

Carbon Footprint of Lithium-Ion Battery Manufacturing: Measuring the Net Global Warming Impact of Localized Mineral Extraction vs. Shipping Supply Chains

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Abstract

The global transition to electric vehicles (EVs) and renewable energy storage has driven unprecedented demand for lithium-ion batteries (LIBs). The environmental integrity of this transition, however, depends on the carbon burden embedded in battery supply chains. This study comparatively evaluates two supply-chain configurations: a globalized model in which raw minerals move across continents for processing and assembly, and a localized model based on near-sourced extraction and regionally co-located manufacturing. A process-based life cycle assessment (LCA), aligned with ISO 14040/44 principles, is applied within a cradle-to-gate system boundary and expressed as kilograms of carbon dioxide equivalent per kilowatt-hour (kg CO₂-eq/kWh) of finished NMC-811 cell capacity. The analysis preserves common material, logistics, processing, and grid-intensity assumptions across the scenarios. Results show that transport distance alone does not determine the lowest-carbon supply chain. The globalized configuration records 76.20 kg CO₂-eq/kWh, while localization under a high-fossil electricity grid increases the footprint to 78.20 kg CO₂-eq/kWh. In contrast, localization combined with a decarbonized regional grid reduces the footprint to 19.40 kg CO₂-eq/kWh, a 74.5% reduction relative to the globalized baseline. The findings indicate that electricity-grid carbon intensity during refining, precursor synthesis, and cell assembly can outweigh the emissions saved by shortening transport routes. For corporate decision-makers, localization should therefore be evaluated together with energy sourcing, supplier-grid characteristics, and clean-power access rather than treated as an inherently low-carbon strategy.

Keywords: Lithium-Ion Battery; Carbon Footprint; Life Cycle Assessment; Supply Chain Localization; Global Warming Potential; Grid Carbon Intensity; Sustainable Supply Chain

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Introduction

The electrification of transport and the expansion of renewable-energy storage have made lithium-ion batteries a central technology in contemporary decarbonization strategies. Yet the climate value of electrification is influenced not only by emissions avoided during vehicle use but also by the environmental burden created before a battery reaches the vehicle or storage system. Lithium, nickel, cobalt, graphite, and other battery inputs pass through extraction, chemical refining, precursor synthesis, cell manufacturing, and logistics stages, each of which consumes energy and generates greenhouse-gas emissions. Consequently, the geographical and energy architecture of the battery supply chain has become a strategic sustainability issue for manufacturers, investors, and policy makers.

Historically, battery and automotive supply chains have been designed around cost efficiency, inventory discipline, scale economies, and just-in-time delivery. This has encouraged geographically dispersed networks in which minerals can be extracted in one region, chemically processed in another, converted into battery materials elsewhere, and finally assembled near end markets. Such networks create long transport routes, but they can also place energy-intensive processing in locations with established industrial infrastructure. The environmental implication is therefore not straightforward: a long supply chain may incur more logistics emissions, while a short supply chain may still carry a high footprint if its processing stages depend on carbon-intensive electricity.

The growing emphasis on carbon disclosure, supply-chain resilience, digital product traceability, and localized sourcing has strengthened the business case for regional battery production. However, localization is frequently discussed as though geographical proximity automatically reduces lifecycle emissions. The central problem addressed in this paper is whether the reduction in transport emissions achieved through localization is sufficient to offset the carbon intensity of the electricity used in extraction, refining, precursor production, and cell assembly. The paper therefore evaluates the interaction between logistics distance and regional electricity-grid intensity rather than considering either variable in isolation.

The study has three linked objectives: first, to compare the cradle-to-gate global warming potential of globalized and localized LIB supply-chain structures; second, to identify the relative contribution of logistics and electricity-intensive processing to the total carbon footprint; and third, to translate the quantitative comparison into sourcing and infrastructure implications for corporate managers. The contribution of the study is a decision-oriented comparison showing that proximity and decarbonization are complementary rather than interchangeable strategies.

