this project are:

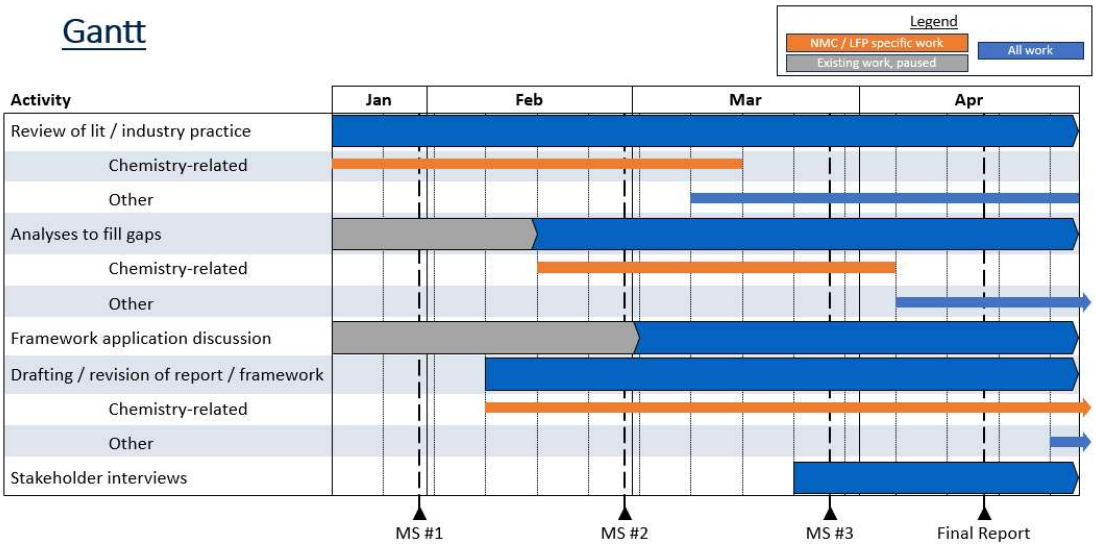
1) A comprehensive report highlighting the LCA tradeoffs between LFP and NMC chemistries.
2) A set of recommendations of which chemistries fit different use cases.
3) A summary of gaps present in this work which would not be addressed using ANL's GREET model.

These deliverables allow the stakeholders to gain an understanding of the environmental LCA impacts of selecting between the LFP or NMC chemistries for an EV. In addition, they provide an understanding of what the stakeholders must review further to have a holistic understanding.

This report is structured to support incorporation into an overarching publication based on the UM CSS framework with minimal revision. It also serves as a preliminary application

of the framework's metrics and principles, helping to identify any gaps or areas for refinement.

1.6 Project Timing



2. Assumptions and Methodology

2.1 Assumptions

The GREET model includes two synthesis paths for the LFP cathode material: solid-state and hydrothermal. Because solid-state is more appropriate for large scale industrial production[8,11], hydrothermal is not represented in this analysis.

The raw material extraction and processing (RME&P) stage encompasses all steps up to and including cathode material production. Assembly of the cathode material into cells marks the beginning of the manufacturing and distribution (M&D) stage. This is further detailed in Table 3.

2.2 Methodology

Argonne National Lab's GREET 2024 is widely recognized as one of the most comprehensive vehicle LCA models available, and is the primary tool used for the original analysis presented here. GREET internally references information including local mining emissions data, averaged regional refining data, averaged energy densities for batteries, and other key parameters relevant to vehicle lifecycle modeling. Some of these GREET defaults are validated against the latest literature, but many are beyond the scope of this project for independent confirmation. Thus, any replication should be conducted with the 2024 version of GREET (released in Jan 2025) and substitution of key parameters as discussed below.

Within GREET 2024, there are two sub-models: the Fuel-Cycle Model (GREET 1), and the Vehicle-Cycle Model (GREET 2). This analysis utilizes both, though primarily focuses on GREET 2. GREET 1 is used primarily for altering electricity grid mixes. GREET 2 is used to conduct the primary comparative analysis for the chemistries. Most default values that are present in GREET 2024 are retained; Tables 1 & 2 summarize the parameter changes applied in this analysis.

To streamline and reduce errors in the data entry/extraction process, custom Excel Scripts were developed. The code for the scripts can be found in Appendix 7.2.

GREET divides the vehicle-cycle-related impacts of lithium-ion battery manufacturing into four primary categories, shown in the first column of Table 3. To analyze impacts by life-cycle stage, each GREET category is mapped to one of the four stages defined in this study. In some cases, GREET categories are divided across multiple life-cycle stages in this analysis due to the complexity of extracting and recalculating the values from the model. This categorization approach aligns with the methodology presented in Figure 1 of Dai et al.[8] A consequence of this division is that there are some

cases where the primary lifecycle stage to which an impact should be attributed is uncertain.

Table 1: GREET1 Key Parameters

Parameter	Value	Units	Note
Target Year for Simulation	2030	Year	
Mix for transportation use	U.S. Mix	N/A	Primarily affects WTP/vehicle operation related impacts. Detailed mix: 0.2% residual oil, 25.9% natural gas, 7.9% coal, 16.6% nuclear, 0.8% biomass, 6.5% hydroelectric, 0.4% geothermal, 21.2% wind, 20% solar PV, 0.4% others
Mix for stationary use	U.S. Mix	N/A	Primarily affects vehicle cycle related impacts. Detailed mix: 0.2% residual oil, 25.9% natural gas, 7.9% coal, 16.6% nuclear, 0.8% biomass, 6.5% hydroelectric, 0.4% geothermal, 21.2% wind, 20% solar PV, 0.4% others
BEV AER	300	miles	Vehicle range, imports to GREET2
Vehicle Type	SUV	N/A	

