Sustainability in Critical Mineral Pathways: Mapping Uncertainty to Strengthen Critical Mineral Supply Chains

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EMSE 6099 Problems in Engineering Management and Systems Engineering

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Date: 04/22/2025

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1. Introduction

Critical minerals are essential for the production of clean energy technologies and high-tech devices. However, their global supply chains are complex, lengthy, and vulnerable. Cobalt, a key component in electric vehicle (EV) batteries, is a prime example. Global electric vehicle adoption is surging, further intensifying the demand for cobalt and the urgency to address these supply chain issues. The Democratic Republic of the Congo (DRC) is the dominant source of cobalt ore, while a large share of refining and battery-grade processing occurs in China. This heavy geographic concentration creates geopolitical and supply risks – any disruption in the DRC or China could threaten the material supply for EVs. This concentration also raises ethical concerns (e.g. political instability and labor issues in mining regions). At the same time, transporting materials across continents adds environmental impacts in the form of greenhouse gas emissions. Companies with net-zero goals and nations seeking secure supply must navigate these trade-offs.

This report evaluates the sustainability and resilience of the cobalt supply chain under uncertainty. We develop a cradle-to-gate supply chain model for cobalt, quantify transportation emissions and costs at each stage, and analyze how various scenarios (e.g. trade policy changes, new routes, cleaner transport technology) affect outcomes. The goal is to identify strategies to strengthen critical mineral supply chains against disruptions while reducing their carbon footprint. By mapping the current pathways and testing alternatives, we can pinpoint where interventions (such as diversifying refining locations or electrifying freight) yield the greatest benefits for both security and sustainability.

2. Literature Review

Multiple studies have highlighted the fragility of critical mineral supply chains. For example, a recent analysis of EV battery materials found that roughly 80% of cobalt eventually flows through China's refineries, creating a single point of failure for the industry[1]. The source-side concentration is similarly stark: the DRC alone accounts for about 70% of global mined cobalt[2]. This reliance on a few regions poses political and ethical challenges, from governance problems to potential human rights issues. Many industry and academic reports emphasize the need for diversification and responsible sourcing to mitigate these risks.

Researchers have also noted the importance of considering sustainability alongside security. The need to decarbonize transport logistics is emphasized in climate reports and tools. For instance, the International Energy Agency (IEA) provides an EV life-cycle assessment tool that estimates the emissions from vehicle material production and transport[3]. These resources indicate that moving minerals across the globe can contribute significantly to a battery's total carbon footprint. Thus, the literature underscores both the supply risk (due to geographic concentration) and the environmental impact (due to long-distance transport) associated with critical minerals. However, integrated analyses that jointly evaluate cost, emissions, and geopolitical risk in these supply chains remain limited. This capstone project addresses that gap by modeling the cobalt supply chain in detail and testing scenarios to improve its resilience and sustainability.

3. Methodology and Model Development

Our methodology followed a structured sequence of tasks, from data collection through model development to scenario and sensitivity analysis. The approach was iterative, with feedback from preliminary results guiding refinements.

Data Collection: We first built a detailed dataset of the cobalt supply network. Key production and trade data were gathered from public sources. The U.S. Geological Survey provides annual country-level cobalt production figures[2], confirming the DRC's dominance. Trade routes and volumes were obtained from the World Bank's World Integrated Trade Solution (WITS) database[3], which compiles UN Comtrade bilateral trade statistics. Using these sources, we identified the major pathways: cobalt mined in each source country, shipped to refining countries, and then sent to battery manufacturing hubs.

Supply Chain Model: We formulated the supply chain flow assignment as a linear programming optimization. The objective function minimizes the total transport cost (or, in an alternate formulation, total transport emissions), subject to constraints that ensure all cobalt from each mine is delivered to battery production and that flows conserve mass at intermediate points. Solving this optimization provides the cost-optimal (or emissions-optimal) routing of cobalt through the network for a given scenario. Using R (with optimization libraries), we developed a comprehensive cradle-to-gate supply chain model mapping cobalt's journey from mine to battery factory. Each link in the chain (e.g., DRC mine → Chinese refinery → Japanese battery plant) carries an associated distance, transport mode, cost, and emissions. We considered land (truck/rail) and sea freight legs. Distances were estimated from shipping routes and overland transport data. Transport costs were modeled per ton-kilometer based on typical freight rates, then aggregated for each route.

