INVESTIGATING ELECTRIC VEHICLE SUSTAINABILITY ASSESSING THE IMPACT OF DOMESTIC MANUFACTURING AND SUPPLY CHAIN DYNAMICS

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Abstract

The transition to electric vehicles (EVs) is a critical step in mitigating negative environmental impacts from fossil fuel consumption, such as climate change. However, the environmental impacts (e.g., carbon footprint) of EVs depends heavily on their production processes, particularly the manufacturing of lithium-ion batteries (LIB) with chemistries like Nickel-Manganese-Cobalt (NMC) and Lithium Iron Phosphate (LFP). This study analyzes NMC811 battery cell production within the material supply chain, leveraging recent legislative frameworks such as the Inflation Reduction Act (IRA), Bipartisan Infrastructure Law (BIL), and CHIPS and Science Act. Tracking manufacturing sites under these frameworks and projecting their estimated production capacity suggests that the U.S. could achieve self-sufficiency in battery production by 2023 exceeding the domestic demand of 1,225 GWh/year by 2032. The study also examines the global warming potential (GWP) and potential for emissions reductions in various stages of the supply chain from domestic (U.S.) manufacturing. A life cycle assessment (LCA) model was used to quantify the Cradle-to-Gate (C2G) GWP of NMC811 battery cell production under two scenarios: the current supply chain scenario and a predicted scenario reflecting onshoring of battery cell manufacturing enabled by new U.S. investments. Results show a 9 % reduction in GWP with onshoring. A hotspot analysis delineating individual contributions of electricity, energy, and resources was conducted for the cathode production, the largest contributor to the GWP per kilogram of NMC811 battery cell. This hotspot analysis showed a 13 % reduction, excluding transportation impacts. This reduction is largely attributed to the use of a less emission-intensive electricity grid in the U.S., accounting for 94 % of the GWP decrease. Emissions from the transportation of critical minerals were separately assessed using embedded resource accounting (ERA), which revealed a 56 % reduction in GWP for the predicted scenario. Thus, this study highlights the environmental benefits (as represented by GWP) of onshoring production and its contribution to the global transition toward sustainable energy. It underscores the importance of domestic manufacturing in reducing emissions and enhancing the sustainability of EVs.

1. Introduction and Motivation

The transportation sector remains a critical area for reducing global greenhouse gas (GHG) emissions. Due to its reliance on oil-based fuels, it is responsible for approximately 28 % of GHG emissions in the US[1], 13 % of the global emissions and over 30 % of total emissions in end-use sectors.[2] Electric vehicles (EVs) offer one potential pathway for mitigating these emissions through improved energy efficiency combined with the decarbonization of electricity sources. Environmental concerns, in addition to vehicle performance and technological advances, play a key role in EV adoption.[3] Previous scholars have estimated EV lifecycle impacts based on numerous conditions, types of vehicles, battery chemistries, and supply chain impacts.[4–6] As EV adoption in the U.S. continues, policies such as the Inflation Reduction Act (IRA), Bipartisan Infrastructure Law (BIL), and CHIPS and Science Act have appropriated over $300 billion toward fostering domestic EV manufacturing and domestic supply chain development to meet the growing EV demand.[7,8]

The production of EV battery materials consists of two major phases, the mining of critical minerals and the production of components and products. Countries such as China, Australia, Indonesia, the Democratic Republic of the Congo (DRC), and South Africa dominate the former phase, while China, South Korea, and Japan are responsible for much of the latter.[9] Within this global supply chain, there exist a variety of sustainability challenges, including land use conflicts, high energy demands, mineral supply issues, recycling difficulties, GHG emissions, and water use.[10] While progress has been made in social and environmental protections, gaps in policies and approaches highlight the need for innovation in mining, technological advancements, investments, and comprehensive frameworks to evaluate and

strengthen institutional capabilities for a sustainable transition.[10] While transitioning to domestic production may offer environmental benefits, it also presents complex trade-offs involving resource use, infrastructure requirements, and policy-driven economic shifts. With an interest in such questions on trade-offs in the supply chain of EVs, our work seeks to evaluate how changing production locations influence life-cycle emissions, addressing critical trade-offs for achieving decarbonization goals under evolving policies.

The motivation for this study stems from three critical factors: (1) the growing importance of detailed, location-specific life cycle assessments (LCAs) to accurately capture emission hotspots, (2) the need to assess how localized production aligns with decarbonization goals, and (3) the policy-driven push to strengthen domestic manufacturing under the IRA, BIL, and CHIPS and Science Act.