Table 2: GREET2 Key Parameters

Parameter	Value(s)	Units
Li-ion Battery Cathode Material for EV	LFP (solid state cathode synthesis method), NMC111, NMC532, NMC622, NMC811, NMC955	N/A
Li-ion Battery Cathode Material Specific Energies	LFP: 144 NMC111: 180 NMC532: 188 NMC622: 190 NMC811: 201 NMC955: 208	Wh / kg
Energy Use of Battery Assembly for Li-Ion	0.161	mmBtu / kWh
Lifetime VMT of a Vehicle, EV Conventional	183,363	miles
Vehicle Type	SUV	N/A
Battery Replacements	0	N/A

Table 3: GREET Li-ion Battery Vehicle Cycle Impact Breakdown

Category	Detail	Life Cycle Stage
Cathode	LFP, NMC111, NMC532, NMC622, NMC811, NMC955	RME&P
NMP	Key solvent for cathode manufacturing	RME&P
Ancillary Materials	Graphite/carbon Silicon Binder Electrolyte: LiPF6 Electrolyte: Ethylene Carbonate Electrolyte: Dimethyl Carbonate	RME&P
	Copper Aluminum sheet Plastic: Polypropylene Plastic: Polyethylene Plastic: Polymer Plastic: Polyethylene Terephthalate Rubber	RME&P / M&D
	Cast aluminum Steel Stainless Steel Thermal insulation Coolant: Glycol Electronic parts	M&D
Assembly	Energy required for battery assembly	M&D

3. Results and Discussion

Two trends are present across most results – LFP shows lower vehicle-cycle impacts, and NMC chemistries exhibit decreasing impacts as the nickel content increases. These patterns will be noted throughout.

3.1 Raw material extraction & processing (RME&P)

3.1.1 Energy usage and GHG emissions

Figures 1a, 1c, and 1d show the energy use and GHG emissions during the RME&P stage for the various battery chemistries analyzed. Additionally, the mass of active material necessary for the scoped vehicle is shown in Figure 1b. Because of the varying specific energies of the chemistries (see Table 2), the energy use and emissions per kg must be scaled by the mass of active material. The total material required for an LFP battery – including cathode and other components – is about 100-200 kg greater than that of an NMC battery. However, the RME&P LFP energy use per kg is less than one-third that of all NMC chemistries. Thus, though requiring more material by mass, LFP RME&P energy use and emissions remain significantly lower than for NMC, illustrating an LFP vehicle-cycle advantage. This is consistent with findings in other recent work.[12, 28]

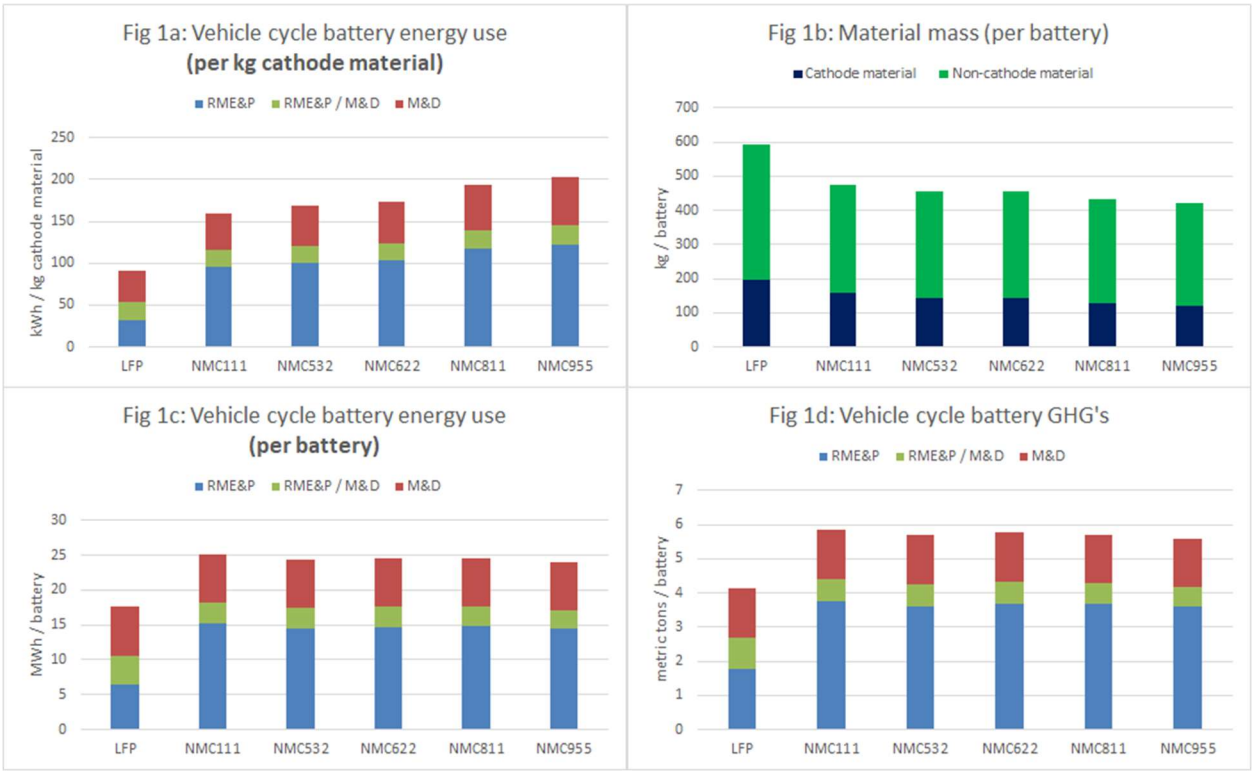


Figure 1a-d: RME&P / M&D category indicates impacts from materials as defined as RME&P / M&D in Table 3. a) Vehicle cycle energy impact per kg cathode material. b) Material mass for a vehicle level battery pack. c) Vehicle cycle energy impact per vehicle level battery pack. This is a direct result of multiplying the Fig 1a with the cathode material mass in Fig 1b. d) Vehicle cycle GHG's per vehicle level battery pack.