Literature Review and Theoretical Framework

Carbon intensity across the LIB manufacturing chain

Life-cycle assessment literature demonstrates that battery production contains substantial embedded emissions before the battery enters service. Majeau-Bettez, Hawkins, and Stromman (2011) established the importance of evaluating battery technologies through a lifecycle perspective rather than focusing only on operational use. Emilsson and Dahllof (2019) similarly reviewed energy use, carbon emissions, metal use, environmental footprint, and recycling in lithium-ion vehicle battery production. These studies support a process-based view in which the total manufacturing footprint is accumulated across extraction, refining, materials processing, logistics, and assembly rather than assigned to a single stage.

For the present study, the total cradle-to-gate global warming potential is represented as:

$$GWP_{total} = GWP_{extraction} + GWP_{refining} + GWP_{transport} + GWP_{assembly}$$

The expression provides the accounting structure used to compare the scenarios. It is particularly relevant to LIB manufacturing because chemical refining, cathode precursor synthesis, climate-controlled production environments, and high-temperature processes can create substantial electricity and thermal-energy demand. The carbon burden of these activities changes materially when the electricity supplying them is generated from different regional energy mixes.

Transport efficiency and the role of grid intensity

The environmental effect of supply-chain distance must be interpreted alongside the efficiency of transport modes. Maritime bulk and container shipping can move large quantities over long distances with relatively low emissions per ton-kilometer compared with road freight. As a result, very long ocean routes can appear visually dominant in a supply-chain map without necessarily being the dominant source of cradle-to-gate emissions. The present model therefore separates logistics emissions from process emissions instead of assuming that distance is a sufficient proxy for carbon intensity.

Electricity-grid characteristics create a second and potentially larger source of variation. Pehl et al. (2017) show the importance of integrating lifecycle considerations into assessments of low-carbon power systems, reinforcing the broader principle that the emissions associated with electricity depend on the underlying generation mix. In battery production, this means that identical or similar industrial processes can produce very different carbon outcomes when powered by fossil-intensive, mixed, or highly decarbonized grids. The

International Energy Agency (2023) also places critical-mineral supply chains within the wider clean-energy transition, highlighting the strategic importance of how minerals are sourced and processed.

Research gap and analytical proposition

The practical debate around battery localization often emphasizes resilience, security of supply, and reduced transport distance. The synopsis underlying this study identifies a narrower analytical gap: localization and transport reduction are frequently treated as direct indicators of environmental improvement even though the energy source used in localized processing can reverse the expected benefit. This paper therefore tests a simple proposition through scenario modeling: the carbon advantage of localization is conditional on the carbon intensity of the regional energy system. A localized high-fossil configuration may perform no better, and may perform worse, than a geographically dispersed configuration, whereas localization coupled with clean electricity can produce a large reduction in total GWP.

Research Methodology

Research design, functional unit, and system boundary

The study applies a process-based Life Cycle Assessment approach consistent with ISO 14040/44 principles. The analytical boundary is cradle-to-gate: the model begins with mineral extraction and follows the material through refining, cathode precursor synthesis, logistics, and final NMC-811 cell assembly at the gigafactory gate. Battery use, vehicle operation, end-of-life treatment, recycling credits, and second-life applications are outside the defined boundary. The functional unit is one kilowatt-hour (1 kWh) of finished battery-cell capacity, and results are reported in kg CO₂-eq/kWh.

A scenario-comparison design is used rather than an observational firm-level dataset. The purpose is to isolate how logistics structure and grid carbon intensity alter the modeled footprint while preserving the supplied assumptions. The material mass balance uses approximately 0.75 kg of lithium carbonate equivalent per kWh of NMC-811 cell capacity. No additional empirical values are introduced beyond the assumptions and results contained in the source study.