2. Review of Related Work

Questions about the environmental footprint of EVs have been explored extensively over the past decade. For example, previous research on the LCA of EVs highlights the GHG emissions associated with battery production, with chemistries like LFP, NMC, and LMO (lithium ion manganese oxide) contributing emissions of 2,705–3,061 kg CO_2-eq for a 28 kWh battery.[11] Regional differences, such as China's coal-based electricity grid, further amplify these emissions compared to the U.S., where cleaner energy sources may reduce impacts.[11] The environmental benefits of EVs across their lifecycle are also highly dependent on the energy mix, emphasizing the critical role of decarbonized energy in maximizing their sustainability.[6] Battery production can also contribute to other environmental concerns such as exposure to carcinogens, ozone depletion, and ecotoxicity.[4,12] Updated databases, such as Ecoinvent, have addressed previous simplifications in life cycle inventory (LCI) models, particularly for nickel and cobalt products, improving accuracy for NMC materials.[13] Finally, recent analyses have explored the potential for onshoring battery production in North America, highlighting existing nickel production in Canada and plans for lithium spodumene mines.[14] However, no study has conducted a regionalized LCA for U.S. battery production scenarios post-IRA and BIL investments, leaving a gap in understanding how domestic manufacturing might reshape environmental outcomes.

In addition to seeking an understanding of EVs' environmental footprint, there is increased attention to the environmental sustainability and security of supply chains.[9,15] The vulnerabilities of the EV battery supply chain have become an increasing area of focus due to its reliance on critical minerals, current geopolitical contexts, and importance in the transportation decarbonization transition.[9,16,17] Supply chain analyses highlight the dependence on certain midstream and downstream processes in a few geographical areas, with these stages heavily concentrated in China.[9] For example, a large share of NMC (80 %) and LFP (92 %) cathodes for LIB rely on minerals refined in China.[9] These concentrations highlight systemic risks and emphasize the need to consider material transport and logistics in emissions assessments. Understanding the environmental impact of transportation within the supply chain offers an opportunity to identify emissions hotspots and inform strategies for building a sustainable EV supply chain that may not be apparent using traditional LCA approaches.

The dynamic policy landscape plays a vital role in understanding vulnerabilities in the critical mineral supply chain while ensuring sustainability. Domestic sourcing requirements under the IRA, such as sourcing 80 % of critical minerals by market value, face significant challenges, particularly for materials like cobalt and graphite.[18] While strategies like recycling and environmental safeguards aim to reduce reliance on geopolitically sensitive regions, policy adjustments may be needed to align with sustainability goals.[18] Unlike prior analyses, the current study seeks to understand how new manufacturing sites established through IRA, BIL, and CHIPS funding might impact the supply chain and emission impacts.

The study seeks to quantify the environmental implications of onshoring the production of NMC 811 batteries used in EVs, from the current globalized supply chain to domestic manufacturing. The GHG emissions trade-offs and benefits of onshoring battery production will be evaluated further, discussing the potential reductions in emissions associated with cathode manufacturing and critical mineral transportation using LCA and embedded resources accounting (ERA), respectively.

3. Technology Approach

3.1 Research Questions

The technological focus of this study is NMC-811 battery chemistry, which is being increasingly favored by EV manufacturers due to its lower cost, higher energy density, and greater potential mileage[19]. The NMC811 LIB cell comprises a graphite anode and nickel-manganese-cobalt (NMC811) cathode separated by a liquid electrolyte. This study seeks to address two questions: (1) What is the impact on the global warming potential (GWP) of an NMC 811 EV battery if production is onshored to the U.S.? (2) What is the GWP contribution of transporting critical minerals for the NMC 811 battery cell, and how might this change in the future with increased domestic manufacturing to meet U.S. EV battery demand? Given the energy and resource intensity along with the geographically dispersed nature of mineral sourcing, refining, and transportation, understanding the GHG contribution across various life cycle stages is key to optimizing supply chain pathways and reducing the carbon footprint of EV batteries. Together, these questions provide a framework for assessing the sustainability implications of transitioning to a domestic supply chain for LIB.

3.2 Methodology

This study's approach to evaluating the environmental impacts of onshoring NMC 811 manufacturing to the U.S., is shown in Figure 1 and summarized in the remainder of this section.