To quantify lifecycle transportation emissions, we applied standard emission factors for each transport mode. Specifically, we used factors from the IPCC's Sixth Assessment Report (AR6) data[4] (e.g., ~0.1 kg CO_2 per ton-km for trucking, ~0.02–0.05 kg/t-km for shipping) to calculate the carbon dioxide equivalent (CO_2e) emitted along each segment. These IPCC figures (including additional data tables[5]) cover well-to-wheel emissions for freight transport. We cross-validated our assumptions with the IEA's EV LCA tool[6] to ensure the emission estimates were in a realistic range. (Processing and mining emissions were not included; the focus is on transport "crate-to-gate".)

Using this network data and parameters, we computed a baseline cost-optimal flow allocation and its associated emissions. The baseline represents the status quo scenario – essentially the real-world distribution of flows as observed, minimizing transport cost. We also computed alternative scenarios (described below) by re-optimizing the network under different constraints or cost structures. In all cases, the model results provide total transport cost and emissions for delivering the cobalt needed for one unit of final output (defined here as the cobalt required for a single 400 kg EV battery, roughly 12–14 kg of cobalt content).

Scenario Definitions: We created several what-if scenarios to explore how changes in the supply chain or policy environment might affect outcomes. These scenarios (developed in consultation with industry advisors) alter the network structure or cost factors:

- *Tariff Scenario:* Simulates a tariff or penalty on cobalt refining in China. We imposed an additional cost on any route passing through China to represent trade barriers, in order to see if and how the supply chain would reroute.
- *U.S. Domestic Refining Scenario:* Introduces a hypothetical refinery in the United States. A new pathway from DRC (and other sources) directly to U.S. refining, then to U.S. battery manufacturing, was added with

appropriate distances (e.g., shipping from DRC to U.S. Gulf Coast) and a higher refining cost (assuming U.S. processing is more expensive than China's). This tests on-shoring a midstream supply chain step.

- *Diversification Scenario:* Forces a more distributed refining model by reducing China's capacity and redirecting a portion of cobalt to other refining hubs (e.g., expanded facilities in Indonesia, Finland/Belgium, or within Africa). We adjusted the data so that no single country (including China) refines more than ~30–40%. This scenario examines whether a more geographically balanced supply chain can reduce risk and emissions, and at what cost.
- *Clean Transport Scenario:* Assumes decarbonization of freight transport. Here we drastically reduced the emission factors for shipping and trucking (to near-zero, as if electric vehicles and ships powered by renewable energy are widely adopted) while keeping transport cost the same. This scenario isolates the impact of greener logistics technology on the supply chain's carbon footprint, without changing the physical route of flows.

For each scenario, the model finds a new cost-minimizing distribution of flows given the scenario's conditions, and we then calculate the resulting total emissions and costs. Additionally, to communicate results, we developed a web-based interactive dashboard using R Shiny. This tool visualizes the supply chain on a world map and allows stakeholders to adjust scenario parameters and immediately see the resulting emissions and cost outcomes. Such visualization aids in interpreting the complex data and can support decision-makers in exploring "what-if" questions beyond the fixed scenarios analyzed here.

Uncertainty and Sensitivity Analysis: In parallel with scenario analysis, we conducted a Monte Carlo sensitivity analysis to capture uncertainty in key parameters. We identified uncertain inputs such as: cobalt content per battery (which could change with battery chemistry), fuel prices (affecting transport costs), transport distances, and possible variability in emission factors. We then ran the model many times (10,000+ simulations), sampling these parameters from plausible distributions. For each run, we recorded outcomes (total transport cost and total transport emissions under each emissions factor set). This yielded a distribution of results and allowed us to compute Pearson correlation coefficients between each input variable and the outputs. The result is a sensitivity profile indicating which uncertainties most strongly drive cost or emissions. We visualized this in a correlation chart (Figure 3) to identify the dominant risk factors.

4. Results and Analysis

4.1 Baseline Supply Chain and Emissions

After validating the model on the current state, we first examined the baseline scenario reflecting the status quo trade flows and routing. Figure 1 illustrates the mapped cobalt supply chain under baseline conditions. (This supply chain map was initially presented in our project's progress report[7].) Several key findings emerged:

- Dominance of the DRC in mining: The model confirms that the DRC contributes the majority of cobalt feedstock by mass (~70% of global supply)[2]. This extreme concentration means a disruption in the DRC (political unrest, mining shutdowns, etc.) could impact over two-thirds of the world's cobalt supply – a critical vulnerability for downstream industries.
- China as a refining bottleneck: An even larger bottleneck exists at the refining stage. We find that roughly 80% of cobalt material passes through China for refining (either originating from DRC or other countries), aligning with reports of China's dominance[1]. In our baseline, almost all cobalt mined in DRC eventually goes to China for processing. Only a small fraction is refined elsewhere (e.g., a portion from Australia goes to Finland; from Morocco to Belgium, etc.). This single-point-of-failure risk means any disruption or policy change involving China can affect a huge portion of the supply chain. It also lengthens transport routes – many shipments travel thousands of extra kilometers to reach China and then get shipped out again to battery manufacturers.
- Global distribution of manufacturing: Downstream, the refined cobalt is used in battery production mainly in Asia. Our baseline output shows that China, South Korea, and Japan together account for nearly all of the cobalt uptake into cathode production. Approximate shares are: China ~57%, South Korea ~27%, Japan ~16%, with the United States and other countries currently <5% (based on recent EV manufacturing volumes). This final manufacturing stage is more diversified than mining or refining – no single country dominates battery assembly. This diversity is positive for resilience (multiple end-use centers of demand and innovation); however, since most manufacturers still rely on cobalt processed in China, the upstream bottleneck undermines the benefit of having varied manufacturing locations.

- Transport costs and economic impact: The total transport and handling cost for the cobalt in one EV battery was estimated to be on the order of \$7,000–\$8,000 in the baseline. This is a significant expense, amounting to roughly 15–20% of an average battery pack's cost. Most of this cost accrues in the long-distance shipping and multiple handling steps across continents. Notably, the model's cost optimization indicates that China's refining hub remains the cheapest route despite the distance, due to economies of scale and low processing costs. Only when we impose new constraints (e.g., tariffs or forced re-routing) does the model shift away from China, and those alternatives invariably come with higher overall costs.
- High transport emissions from long distances: The baseline logistics for cobalt are carbon-intensive. We estimate that transporting the cobalt needed for one 400 kg EV battery results in approximately 50–100 kg CO_2 emitted, depending on the emissions factor assumptions. Using the IPCC average factors (our central case), the transport emissions per battery are about ~93 kg CO_2. Using a low-end factor (from Ecoinvent datasets) yields ~48 kg, and a high-end factor (from GREET) about ~63 kg. This range (48–93 kg) represents the uncertainty in logistics emissions for one battery's cobalt. Importantly, even the lower bound is on the order of tens of kilograms of CO_2. For perspective, producing a 60 kWh EV battery (all materials and manufacturing) can emit around 100–150 kg CO_2 in total, depending on energy sources. Thus, cobalt transport alone may contribute a significant fraction of a battery's lifecycle emissions. We also found that roughly 80% of the transport emissions come from the intercontinental shipping segments (e.g., DRC → China → battery plant routes), with only ~20% from inland trucking/rail. Despite ocean freight being efficient per km, the very long distances (often >20,000 km total journey) make maritime transport the dominant emissions source in absolute terms.

These baseline findings illustrate why industry and policymakers are concerned about the current cobalt supply chain. It is a highly centralized network (DRC for mining, China for refining) with significant embedded emissions and non-trivial transport costs. The baseline provides a benchmark against which we can evaluate improvements or trade-offs in the scenarios.