Within the NMC variants, those with higher Ni content show a modest trend toward reduced active material quantity, energy use, and emissions. These improvements stem from the higher energy density of high-nickel NMC chemistries and suggest that increasing Ni content may enhance sustainability in the RME&P phase. The magnitude here is small and variable – however, the reduction of material production requirements will compound sustainability benefits in the use phase.

3.1.2 Local environmental pollutants

The LFP vehicle-cycle advantage remains for RME&P local environmental pollutants. However, high-Ni NMC chemistries do not trend toward reduced impact – only 2 of 8 of the evaluated local pollutants decrease as Ni increases (PM10 and PM2.5). The most impactful RME&P pollutants relative to the total vehicle cycle impact were found to be PM10, NO_x, SO_x, and black carbon (BC), as shown in Fig 2a-d. Examining GREET's underlying emissions databases reveals the material-specific drivers behind these impact trends. For the LFP – NMC comparison, the lower emission factors of phosphoric acid and iron sulfate (key precursors for LFP cathodes) contribute to consistently lower local pollutant impacts for LFP across the RME&P stage, even when accounting for lithium's higher emissions in certain categories. For the NMC impacts, the causes are more nuanced. The decline in PM10 across higher-Ni NMC chemistries primarily results from

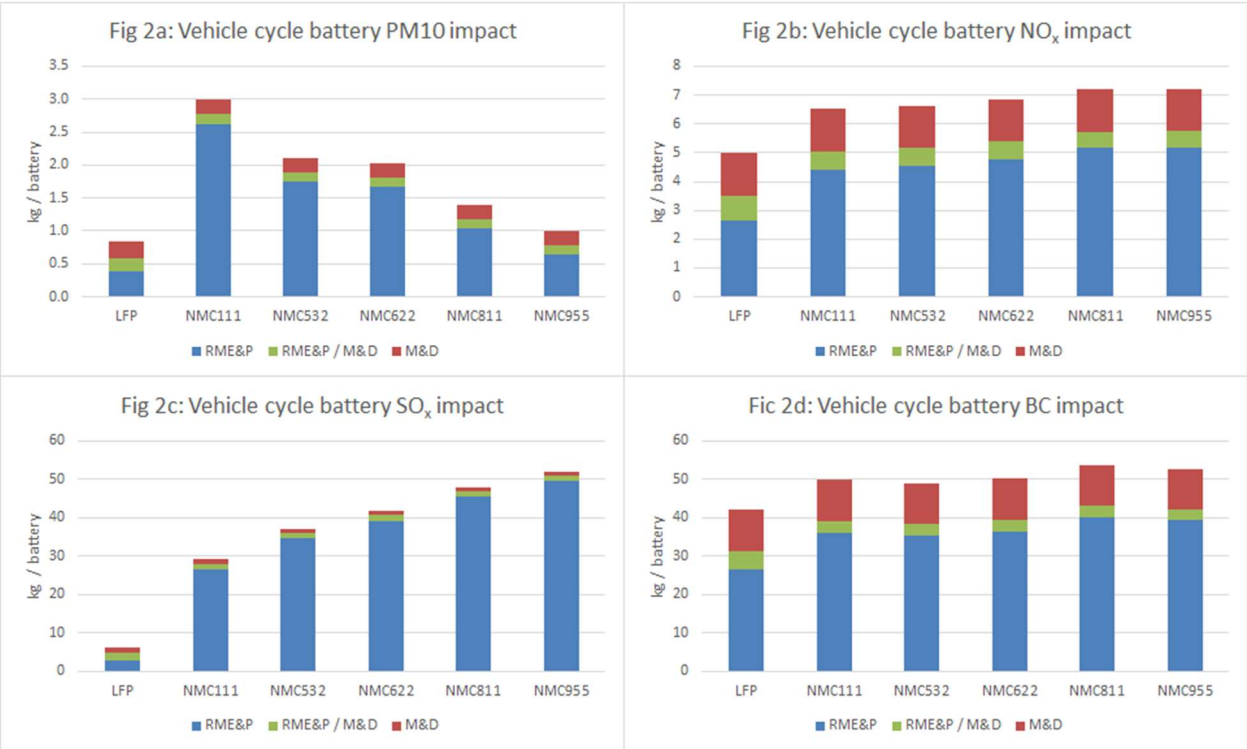


Figure 2a-d: RME&P / M&D category indicates impacts from materials as defined as RME&P / M&D in Table 3. a) Vehicle cycle PM10 impact per vehicle level battery pack. b) Vehicle cycle NO_x impact per vehicle level battery pack. c) Vehicle cycle So_x impact per vehicle level battery pack. d) Vehicle cycle BC impact per vehicle level battery pack.

reduced cobalt content; according to GREET, cobalt sulfate production emits approximately 15 times more PM10 per ton than nickel sulfate. The increase in NO_x emissions with higher nickel content stems from nickel's NO_x emissions being roughly 4.5 times greater per ton than the average of cobalt and manganese. However, it is tempered by the reduction in total cathode mass required, as seen in Figure 1b. The upward trend in black carbon emissions similarly reflects nickel's higher per-ton emissions compared to the average of cobalt and manganese – though in this case, cobalt has lower emissions than manganese. The SO_x emissions result from a significant portion of Ni being found in sulfide-based deposits. [13, 14] When extracted and smelted, the sulfur combines with oxygen to generate SO_x.[15] GREET indicates that most of these emissions occur during nickel primary extraction. GREET assumes that 80% of Ni comes from sulfide-based deposits, driving the alignment between Ni content and SO_x emissions. Future SO_x emissions may decline as sulfide-based ores become exhausted and replaced with laterite ores, although the transition to non-sulfide-based ores will result in higher mining energy intensity.[16, 14]