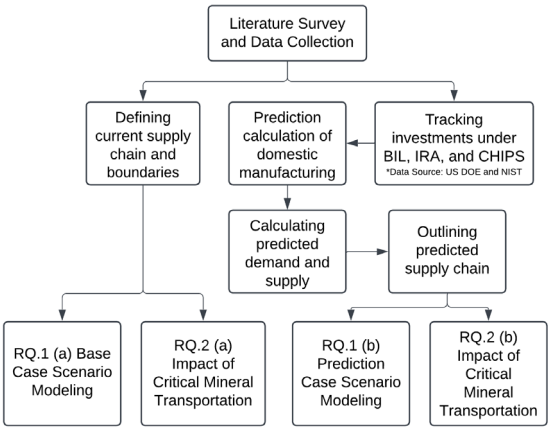

Figure 1. Methodology

3.2.1 Mapping Potential Domestic Manufacturing Capacity

Based on the information available from the new federal investments previously highlighted and the U.S. battery production capacity estimates (in GWh/year) from the Argonne National Laboratory (ANL)[20], the study estimated the total potential production of these newly identified manufacturing sites.

3.2.2 Identifying Current and Potential Supply Chain Scenarios

The emissions for an NMC811 battery cell were analyzed under two scenarios: a base case and a prediction case. The base case scenario represents the current globalized supply chain, where most battery components used in the U.S. are manufactured abroad. After manufacturing, these components are transported to the U.S. for assembly and distribution. According to the literature[21], the cathode, which accounts for approximately 41 % of the battery cell's weight, is entirely imported into the U.S. Specifically, 42 % of the cathodes used in U.S. battery assembly are sourced from China, 33 % from Japan, 15 % from South Korea, and the remainder from other countries. The anode, contributing ≈38% of the battery's weight, is also mainly imported, with 65 % sourced from China, 19 % from Japan, 6 % from South Korea, and 10 % produced domestically. The electrolyte (≈16 % of the battery's weight) is similarly dominated by imports, with 65 % from China, 12 % from Japan, 4 % from South Korea, 17 % from other countries, and 2 % domestically. The battery separator (≈2 % of the battery cell's weight) shows a similar trend. These data form the foundation for the regionalization of the base case LCA model.

Critical minerals are also widely dispersed across geographic regions. China imports approximately 67.5 % of its refined cobalt from the DRC for various uses[22], of which about 40% is specifically allocated for EV battery production that eventually reaches the US. Similarly, 10 % of Japan's refined cobalt imports come from refineries in Finland. For lithium, China depends on Australia for around 34 % of its imports, and South Korea receives roughly 14 % of its lithium from Chilean refineries. Additionally, 29 % of nickel and 23 % of manganese that China uses for NMC battery production are sourced from the Philippines and South Africa, respectively[9]. This global distribution of critical mineral mining, refining, and production processes is important in the high GWP associated with the base case transportation of these minerals.

The prediction case simulates a future scenario where the U.S. meets its domestic battery component demand through localized production, holding all else constant. In this scenario, critical minerals continue to be mined internationally, consistent with the status quo but are assumed to be transported directly to the U.S. for refining, component manufacturing, and battery assembly within newly established domestic facilities. The data used for regionalization in the prediction case is based on the funding allocated to individual domestic facilities. It is important to recognize that supply chain shifts do not occur in isolation; global competitors (e.g., China, South Korea, and Japan) are simultaneously investing in processing and production of battery components to strengthen their position in the global EV supply chain as well as making efforts to decarbonize their energy resources.[23,24]

Furthermore, while the projection assumes that refining of critical minerals shifts entirely to the U.S., this is a theoretical best-case scenario rather than a likely outcome. In reality, geopolitical constraints, regulatory barriers, and economic feasibility factors may result in partial reliance on foreign refining and processing for the foreseeable future. Thus, results from this study should be considered general magnitude estimates of the maximum potential impacts. Future work could explore mixed onshoring models where some upstream processing remains global while midstream and downstream processes are increasingly localized.