Operational scenarios

Scenario A represents a globalized or dispersed supply chain. Lithium is mined in Western Australia, transported by oceanic bulk carrier to mainland China for chemical processing and cathode precursor production, and subsequently moved by container ship to a European gigafactory for final cell assembly. Scenario B represents a localized or regionalized structure in which lithium is extracted through direct lithium extraction or localized hard-rock methods within Europe, refined regionally, and moved by rail or truck to a co-located European manufacturing system. To distinguish geography from electricity effects, the localized configuration is evaluated under both a high-fossil grid (Scenario B-1) and a decarbonized grid (Scenario B-2).

Table 1. Operational Logistics and Transport Parameter Assumptions

Supply Chain Phase		Scenario A (Globalized) Mode & Distance	Scenario B (Localized) Mode & Distance	Assumed Carbon Factor
Mine to Refinery		Oceanic Bulk Carrier (11,000 km)	Electric Freight Rail (400 km)	Bulk Ship: 5 g CO ₂ /t-km; Rail: 12 g CO ₂ /t-km
Refinery to Precursor	to	Heavy-Duty Trucking (250 km)	Co-located (0 km)	Truck: 85 g CO ₂ /t-km
Precursor to Gigafactory	to	Oceanic Container (15,000 km)	Heavy-Duty Trucking (300 km)	Container: 8 g CO ₂ /t-km

Table 1 preserves the original logistics assumptions. Its role is to make the comparison transparent: the globalized scenario carries long maritime distances, whereas the localized scenario replaces them with shorter rail and road movements and co-location at the refinery-to-precursor stage.

Electricity-grid carbon intensity

The model treats the carbon intensity of electricity used in chemical processing and kiln synthesis as a dominant sensitivity variable. Three static grid conditions are retained from the source study: a high-fossil industrial grid of 620 g CO₂-eq/kWh, a mixed continental grid of 310 g CO₂-eq/kWh, and a decarbonized regional grid of 45 g CO₂-eq/kWh. These values are used as scenario inputs rather than as claims about a single facility. The comparative logic is to determine whether logistics savings from localization remain meaningful when energy-intensive stages operate under different electricity mixes.

Results and Discussion

Consolidated global warming potential

Applying the supplied material mass balance and process assumptions produces the consolidated GWP results shown in Table 2. The table is reproduced as an editable Word table without altering the source values.

Table 2. Consolidated GWP Breakdown (kg CO₂-eq/kWh of Finished Cell)

Process Stage	Scenario A: Globalized	Scenario B-1: Localized + High-Fossil Grid	Scenario B-2: Localized + Decarbonized Grid
Raw Mining & Sorting	3.20	4.10	1.10
Chemical Refining & Purifying	18.50	22.40	3.80
Cathode Precursor Synthesis	24.10	28.50	5.20
International / Local Logistics	8.40	1.20	0.80
Cell Assembly (Gigafactory)	22.00	22.00	8.50
Net Global Warming Potential	76.20	78.20	19.40

Scenario A produces a total cradle-to-gate footprint of 76.20 kg CO₂-eq/kWh. Its logistics component is 8.40 kg CO₂-eq/kWh, while the larger contributions arise from chemical refining and purifying (18.50), cathode precursor synthesis (24.10), and cell assembly (22.00). This distribution indicates that the visually extensive transport network is not the largest component of the modeled footprint.

Scenario B-1 sharply reduces logistics emissions to 1.20 kg CO₂-eq/kWh, but the total footprint rises to 78.20 kg CO₂-eq/kWh. Raw mining and sorting increase to 4.10, chemical refining and purifying to 22.40, and cathode precursor synthesis to 28.50 kg CO₂-eq/kWh. Because cell assembly remains 22.00, the savings achieved through shorter transport are more than offset by higher process-related emissions under the high-fossil grid assumption. This is the central result of the comparison: localization by itself does not guarantee carbon reduction.

Scenario B-2 demonstrates the opposite outcome when localization is paired with a decarbonized grid. Logistics decline further to 0.80 kg CO₂-eq/kWh, but the decisive reductions occur in the energy-intensive stages: raw mining and sorting fall to 1.10, chemical refining and purifying to 3.80, cathode precursor synthesis to 5.20, and cell assembly to 8.50 kg CO₂-eq/kWh. The resulting total is 19.40 kg CO₂-eq/kWh. Relative to the 76.20 kg CO₂-eq/kWh globalized baseline, the source study reports a 74.5% reduction.