Beyond the emissions impacts of the RME&P stage, there exist environmental impacts driven by waste and biodiversity concerns. Lèbre et al.[17] examine the environmental, social, and governance (ESG) risks associated with mining key minerals for the energy transition. Their findings categorize relative risks by mineral type across ESG dimensions. In the waste category, materials used in LFP chemistries (e.g., iron, phosphate) have lower impact than those used in NMC variants, with waste burden increasing alongside nickel content. For conservation-related impacts (driven primarily by biodiversity concerns), LFP falls amid the NMC chemistries, with increasing Ni content gradually increasing the biodiversity impact.

3.1.3 Water consumption

Figure 3 highlights a case where the uncertain RME&P / M&D (shown in green) occupies a significant portion of the impact. This drives some uncertainty in the comparison between LFP and NMC water consumption. In GREET, green segment primarily originates from aluminum sheet manufacturing, specifically from electricity generation. According to GREET's 2030 grid assumptions, U.S. electricity-related water consumption is driven largely by hydroelectric power generation (62%), followed by nuclear (15%), natural gas (9%), and coal (7%). The consumption due to hydroelectric power stems mostly from reservoir evaporation. Dai et al.[8] similarly identify aluminum production as a major driver of water use in cell manufacturing, attributing it to electricity demands as well. Among NMC

chemistries, higher nickel content is associated with slightly reduced water consumption. The magnitude of RME&P water consumption is relatively small (<5L per battery).

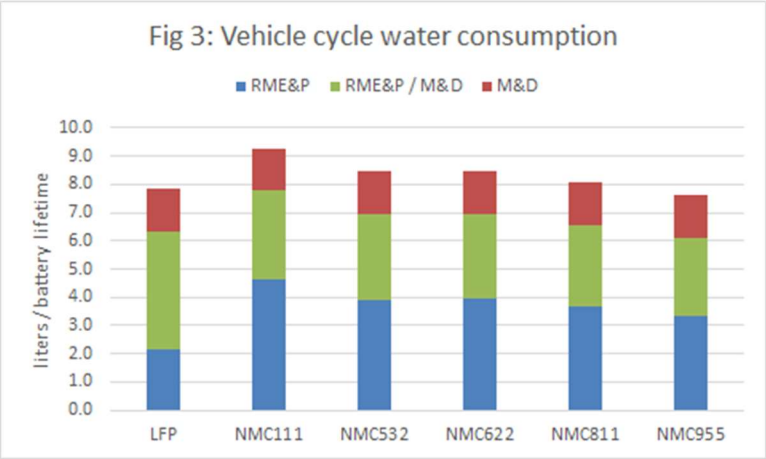


Figure 3: Vehicle cycle water consumption of various chemistries. Green indicates the portion which is split in belonging to the raw material extraction & processing and manufacturing & distribution phases.

Existing literature supports the trend for high Ni content to align with lower water consumption, but not for LFP to have lower water consumption. Lèbre et al.[17] classify Mn and Li as high water risk elements (0.68 and 0.6, respectively); Co (0.31) and Ni (0.4) are lower. Kiemel et al.[18] evaluates water impact in terms of freshwater ecotoxicity and eutrophication, finding (in decreasing order) Li, Co, Ni, and Mn to be the most intensive, and Al, Fe, and P to be significantly less water intensive. This indicates agreement with Lèbre et al.'s results - increasing the lithium content (through LFP) would result in higher water intensity, while replacing Mn with Ni (as in high-Ni NMC chemistries) would decrease the relative intensity.

3.1.4 Tradeoff summary:

Because the analysis assumes a fixed vehicle range, and LFP has a lower specific energy than NMC, selecting LFP drives an increase in the mass of all battery materials produced. However, due to LFP's lower emissions rate per kg, it generally results in lower RME&P impacts. Within the NMC chemistries, selecting a high Ni content will generally lead to lower RME&P impacts in energy, GHG's, particulate matter, and water consumption, but may increase other impacts, particularly SO_x emissions.

3.2 Manufacturing and distribution (M&D)

Throughout this section, it should be noted that the impacts are fractions of the M&D phase alone. Figures 1-3 illustrate that the M&D phase is generally a minor portion of the vehicle cycle relative to RME&P, and thus should be taken in that context.

3.2.1 Energy usage and GHG emissions

Figures 1a, 1b, and 1d show the energy use and GHG emissions during the M&D stage for various chemistries, alongside corresponding RME&P data. Trends 1 & 2 no longer hold – the emissions intensive portion of NMC production has passed, while the mass-related disadvantage of LFP has yet to appear in the use phase. Although material mass plays a smaller role in M&D than in RME&P, a slight reduction in the M&D bars in Figure 1c (compared to 1a) indicates the effect is still present. This is primarily due to a reduction in the quantity of ancillary materials used in the pack – electronic parts, coolant, insulation, and steel, as well as a portion of the plastics, aluminum, and copper. Across chemistries, approximately 80% of the M&D energy is consumed by battery assembly.

A significant assumption for this stage of the analysis that cascades into other environmental areas is the amount of energy required for battery assembly. For our analysis, "battery assembly" includes cell, module, and pack level assembly. Ellingsen et al.[19] discusses the variability in literature for cell assembly, with values as low as 586 MJ/kWh and an average of 2318 MJ/kWh. Dai et al.[8] estimate that the cell production and pack manufacturing energy found in another study corresponds to 525 MJ/kWh. They also conducted their own data collection with a Chinese cell manufacturer, reporting a lower energy requirement of 170 MJ/kWh at the cell level.