3.2.3 Calculating Emissions under each Current and Predicted Supply Chain Scenario

For both scenarios, cradle-to-gate (C2G) GHG emissions (i.e., embodied emissions) were calculated for 1 kg of NMC811 battery cell, encompassing all supply chain life cycle stages, from raw material extraction to production of the battery cell. The quantification of GHG emissions associated with battery cell production was conducted using the LCA methodology in accordance with ISO 14040 and ISO 14044 standards. LCA provides a scientific methodology for calculating the potential environmental impacts of a product or service over its entire life cycle[25,26]. The impact assessment method applied was TRACI v2.1[27] and only GWP was considered in this study. The Functional Unit (FU) is ‘production of 1 kg of NMC 811 battery cell’. The LCA was completed in openLCA[28] (OLCA) using the Ecoinvent 3.10 (E310) database[29].

E310 includes an LCI for the NMC811 battery cell, based on the methodology presented by Dai et al. (2017)[30] and supplemented with expert judgment as documented in the database. The specific model used as a base model in this study is "Ecoinvent 3.10 battery cell production, Li-ion, NMC811 CutOff-U," representing production in China, with data partially collected from a Chinese company[29]. This base model was the preferred choice because its LCI aligns with the production characteristics of NMC811 analyzed in the study. According to Ecoinvent, the specific energy density of the cell is 0.209 kWh/kg, calculated using data from ANL[30–32]. The dataset encompasses the entire production process for LIB cells (i.e., C2G), from battery cell components and materials for additional parts (e.g., external casing) entering the factory gate through the production of Li-ion battery cells.

ERA, a similar approach to carbon accounting, was used to quantify the GWP of critical mineral transportation. Like C2G LCA, ERA calculates the embodied emissions of a product or service over its C2G lifecycle[33]. However, ERA does not rely on proprietary LCA software or specialized databases. Instead, it utilizes publicly available emission factors from general literature, making it a viable option when access to proprietary LCA databases is restricted or specific processes are not available in those databases. In this study, ERA was applied to quantify GHG emissions associated with critical minerals. While these emissions could have been calculated as part of the LCA, the use of a pre-existing model from E310 presented challenges. The upstream processes, such as mining and refining of critical minerals, are modeled in E310 as a system of systems. This complexity made it difficult to isolate the bill of materials exclusively for critical minerals, thereby complicating the assessment of transportation impacts. To address this limitation, ERA was employed alongside transport mode-specific emission factors from E310 and literature-based data to quantify transportation-related GWP of critical minerals outside of the OLCA software.

3.2.3.1 Regionalization of the battery cell production (RQ 1a & RQ 1b)

The base model mentioned in Section 3.2.2 was regionalized to enhance the geographic representativeness of the supply chain by updating electricity grids and substituting country-specific raw materials in a few cases when data was readily available in the E310 database, with a focus on processes with significant contributions to a battery cell's GWP. Regionalization in this study has been conducted at the national level. The base case scenario assumes that when a specific battery component is manufactured in a country, all upstream inputs are fully sourced and processed within the same country, including raw materials and energy required to meet supply chain demands for that product.

While this assumption does not align with the complexity of actual global supply chains, it simplifies the modeling process by circumventing the intricate and often challenging task of tracing upstream supply chain activities. For the predicted scenario, the model input assumptions for onshoring were determined based on the allocation of legislative funding. For instance, some U.S. facilities received funding to produce sulfate salts required in producing precursor cathode active material (pCAM)[8]. Consequently, the production of sulfate salts and subsequent downstream processes were assumed to be onshored while inputs required for producing the upstream materials maintain the base case supply chain pathways. Similarly, inputs for which no dedicated funding was allocated for onshoring in relation to EV production were also modeled under the base case assumptions (e.g., production or extrusion of plastics used in battery cell manufacturing). Figure 2 illustrates the hierarchical structure of supply chain "levels" for battery cell production, providing a framework for the regionalization process used to enhance the geographic specificity of the LCA model.