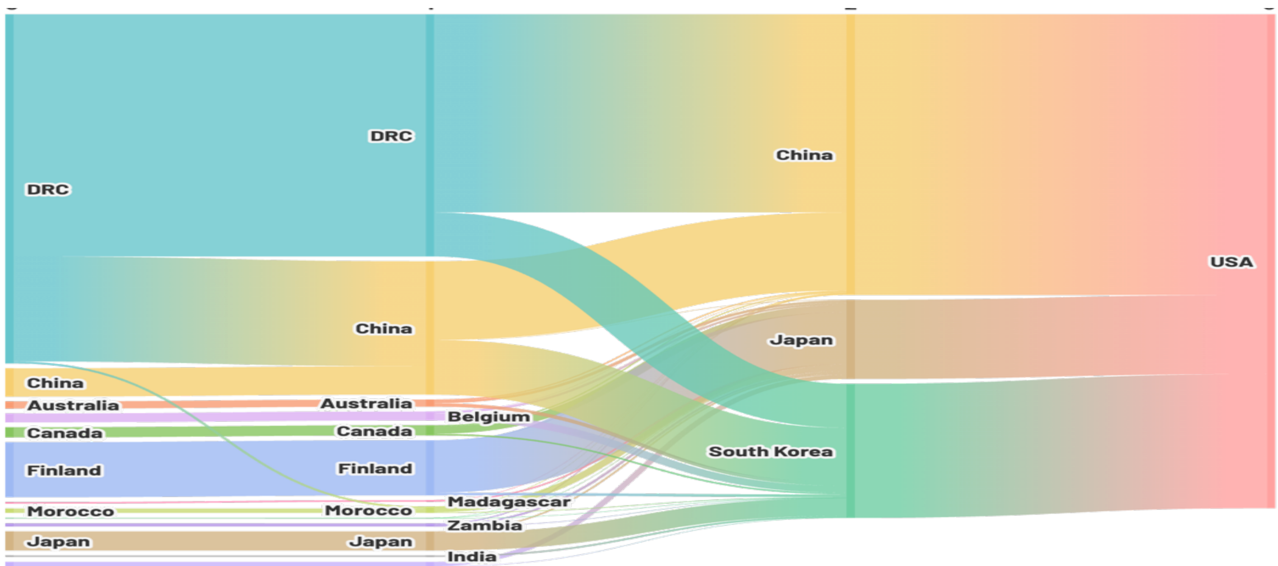

Figure 1: *Global cobalt supply chain map, showing major flows from DRC mining through China's refining to battery manufacturing centers.*

4.2 Scenario Analysis Results

The scenario analysis explores how changes in supply chain structure, policy interventions, and technological assumptions influence transport emissions and cost outcomes. Table 1 outlines the structural assumptions and key supply chain parameter changes modeled in each scenario (FS-2032 A–E). These adjustments frame the simulation results discussed below, where we examine the trade-offs between cost, emissions, and resilience for each modeled pathway.

	Name	Scenario Condition	Influencing Variables					
			US Import Reliance%					
			Cathode	Anode	Electrolyte	Separator	Co	Cost (categorization)
Base case Scenario (BS)	BS-2023	Same as current (battery assembly in the US)	100	90	98	94	100	Sum of importing cost from CHN, JPN and SK
Future Scenario (FS)	FS-2032 A	100% US production (post-mining import)	0	0	0	0	100	Importing cost of raw Co from top 3 Co exporters to the US

	FS-2032 B	100% China	100	100	100	100	100	Importing cost from only CHN		
	FS-2032 C	Only JPN and SK suppliers to the US	100	90	98	94	50	Sum of importing cost from JPN and SK		
			(Cost) Country Specific %							
			Cathode	Anode	Electrolyte	Separator	A	B	C	D
	FS-2032 D	A: Canada, B: Norway, C: Australia, D: Finland	70	75	80	94	35	30	25	10
	FS-2032E	A: Canada, B: Mexico, C: Australia, D: Finland	60	70	75	90	45	40	15	0

Table 1: *Scenario Assumptions and Supply Chain Parameters.*

- Tariff on Chinese Refining: Imposing a cost penalty on routes that involve China (simulating a tariff) had the intended effect of diverting some supply away from China, but at a notable cost increase. In this scenario, about half of the cobalt that would normally go through China shifted to alternate refining locations (for example, more material went directly from DRC to refiners in Belgium and Finland, and some to expanded capacity in South Korea). China's share of refining dropped from ~80% to ~40% in the model. However, the total transport cost per unit (per battery's worth of cobalt) jumped by roughly 15–20%. This is because the alternate routes were longer or less efficient, incurring higher shipping distances and expenses. A side effect was a slight increase in transport emissions (~5%) in this scenario. The rerouted flows in many cases traveled farther (e.g., DRC to Europe is a longer sea journey than DRC to China), offsetting any emissions savings from reducing China's leg. In essence, the tariff scenario achieved diversification of refining but made the overall supply chain more expensive and slightly more carbon-intensive. This suggests that trade penalties alone may lead to unintended environmental consequences unless accompanied by efforts to green those alternate routes.
- U.S. Domestic Refining: In this scenario, we introduced U.S.-based refining for a portion of the supply. We assumed the U.S. could refine about 25% of DRC's cobalt output (with the rest still going to China as usual). The outcome was a moderate emissions benefit but a large cost penalty. Cobalt routed DRC → U.S. → U.S. (refining then manufacturing domestically) did have ~10% lower transport emissions for

that portion compared to the DRC → China → U.S. route it replaced, because the transatlantic shipping distance is shorter than the DRC→China→U.S. trip (which effectively sends material on two ocean voyages). On a global scale, the emissions reduction was small (since a majority of cobalt still went to Asia as in the baseline), but from a U.S. perspective, the supply serving domestic factories became a bit cleaner. The transport cost, however, rose dramatically for that rerouted portion, by ~30% per unit, due to the higher assumed refining cost and less optimized logistics. In fact, in the model's cost-optimal solution, China remained the preferred refiner unless we explicitly forced some flow to the U.S. (indicating that purely market-driven re-routing wouldn't occur without policy incentive). The takeaway is that unless U.S. refining becomes much more cost-competitive (through innovation or subsidies), companies would not voluntarily shift refining there. It might require strategic investment or policy support to absorb that cost premium. This scenario demonstrates a classic security vs. cost trade-off: slightly lower emissions and reduced geopolitical risk (more self-sufficiency) come at a significantly higher cost.