When converting to units of MJ/kWh, our analysis gives battery production energies ranging from 883 MJ/kWh (low NMC111) to 1450 MJ/kWh (high LFP). These values are in within the wide band mentioned above, particularly when considering differences in assumed throughput, cell design, and manufacturing efficiency / setup, key drivers for differences in EV battery LCA's.[9]

3.2.2 Local environmental pollutants

The effect of the M&D phase on local environmental pollutants is generally less than 20% of the total vehicle cycle – Figures 2a–2d present some of the impacts, with the full dataset available in Supplemental Section 1. As noted above, approximately 80% of the energy used in the M&D phase can be attributed to battery assembly. As a result, battery assembly energy is the primary driver of local pollutants in M&D; impact varies significantly by pollutant, but not significantly by chemistry (maximum of 4% variation). Table 4 shows the percentage of the M&D phase pollutants attributed to energy used in the battery assembly.

	Energy	GHGs	Water	VOC	NOx	PM10	PM2.5	SO_x	BC	OC
%	81-83	79-81	87-88	43-47	79-81	28-31	41-44	22-25	88-89	86-88

Table 4: Estimated share of M&D phase impacts attributable to battery assembly energy.

This indicates that local environmental impacts during the M&D phase are heavily dependent on the electricity grid mix. Combined with the low sensitivity to chemistry, this suggests that a good tool to reduce environmental impacts for manufacturers who cannot influence battery design is improving the cleanliness of their manufacturing grid.

3.2.3 Water consumption

Figure 3 shows water consumption from the M&D phase, which – when considered alongside Table 4 – appears relatively small and primarily driven by battery assembly energy. As discussed in Section 3.1.3, most of this water consumption results from hydroelectric power generation, particularly evaporation from reservoirs. Dai and Kelly[8] agree that cell production water use is small relative to that which is consumed in aluminum and NMC111 powder, and others[19,20] indicate that module and pack energy consumption (and hence water consumption) are expected to be minimal.

3.2.4 Tradeoff summary:

Impacts in the M&D phase are less sensitive to battery chemistry than in the RME&P phase and GREET identifies no significant tradeoffs at this stage. However, energy used during battery assembly (which is a major contributor to M&D phase impacts) is generally defined in literature per kWh. This convention effectively overlooks the mass and volume advantages of NMC chemistries. In practice, the reduced handling, packaging, and intra-plant transport associated with NMC's higher energy density could offer modest efficiency gains, though these are likely small compared to RME&P impacts.

3.3 Use

The vehicle-cycle impacts discussed above refer solely to emissions from battery production. However, the use phase focuses on the emissions incurred from the entire vehicle (and grid) during operation. Thus, comparing the vehicle cycle values above and the use phase values below will not consider the production burdens for the non-battery portions of the vehicle.

3.3.1 Energy usage and GHG emissions

Use-phase impacts clearly favor chemistries with higher specific energy. This is logical, as all the use phase energy and GHGs are directly tied to electricity generation. A lower total mass corresponds to improved energy efficiency, and less energy required by the vehicle. Specific values and percentage reductions relative to LFP are in Table 5. This trend of high specific energy materials having lower use phase impact is consistent in literature.[12, 21]

The simulated mass delta is entirely in the battery pack materials, not the rest of the vehicle. For the case of comparing LFP to NMC955, 53% of the mass delta originates from

	LFP	NMC111	NMC532	NMC622	NMC811	NMC955
Energy (mmBtu)	**100%** 441	**91%** 403	**90%** 397	**90%** 396	**88%** 390	**88%** 387
Water (gal)	**100%** 10.2	**91%** 9.3	**90%** 9.2	**90%** 9.2	**88%** 9.0	**88%** 9.0
CO2 (kg)	**100%** 17,159	**91%** 15,680	**90%** 15,450	**90%** 15,421	**88%** 15,179	**88%** 15,044
GHGs (kg)	**100%** 18,315	**91%** 16,736	**90%** 16,490	**90%** 16,459	**88%** 16,201	**88%** 16,057
VOC (kg)	**100%** 2.3	**91%** 2.1	**90%** 2.0	**90%** 2.0	**88%** 2.0	**88%** 2.0
NO_x (kg)	**100%** 13.4	**91%** 12.3	**90%** 12.1	**90%** 12.1	**88%** 11.9	**88%** 11.8
PM10 (kg)	**100%** 7.4	**91%** 7.3	**90%** 7.3	**90%** 7.2	**88%** 7.2	**88%** 7.2
PM2.5 (kg)	**100%** 1.8	**91%** 1.7	**90%** 1.7	**90%** 1.7	**88%** 1.7	**88%** 1.7
SO_x (kg)	**100%** 9.4	**91%** 8.6	**90%** 8.5	**90%** 8.5	**88%** 8.3	**88%** 8.3
BC (kg)	**100%** 0.1	**98%** 0.1	**98%** 0.1	**98%** 0.1	**97%** 0.1	**97%** 0.1
OC (kg)	**100%** 0.5	**95%** 0.5	**94%** 0.5	**94%** 0.5	**93%** 0.4	**93%** 0.4

Table 5: Use phase impacts as evaluated in GREET. Percentages are relative to LFP.

the materials designated as RME&P in Table 3. 14% of the mass delta is from materials designated as M&D, and the remaining 33% is from the mixture category, as defined in Table 3. The total mass reduction between the two specific energy extremes is simulated at 215 kg, or 31%.

3.3.2 Local environmental pollutants

The reduction in local environmental pollutants during the use phase (see Table 5) mimics the energy / global emissions trend, again resulting entirely from a reduction in required electricity generation. The exception to this is black carbon and organic carbon, where the impact is partially from tire and brake pad wear.