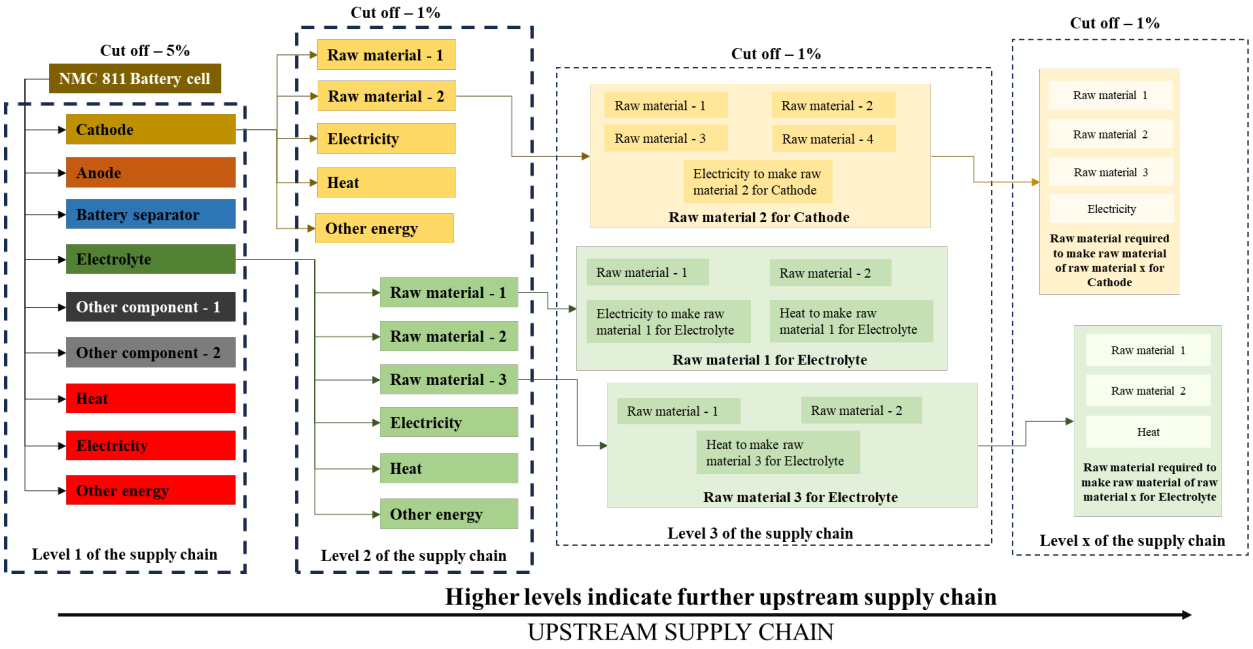

Figure 2. Supply chain level characterization

The regionalization process began at Level 1 of the supply chain and extended progressively to higher levels (i.e., Levels 2 and 3) further upstream. Level 1 of the supply chain encompasses the major battery components, including the cathode, anode, battery separator, and energy inputs (such as electricity) required for assembling a battery cell. Regionalization at this level involved modifying the electricity grid source to reflect region-specific energy systems. For components contributing more than 5 % of the overall GWP in the base model, regionalization was extended to Level 2 by updating sources for electricity grids and relevant inputs (when available), which includes raw materials and energy required to produce Level 1 components. If a raw material in Level 2 contributed more than 1 % to the overall GWP of the battery cell, it was further regionalized at Level 3 by updating the source electricity grid and incorporating region-specific processes. This iterative process continued upstream in the supply chain until the contribution of a given process input fell below 1 % of total GWP. This systematic approach prioritized the regionalization of components and raw materials with substantial contributions to GWP, while those with minimal impacts were excluded from further iterations. By focusing on significant contributors, the method improved the geographic specificity of the model without compromising efficiency or unnecessarily increasing complexity.

One of the primary limitations of the current study is that only the electricity grid and a limited number of raw materials were regionalized to represent the region of interest. Other energy sources, such as industrial energy and other process inputs that do not have pre-existing models in the E310 database, were not regionalized due to the lack of readily available data. Additionally, while the prediction case assumes the current grid mix and emission profile, national emissions profiles will change over time because of decreasing cost of renewable energy and decarbonization efforts both domestically and internationally. For example, China's electricity mix is projected to decarbonize substantially by 2030[34]. Even if the U.S. electricity grid continues to decarbonize, the emissions gap between U.S.-based and China-

based battery production may narrow over time and lower the potential reductions estimated in this study. These aspects should be addressed in future studies to enhance the model's geographical representativeness and accuracy.

3.2.3.2 Critical mineral transportation modeling (RQ 2a & 2b)

This study traces the supply chain and travel path of critical minerals (lithium, cobalt, nickel, and manganese) used in the production of NMC811 battery cells, from mining and refining through intermediate stages (e.g., cathode production) and final battery cell assembly stage. ERA was used to quantify the impact of this transportation for both the base case and prediction case scenarios.