The logistics fallacy in carbon auditing

The results support what the source study describes as the “Logistics Fallacy”: the assumption that the longest geographical route must also be the largest source of emissions. In Scenario A, international and local logistics contribute 8.40 kg CO₂-eq/kWh, approximately 11% of the total cradle-to-gate footprint reported in the study. The remaining footprint is dominated by industrial stages whose emissions depend strongly on the energy used to operate them. Therefore, a sourcing decision based only on kilometers traveled can misidentify the dominant carbon lever.

This finding does not imply that logistics are environmentally irrelevant. The localized scenarios clearly reduce the modeled transport contribution. Rather, it shows that logistics must be interpreted in proportion to the complete manufacturing system. A manager who removes ocean freight but shifts production to a more carbon-intensive electricity environment can achieve a shorter supply chain while increasing total GWP. Conversely, a longer supply chain can remain competitive in carbon terms if energy-intensive production occurs under a lower-carbon power system.

Localization and clean-grid synergy

The comparison between B-1 and B-2 isolates the strategic importance of electricity. Both are localized configurations, yet their total footprints differ substantially: 78.20 versus 19.40 kg CO₂-eq/kWh. The geographical logic of localization is therefore insufficient as a standalone decarbonization criterion. Its environmental value is realized when regional extraction, refining, precursor synthesis, and assembly are supported by a low-carbon electricity mix.

This result also clarifies the role of the mixed continental grid assumption of 310 g CO₂-eq/kWh in the methodological framework. It represents an intermediate energy context and reinforces the broader analytical point that supply-chain carbon performance should be treated as a function of both physical movement and energy-system characteristics. The source study does not report a separate consolidated GWP total for this intermediate grid, so no additional result is inferred here.

Managerial and Strategic Implications

The first managerial implication is that proximity should not be used as a proxy for sustainability. Procurement teams evaluating lithium, refined chemicals, cathode materials, or cell-manufacturing partners should assess the electricity mix associated with supplier operations alongside distance, cost, capacity, and geopolitical exposure. A geographically close supplier operating on a high-fossil grid can have a less favorable carbon outcome than a more distant supplier using cleaner energy.

Second, infrastructure selection becomes part of supply-chain strategy. Battery OEMs and related manufacturers can strengthen carbon performance by locating energy-intensive operations near regions with access to hydropower, wind, solar, nuclear, or other low-carbon electricity resources. The quantitative contrast between B-1 and B-2 shows why clean-power access can be a structural source of environmental advantage rather than a secondary operational consideration.

Third, the source study identifies power purchase agreements (PPAs) as a practical response where relocation is not feasible. Direct or virtual clean-power procurement can help address the electricity component of the footprint while preserving existing industrial assets. The broader management implication is that sourcing, operations, finance, and sustainability functions should evaluate localization and energy procurement jointly rather than through separate decision processes.

Finally, carbon accounting should remain process-specific. Table 2 shows that refining, precursor synthesis, logistics, and assembly contribute differently under each scenario. Corporate carbon-reduction programs can therefore prioritize the stages with the largest modeled contributions instead of applying uniform reduction targets across the chain. This stage-level view is particularly useful when firms must decide whether to renegotiate supplier energy requirements, change logistics modes, co-locate facilities, or invest in cleaner manufacturing infrastructure.

Decision Framework for Sustainable Sourcing

The scenario results can be translated into a practical sequence for sourcing decisions. The first step is to establish the cradle-to-gate boundary consistently across candidate suppliers so that extraction, refining, precursor synthesis, logistics, and cell assembly are compared on the same functional basis. The second step is to identify the electricity carbon intensity associated with the energy-intensive stages rather than relying only on national location or transport distance. The third step is to calculate the logistics contribution using the actual modes and distances expected in the supply chain. Only after these components are viewed together should the firm determine whether localization produces a net carbon advantage.