3.3.3 Water consumption

Water consumption can also be seen in Table 5, exclusively originating from electricity generation. As discussed in section 3.1.3, the electricity generation-based water consumption modeled by GREET primarily comes from hydroelectric reservoir evaporation.

3.3.4 Tradeoff summary:

Use-phase tradeoffs between LFP and NMC are significant and opposed to those in the RME&P phase. The higher specific energy of the NMC chemistry results in improved energy efficiency and lower impacts across all metrics. Additional weight-related benefits – such as reduced road and component wear – are not captured by GREET but further support NMC as the more sustainable option during the use phase.

3.4 End-of-Life (EOL)

EOL modeling enables comparison of the environmental benefits of different recycling strategies across battery chemistries. An idealized 100% recycling rate is assumed in these simulations to highlight the theoretical tradeoffs between chemistries and recycling methods. This implies that all of the value metal (Ni/Mn/Co or Li) used in manufacturing the batteries originates from a given recycling process.

GREET supports three recycling pathways for analysis: pyrometallurgy, hydrometallurgy, and direct recycling. Pyrometallurgy (pyro) is a high-temperature process to separate and extract metals from solid materials by leveraging differences in their melting and boiling points.[22] Hydrometallurgy (hydro) is a process that uses chemical solutions to selectively dissolve and extract metals from solid resources, enabling efficient separation and high-purity recovery at relatively low energy consumption.[22] Direct recycling (direct) restores spent cathode materials by replenishing lithium and repairing structural integrity, enabling recovery with minimal energy input and preserving the original material's electrochemical performance.[22]

3.4.1 Energy usage and GHG emissions

The implementation of any recycling method decreases energy use and GHG emissions across chemistries. NMC-based chemistries benefit more than LFP largely due to the greater recovery potential of high-impact metals like Ni and Co.[24] Percentage reductions in energy and GHG emissions are relatively consistent across NMC variants. Notably, direct recycling yields 2–3 times greater impact compared to hydro- or pyrometallurgical recycling. Table 6 shows detail on the percentage improvements across chemistries and recycling methods.

Literature generally agrees with these findings, although results vary due to recovery rates, grid mixes, and cell formats. Quan et al.[28] found minimal reductions in global warming potential (GWP) in China for both NMC and LFP across all three recycling methods, although hydro is shown to be most favorable. Kallitsis et al.[23] reported reductions in GWP for NMC111 for both hydro and pyro. Mohr et al.[24] review literature to find a range of GWP and energy impacts for hydro and pyro, including some that indicate greater GWP by implementing recycling. However, studies found an average benefit, with NMC trending toward greater reduction.

	Energy					Water consumption					GHG				
	LFP	NMC111	NMC532	NMC622	NMC811	LFP	NMC111	NMC532	NMC622	NMC811	LFP	NMC111	NMC532	NMC622	NMC811
Hydro	1%	2%	2%	3%	2%	1%	3%	2%	2%	1%	2%	3%	4%	4%	3%
Pyro	1%	4%	4%	4%	3%	1%	5%	4%	4%	2%	2%	3%	3%	3%	1%
Direct	1%	6%	6%	6%	7%	2%	7%	6%	6%	6%	1%	9%	9%	9%	9%
	VOC					CO					NO_x				
	LFP	NMC111	NMC532	NMC622	NMC811	LFP	NMC111	NMC532	NMC622	NMC811	LFP	NMC111	NMC532	NMC622	NMC811
Hydro	0%	0%	0%	1%	0%	1%	3%	3%	4%	3%	3%	8%	9%	11%	9%
Pyro	0%	1%	1%	1%	1%	1%	4%	4%	5%	4%	3%	11%	12%	13%	10%
Direct	0%	1%	1%	1%	1%	1%	5%	6%	6%	6%	6%	14%	15%	16%	17%
	PM10					PM2.5					SO_x				
	LFP	NMC111	NMC532	NMC622	NMC811	LFP	NMC111	NMC532	NMC622	NMC811	LFP	NMC111	NMC532	NMC622	NMC811
Hydro	1%	20%	14%	13%	7%	3%	13%	11%	11%	6%	2%	49%	56%	60%	63%
Pyro	1%	20%	14%	14%	7%	3%	15%	12%	12%	7%	2%	50%	57%	60%	63%
Direct	3%	20%	14%	14%	9%	6%	15%	13%	13%	11%	7%	51%	58%	61%	65%
	BC					OC									
	LFP	NMC111	NMC532	NMC622	NMC811	LFP	NMC111	NMC532	NMC622	NMC811					
Hydro	3%	6%	6%	7%	4%	3%	5%	6%	6%	4%					
Pyro	4%	8%	8%	8%	4%	3%	7%	7%	8%	5%					
Direct	6%	11%	11%	12%	14%	6%	9%	9%	10%	11%					

Table 6: The percent improvement from implementing 100% recycling across chemistries and recycling methods for various impacts, as compared to 100% virgin material.

3.4.2 Local environmental pollutants

The effect of recycling on local environmental pollutants is variable, with the most pronounced improvements shown for NO_x, PM10, and SO_x. The substantial reduction in SO_x emissions is due to avoidance of mining and refining, as discussed in Section 3.1.2. Kallitsis et al.[23] also find reductions in general pollutants due to implementing recycling on NMC chemistries, highlighting particulate matter and sulfur dioxides.

3.4.3 Water consumption

Improvements in water consumption from recycling closely follow the reduction in energy demand, as discussed in Section 3.1.3. and noted in literature.[23] Variability arises from water used during the recycling process itself, and from additional savings related to avoided material production that is not directly tied to energy inputs.