For the base case, this study maps the supply chain consistent with Cheng et al.[9], which reflects the current global situation. For the prediction case, this study assumes that the U.S. will continue trading with the same countries from which it currently imports these commodities (which slightly deviates from the status quo countries that supply critical minerals to the battery component-producing countries). This assumption allows a practical analysis of transportation impacts while accounting for existing trade relationships. The movement of critical minerals cannot directly be observed; thus, imported commodities for the production of EV batteries are tracked using Harmonized System (HS) codes[35]. These commodities include critical minerals in both their raw and refined forms. For instance, raw cobalt is found primarily in cobalt ores and concentrates as well as in nickel ores and concentrates. Refined cobalt appears as cobalt sulfates, oxides, and other derivatives essential for cathode production. To track the flow of each mineral in terms of actual product traded, rather than numerous commodities having different amounts of mineral content, conversion factors identified by Cheng et al.[9] are used to standardize all trade in terms of units of contained mineral as shown in Equation 1.

$$m_{\alpha} = \sum w_{\alpha,\iota} \times c_{\alpha,\iota} \tag{1}$$

Where m_{α} refers to the total weight of the contained critical minerals (α), $w_{\alpha,\iota}$ represents the weight of the imported commodity with HS code (ι) containing critical minerals (α), and ($c_{\alpha,\iota}$) represents the conversion factor. This weight of the critical mineral required to produce 1 kg of NMC811 battery cell is used to calculate emissions associated with their transportation pathways from C2G. These pathways include truck transport from mining sites to refining locations within countries, rail transport for longer intra-country domestic distances, and sea transport for international shipping of raw or processed materials. This is achieved by multiplying the weight of the transported mineral by the distance it travels via a specific mode of transport and the emission factor associated with that mode, as shown in Equation 2. The emission factor, which is unique for each transport mode, is sourced from the E310 database. The base case and predicted case follow the transportation pathway highlighted in Section 3.2.2.

$$E_{\gamma} = m_{\alpha,\gamma}\big((d_w \times e_w) + (d_t \times e_t) + (d_r \times e_r)\big) \tag{2}$$

Where E_{γ} refers to the total emission of transporting critical mineral α from country γ. (d) Represents the distance traveled, and (e) represents the emissions associated with said mode of transport where (w) represents water (ocean transport), (t) represents land (truck transport), and (r) represents rail transport. The calculation in Equation 2 is repeated for each mineral and each corresponding country and then aggregated to provide total emissions from transporting critical minerals through the supply chain for both scenarios.

4. Discussion

This study identified at least 68 new manufacturing sites under the previously mentioned federal investments. Using battery production capacity estimates from ANL,[20] it was estimated that the U.S. could achieve a total battery production capacity of 1,564 GWh/year by 2032. The Environmental Defense Fund projects a domestic demand of 1,225 GWh/year by 2032[36], indicating that domestic manufacturing is well-positioned to meet the nation’s demand.

With the current reliance on imports for battery components, as outlined in the base case scenario in Section 3.2.3, total emissions associated with production of 1 kg of NMC811 battery cell amount to 16.16 kg CO_2-eq. This value lies within the range of Winjobi.et.al[37], who reported GWP of NMC811 battery cells ranging from 14.63 to 24.01 kg CO_2-eq/kg cell (depending on various battery specifications, electricity grid mixes and energy conversion factors etc). The Sankey diagram (Figure 3) illustrates the GWP contributions from various parts of the supply chain under the base case scenario. China contributes the most to the overall GWP of the battery cell assembled in the U.S. for two primary reasons. First, China is the largest supplier of components imported to the U.S. Second, the electricity grid mix in China significantly influences its emissions profile. According to the latest IEA data[38], over 60 % of China's electricity is generated from coal, compared to approximately 17 % in the U.S.[39]. This is also reflected in the emission factors in the E310 database, where the GWP of China's electricity grid is nearly double that of the U.S. This disparity is evident when comparing the base case to the predicted scenario, where most components and raw materials required for battery cell production are assumed to be manufactured domestically. In the predicted scenario, the GWP associated with the production of 1 kg of NMC811 battery cell is approximately 14.79 kg CO_2-eq, representing a 9 % reduction. It is important to note that only the electricity grid and a limited number of input processes are regionalized in this study. Once other significant GWP contributors (heat, mechanical energy sources, and other raw materials) are regionalized, this percentage reduction is expected to increase because the U.S. predominantly relies on natural gas for industrial energy[40,41] while China primarily relies on coal, which has higher emissions comparatively. Although this study does not model equilibrium effects or indirect emissions changes, future work could assess system-wide impacts beyond direct emissions calculations, incorporating additional regionalization as part of a broader analysis.