Within the supplied model, this sequence changes the interpretation of Scenario B-1. On a logistics-only basis, B-1 appears preferable because transport falls from 8.40 to 1.20 kg CO₂-eq/kWh. A complete cradle-to-gate assessment, however, shows that the total rises from 76.20 to 78.20 kg CO₂-eq/kWh. The decision framework therefore prevents a firm from claiming a carbon benefit solely because materials travel fewer kilometers. It requires the reduction in freight emissions to be tested against changes in mining, refining, precursor, and assembly emissions.

The same framework explains why Scenario B-2 is materially different from B-1 even though both are localized. B-2 combines short transport routes with the decarbonized-grid assumption and therefore lowers emissions across the stages that dominate the model. The result is not simply a logistics improvement but a system-level change in which low-carbon electricity and regional proximity reinforce one another. For managers, this means that localization projects should include an energy plan at the design stage, rather than treating electricity procurement as a separate operational issue after the location decision has been made.

The framework also supports more transparent internal carbon auditing. Procurement teams can report transport emissions separately from process-energy emissions, while sustainability teams can identify which stage creates the largest marginal opportunity for reduction. Finance teams can then evaluate infrastructure or clean-power commitments against the carbon benefit expected at the relevant production stage. This cross-functional interpretation is consistent with the source study's conclusion that supply-chain, financial, and environmental sustainability teams must collaborate as carbon regulation and reporting become more sophisticated.

Implications for Carbon Reporting and Supplier Evaluation

The findings imply that supplier scorecards should distinguish between geographical localization and carbon localization. A supplier may be geographically local but carbon intensive if its processing electricity is fossil dominated. Conversely, a geographically distant supplier

can retain a competitive lifecycle profile when efficient maritime transport is combined with lower-carbon processing. The distinction is important because a simple “local content” indicator cannot capture the interaction demonstrated by the modeled scenarios.

For reporting purposes, the functional unit of kg CO₂-eq per kWh of finished cell capacity provides a consistent basis for comparing alternative configurations. Stage-level disclosure also makes the source of improvement visible: in B-2, the major reduction is associated with mining, refining, precursor synthesis, and assembly rather than transport alone. Retaining this disaggregation can reduce the risk that a headline logistics improvement obscures an unfavorable change elsewhere in the manufacturing chain.

Conclusion, Limitations and Future Research

This study evaluates whether localized mineral extraction and manufacturing necessarily reduce the carbon footprint of lithium-ion battery production. Using a cradle-to-gate LCA structure and the supplied NMC-811 scenario assumptions, the analysis shows that the answer depends fundamentally on electricity-grid carbon intensity. The globalized configuration produces 76.20 kg CO₂-eq/kWh. Localization under a high-fossil grid reduces transport emissions but raises the total footprint to 78.20 kg CO₂-eq/kWh. Localization under a decarbonized grid reduces the total to 19.40 kg CO₂-eq/kWh, corresponding to the reported 74.5% reduction relative to the globalized baseline.

The central conclusion is therefore not that globalized supply chains are environmentally preferable, nor that localization is ineffective. Rather, geographical localization and energy decarbonization must be pursued together. Shorter transport routes improve the logistics component, but clean electricity is required to unlock the larger reductions available in refining, precursor synthesis, and assembly. Corporate sourcing strategies that focus only on distance risk overlooking the dominant energy-related sources of lifecycle emissions.

The analysis is subject to the boundaries of the supplied scenario model. It uses static transport factors and grid-intensity assumptions, focuses on an NMC-811 cradle-to-gate system, and does not include battery use, recycling, second-life applications, water scarcity, or a facility-specific longitudinal dataset. These limitations should be considered when applying the results to individual companies or regions. Future research can extend the framework by testing alternative battery chemistries, dynamic grid mixes, recycling pathways, and the water-energy trade-offs of direct lithium extraction. The source study specifically identifies water scarcity impacts associated with localized DLE as an important next area of investigation.

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