3.4.4 Tradeoff summary

The EOL tradeoff primarily revolves around the opportunity for improvement present for NMC chemistries. NMC chemistries exhibit greater environmental gains from recycling

due to the recoverability and impact intensity of their cathode metals: nickel, manganese, and cobalt.[24]

In contrast, GREET indicates LFP offers fewer benefits at EOL. This is due to the difficulty of recovering lithium[22], the primary value metal in LFP, and the lower impact contribution from its other cathode materials. As a result, selecting LFP today – while beneficial for cost or SO_x reduction – offers limited environmental benefit for future batteries under recycling scenarios. If recycling processes are implemented, an NMC battery produced today can reduce environmental impacts for future NMC batteries. This contrast between LFP and NMC recycling benefit is supported by previous findings.[25, 26]

This GREET-based analysis does not consider the impact of LFP's enhanced cycle life on EOL. Literature that considers cycle life finds that when considering a 33% enhanced LFP cycle life, implementing recycling still favors NMC for resource efficiency and environmental sustainability.[12] LFP batteries are, however, better matched for second life applications due to their superior cycling and thermal stability, as well as that its low specific energy is not so impactful in a stationary application.[25, 26, **Error! Bookmark not defined.**] These can lead to significant environmental and financial benefits that do not present themselves with NMC chemistries.[29]

Our analysis does not consider the benefit recycling provides from minimizing mining related land-use disruption, or the value of waste reduction and supply chain stabilization. Given the high mineral usage of EV's[22], establishing recycling will be critical even if the environmental benefit is small, as with LFP.

3.5 Vehicle Cycle and Use Overview

While it is important to understand the drivers and tradeoffs unique to each lifecycle stage, a full lifecycle comparison is necessary to evaluate net environmental performance. Table 7 summarizes the relative environmental impacts of the chemistries across the entire vehicle lifecycle, under the assumption of all virgin materials and no recycling.

From this high-level view, it is apparent that high-nickel NMC chemistries result in slightly lower impacts across most categories due to their improved energy density and reduced use-phase energy demand. However, these gains are modest: switching from LFP to NMC955 reduces total lifecycle energy use by 6%, water consumption by 10%, GHG emissions by 3%, PM2.5 by 3%, and organic carbon by 4%.

A critical exception is SO_x emissions, which increase by 158% when moving from LFP to NMC955. This reinforces the key theme of this analysis: each choice contains tradeoffs that will have impacts within and outside of the lifecycle phase where the choice is made.

	LFP	NMC111	NMC532	NMC622	NMC811	NMC955
Energy	**100%**	**98%**	**96%**	**96%**	**95%**	**94%**
(mmBtu)	581	568	559	559	553	548
Water	**100%**	**96%**	**94%**	**93%**	**92%**	**90%**
(kg)	53	51	50	50	49	48
GHGs	**100%**	**100%**	**99%**	**99%**	**98%**	**97%**
(tonne)	28	28	27	27	27	27
VOC	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
(kg)	64	64	64	64	64	64
NO_x	**100%**	**101%**	**101%**	**102%**	**103%**	**102%**
(kg)	24	24	24	24	25	25
PM10	**100%**	**120%**	**111%**	**110%**	**104%**	**100%**
(g)	10	12	11	11	11	10
PM2.5	**100%**	**106%**	**102%**	**102%**	**99%**	**97%**
(kg)	3.4	3.6	3.5	3.5	3.4	3.3
SO_x	**100%**	**179%**	**207%**	**223%**	**245%**	**258%**
(g)	28	50	58	63	69	73
BC	**100%**	**101%**	**100%**	**101%**	**102%**	**101%**
(g)	218	220	218	219	222	221
OC	**100%**	**97%**	**96%**	**96%**	**97%**	**96%**
(g)	667	649	641	643	646	641

Table 7: Total lifecycle environmental impact of LFP and NMC-based chemistries for various pollutants, relative to LFP impact.

4. Recommendations and Tradeoffs

Choosing between an NMC or LFP battery chemistry involves balancing LFP's lower per-kilogram impacts against NMC's higher specific energy and associated reductions in material demand during the production and use phases. This tradeoff is not uniform across the lifecycle: LFP performs best in the raw material extraction and processing (RME&P) stage, while NMC shows greater benefits in the use and end-of-life (EOL) phases, where its lower weight and better recyclability reduce long-term impacts. The most significant chemistry-based impact is the increase in SO_x emissions when implementing high Ni content chemistries, as seen in Table 7. This stems from an increase in the mining and refining of Ni containing ores. However, this is paired with a decrease in total energy and water consumption, as well as organic carbon, GHG's, and PM2.5 (to a lesser extent). Two recommendations result from this:

1. Avoid selecting a low Ni content chemistry, as it is the least optimal solution. It results in significantly increased SO_x emissions while obtaining nearly none of the benefits of the high Ni content chemistries.

2. Between high-Ni NMC and LFP, selecting high-Ni NMC is the better environmental choice. Although it results in higher SO_x emissions, these are geographically concentrated around refining facilities – locations where mitigation strategies can be more easily implemented.[27] In contrast, LFP's impacts during the use phase depend on decarbonizing the broader electricity grid, which is a slower and less targeted process. Furthermore, high-Ni NMC chemistries present greater opportunities for future impact reduction via recycling, particularly in addressing SO_x emissions. This reflects NMC's broader potential for environmental circularity: while LFP currently offers upstream cost and emissions advantages, NMC is better positioned to deliver long-term sustainability gains as recycling infrastructure and policy mature. LFP is potentially the superior choice when a battery second life is assured.