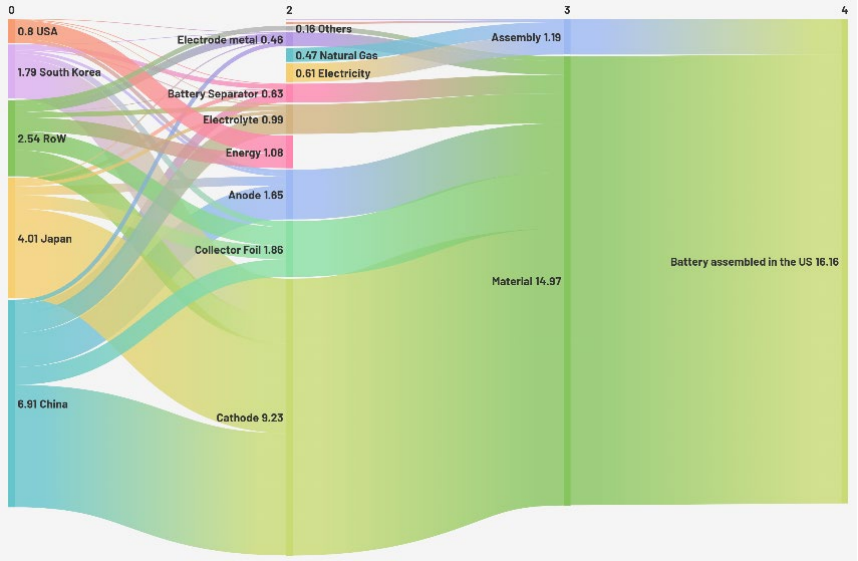

Figure 3. GWP of NMC811 Battery Cell Production per base case Scenario (in kg CO_2-eq per kg of battery cell) Numbers along the x-axis above the plot represent manufacturing stages: 0 corresponds to the location, 2 to components and energy source, 3 to resource and energy, and 4 to final assembly.

4.1 Hotspot Analysis - Cathode production without transportation

To further assess the sources of emissions, the contributions of various input processes like resources, electricity, waste/by-products, and heat and mechanical energy were disaggregated to provide a hotspot analysis (Figure 4) for the cathode manufacturing process. The biggest contributors to the production of the cathode are electricity, energy, and resources. For the hotspot analysis, the inputs that are regionalized are electricity and a few resource inputs. The FU used in hotspot analysis is the "quantity (in kg) of cathode required to produce 1 kg of NMC 811 battery cell". Note that the production hotspot analysis excludes transportation, and a separate analysis was conducted for transportation impacts (Figure 5). Consequently, the total impact for the cathode under the base case in Figure 4 is 9.00 kg CO_2-eq, which differs from the value presented in Figure 3 due to transport exclusion. Among these factors, the US electricity emerged as the dominant contributor to emission reductions from onshoring. This resulted in a 13 % decrease in emissions, from 9.00 kg CO_2-eq to 7.92 kg CO_2-eq per, with electricity accounting for 94 % of this reduction.