The agreement of these results with literature is mixed. Almeida et al.[7], statistically evaluate the impact of chemistry change using GREET, finding that LFP is statistically cleaner than NMC811 (NMC955 was not evaluated). A portion of the conflict may be a result of vehicle choice - Almeida uses 2018 model year vehicle efficiency, with lower battery specific energy. Advances in battery or vehicle technology in the 7 years between vehicle model years would play a significant part in altering the results. Almeida et al evaluate two chemistries no longer available in GREET: LMR-NMC: Gr and LMR-NMC: Gr-Si, finding these to be the cleanest chemistries. However, more recent results agree with our analysis, finding NMC to have lower global warming potential than LFP.[12, 28]

In addition to environmental impacts, economic, and social factors play a critical role in sustainability. These impacts are not captured within GREET, and their absence represents a key limitation of this analysis. They will have their own standalone impacts, but may also augment or hinder the environmental impacts. For example, LFP is less expensive than NMC. Lower battery prices could accelerate BEV adoption, displacing more ICEVs. This broader systems-level benefit may outweigh the chemistry-specific environmental differences modeled here. However, because LFP's affordability stems from raw material prices, the financial incentive for recycling is lower.[22] The economically incentivized EOL for LFP EV batteries may instead lie in a second life[29], enhanced by LFP's longer cycle life. Nonetheless, implementing LFP recycling after this second life is good waste management practice, though it may require policy intervention.[30]

5. Impact

The impact of the work is most succinctly defined by comparing the effect of following vs. ignoring the recommendations. In 2023, 15.6 million vehicles were sold in the U.S.[31] Of these, ~8% were BEVs[32], giving a total of 1.25 million BEVs sold in 2023. If 50% of these were able to be converted from NMC111 to NMC95, the lifecycle GHG and water consumption reductions would be 582 kilotonnes and 2 kilotonnes, respectively. However, this would incur an increase in SO_x emissions of 14 kilotonnes. To put this in further context, this would be the equivalent of avoiding the total lifecycle impact of 21,700 vehicles worth of GHG's and 41,200 vehicles worth of water, and adding the impact of 192,500 extra vehicles worth of SO_x emissions.

In addition to the environmental effects, changing battery chemistry at large scale would have significant social effects. In this area, it is likely that LFP has an advantage. Mining of cobalt is concentrated in the Democratic Republic of the Congo, and is well known to rely on conditions with human rights issues[17, 33]. A push toward higher Ni content chemistries would lessen the reliance on Co, but changing to LFP would eliminate it entirely. Ni's high SO_x emissions not only pose a risk to the environment, but also to local communities.[33] LFP is not without issue – the higher lithium content drives an increase in water consumption that affects local community farming and wildlife habitat.[33, 34] As stated previously, the environmental tradeoffs of NMC vs. LFP are only one aspect of a complex issue; this work is one part of the work being done by UM CSS to understand the full context.

6. Summary/Conclusions

This report set out to evaluate the life cycle tradeoffs between Lithium Iron Phosphate (LFP) and Nickel Manganese Cobalt oxide (NMC) battery chemistries, using the University of Michigan Center for Sustainable Systems (UM CSS) framework and GREET 2024 modeling tools. The objective was to inform environmentally conscious chemistry selection for EV applications by assessing energy usage, emissions, water consumption, and pollutant generation across four major lifecycle stages: raw material extraction and processing (RME&P), manufacturing and distribution (M&D), use, and end-of-life (EOL).

Through both original GREET modeling and existing literature, we found that LFP chemistries tend to have lower environmental burdens during the RME&P phase due to less intensive material processing, despite requiring more material overall due to lower specific energy. However, NMC chemistries - especially those with high nickel content - offer lower impacts during the use phase due to their higher specific energy and associated vehicle weight savings. This results in lower overall energy consumption and GHG emissions over the vehicle's operational life. At EOL, NMC chemistries also offer greater environmental benefit through recycling pathways, particularly when using advanced direct recycling techniques.

Based on these findings, our key recommendations are:

1. When optimizing for environmental benefits, void low-Ni NMC chemistries, which incur the sulfur oxide (SO_x) burdens associated with Ni without reaping the energy or use-phase benefits.
2. Prefer high-Ni NMC chemistries over LFP when evaluating long-term environmental benefit, as they enable more efficient use-phase performance and future benefits through recycling – despite localized SO_x impacts.

If adopted at scale, these recommendations could lead to lifecycle reductions in GHG emissions and water consumption - by up to 582 kilotonnes and 2 kilotonnes respectively for 50% of U.S. 2023 BEV sales transitioning from NMC111 to NMC95. However, this would be offset by a localized increase of 14 kilotonnes of SO_x emissions - highlighting the importance of site-specific mitigation efforts at Ni refining operations.

Further research should explore:

- Economic and social dimensions of chemistry selection, including labor practices, supply chain ethics, and end-user affordability.
- Grid decarbonization scenarios, as use-phase benefits are tightly coupled to electricity source.

- Alternative cathode materials, such as LMR-NMC variants no longer supported in current GREET versions but promising in prior literature.

Finally, this analysis underscores the importance of considering lifecycle-wide impacts rather than isolated metrics. While there is no one-size-fits-all solution, aligning chemistry selection with vehicle use-case, grid context, and long-term recyclability potential will be critical to achieving sustainable electrification at scale.

7. Appendices

7.1 Analysis Procedure

Analysis procedure:

1. Within Excel Script Code "GREET2_LFP_NMC", set Table 1 and Table 2 inputs.
2. Run "GREET2_LFP_NMC".
3. Perform adjustments as necessary to combine results. For example, manually sum results for components within categories to achieve results for RME&P, M&D, and RME&P / M&D categories. See "Supplemental_1" Tab "TEC_Results_Copy" for detail.
4. Manually build charts, or use additional scripts to build charts for review and comparison. Examples of these additional scripts are given in the "TEC_Results_Copy" tab of Supplemental 1. Adjustments to existing chart building scripts may be necessary depending on the information desired to be represented.

7.2 Excel Scripts

See Supplemental_1 for Excel Scripts.

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