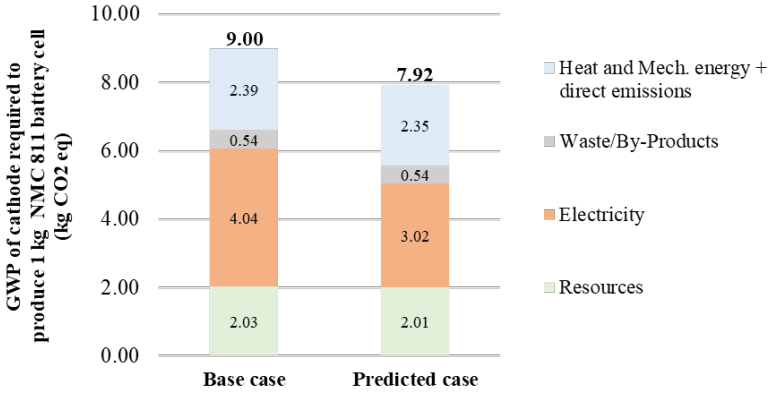

Figure 4. GWP of NMC811 Cathode Production

4.2 Hotspot Analysis - Transportation

Literature[19,42,43] shows transportation-based emissions ranging from 3 % to 5 % of total battery production emissions. The ERA conducted in this study yielded a consistent result, showing that transport contributes to about 5 % of the overall battery cell's GWP in the base case scenario. Although existing studies often mention transportation emissions, they rarely include a detailed analysis of these emissions. In contrast, this study provides a more granular assessment by performing an ERA as explained in Section 3.2.3.2. When analyzed independently, these emissions demonstrate a significant decline when comparing the base case to the prediction case. Amongst these critical minerals, cobalt has the highest GWP impact, contributing 0.60 kg CO_2/kg of NMC811 battery cell produced, followed by lithium at 0.14 kg CO_2 eq, nickel at 0.03 kg CO_2 eq, and manganese at less than 0.01 kg CO_2, as seen in Figure 5. GWP of Critical Mineral Transportation. Together, these emissions total 0.77 kg CO_2 equivalent per kg of NMC811 battery cell produced. For the prediction case, the projected emissions are 0.34 kg CO_2-eq per kg of NMC811 battery cell, showing a 56 % decrease from the base case, as observed in Figure 5. Note that the prediction case assumes all refining occurs in the US, which, as previously noted, is unlikely to fully materialize, which would cause the reduction in transportation related emissions

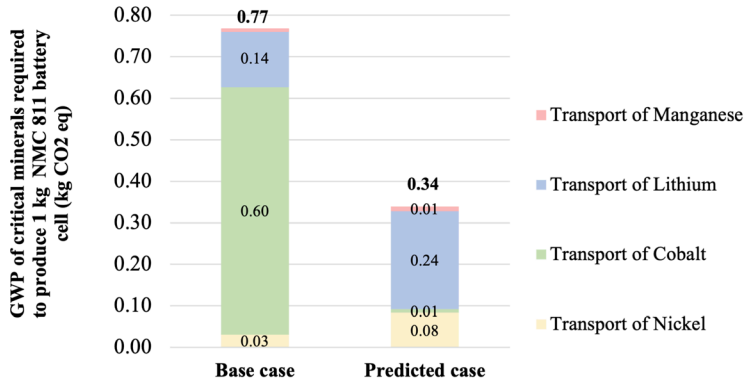

Figure 5. GWP of Critical Mineral Transportation

to still be measurable but not as substantial as in the predicted scenario. Additionally, supply chain restructuring could lead to alternative transportation modes with different emissions profiles.

5. Conclusions & Recommendations

This study highlights the potential for reducing GHG emissions in EV battery production based on changes to locations of component refining and manufacturing. Our findings indicate that domestic manufacturing, supported by investments from policies like the BIL, IRA, and CHIPS Act, could reduce emissions associated with both production and transportation of critical minerals if these manufacturing investments lead to the targeted manufacturing capacity.

However, it is important to note that several limitations in this study's approach exist. For example, in the transportation ERA, a large environmental benefit could be obtained if minerals mined in Africa and South America come directly to the U.S. for refining and manufacturing instead of transiting around the world to other countries (e.g., China). In reality, existing U.S. laws and norms that govern conflict minerals and human rights in other countries (e.g., DRC) would essentially prohibit whole-scale shift of importing a commodity (e.g., cobalt) directly to the U.S.,[44,45] and market conditions are not conducive to mining Cobalt domestically.[46] However, the results highlight the importance of addressing systemic bottlenecks, such as in cathode production and mineral processing, to realize environmental benefits from onshoring.

Future research should address several limitations to further advance the understanding of EV battery sustainability. First, expanding the scope and complexity of the analysis would provide more accurate estimates, including regionalizing other significantly contributing inputs (like heat/mechanical energy and other resources), incorporating dynamic electricity grid projections, considering policy changes in other countries that may impact the supply chain aligned with anticipated production capacity timelines, and introducing sensitivity and uncertainty analysis into the estimates. Second, while this study focused on NMC811 batteries, future work could expand to other chemistries, such as LFP, to capture a broader spectrum of supply chain dynamics and emissions. Investigating the use of domestic recycled content for battery production offers another promising pathway for reducing the environmental impact of critical mineral extraction and refining. Finally, developing public models that rely solely on publicly available data could promote transparency and accessibility, enabling broader collaboration and application of these findings. These efforts will be critical to advancing sustainable practices in EV battery manufacturing and supporting the transition to a low-carbon transportation sector.

6. Acknowledgments

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