- Diversified Refining (Non-China): This scenario distributes refining across multiple countries to reduce reliance on China. We allocated portions of the cobalt flow to Indonesia (leveraging their nickel/cobalt refining projects), to Europe (Finland & Belgium), and even a hypothetical refining facility in Africa (e.g., in DRC or Zambia), such that no single country processed more than ~30% of the cobalt. The result was a more distributed network and, interestingly, a small drop in total transport emissions (~8%) compared to the baseline. Emissions fell because some alternate routes were more direct: for example, refining in-country in the DRC eliminates the need to ship ore out and then ship refined product back into Africa or Europe for local battery production, avoiding double ocean crossings. Also, sending some cobalt to closer refining hubs (Indonesia is nearer to DRC than China is, via the Indian Ocean) trimmed the distance. However, the total transport cost increased by ~10% in this diversified scenario. This is attributed to losing some economies of scale and efficiency – the Chinese refining infrastructure is highly cost-effective, so splitting the flow among smaller or less optimized operations introduces some inefficiencies. In short, diversification can be a win-win on security and emissions (lower reliance on one country and slightly lower CO_2) but comes at a modest cost increase. If companies or governments are willing to bear a bit more cost (or internalize the carbon benefits via a carbon price), this strategy could be attractive. Notably, this scenario shows that smart routing can reduce emissions by avoiding unnecessary shipping loops through faraway hubs, even as it improves resilience.

- Clean Transport Technology: This scenario had the most dramatic impact on emissions. By electrifying and decarbonizing freight transport, we effectively eliminated most of the transport emissions without altering the physical supply chain. In our simulation, setting land and sea transport emissions factors to near-zero (as if all trucks are electric and ships use zero-carbon fuels) drove the transport emissions per battery down to almost 0 kg CO_2. The cost in this scenario was assumed unchanged (we did not add any cost for greener technology, imagining future cost parity or policy support for clean transport). As expected, emissions plummeted across the board. This underscores that even if the supply chain routes and dependencies remain exactly the same, technology improvements in transportation can virtually erase the carbon footprint of moving minerals. In reality, zero-carbon shipping might involve some cost premium, but even partial adoption (say 50% of trucks being electric, or using cleaner fuels for ships) would directly cut a corresponding fraction of transport emissions. This finding aligns with broader climate studies stressing transport sector decarbonization[10]. It suggests that one of the most impactful levers for sustainable supply chains is external to the supply chain structure itself – i.e., greening the transport sector. Of course, this should ideally go hand-in-hand with structural changes like diversification, but it highlights that even without rerouting, switching to low-carbon transport energy can yield massive emissions savings.

Across all scenarios, there were clear trade-offs. Diversifying away from an optimal-but-risky configuration typically raises costs, and certain policy interventions can have unintended side effects on emissions. Conversely, investing in clean transport yields large emissions benefits with minimal downside (aside from the technology investment itself). These insights can inform decision-makers about which strategies are most promising for achieving a balance between supply security, affordability, and sustainability.

4.3 Sensitivity Analysis Results

The Monte Carlo simulations produced a distribution of possible outcomes for transport emissions and cost. Figure 2 illustrates the probability density of total transport emissions per battery under baseline conditions, showing the range of likely outcomes (~50–100 kg CO_2). From this analysis, we identified the following key sensitivity findings:

- Battery cobalt content is a crucial factor. In every scenario, one of the top sensitivities for both cost and emissions was the amount of cobalt required per battery. If future EV batteries increase their cobalt content (or if demand surges because more batteries are produced), the total transport emissions and costs would rise substantially. Conversely, battery innovations that reduce cobalt per battery (or shift to alternative chemistries) would significantly mitigate both cost and emissions. This sensitivity was often larger than the effects of the policy scenarios themselves, indicating that technological trends in battery chemistry can outweigh supply chain configuration changes in impact.
- Transport distance and modes are key drivers. The total kilometers traveled (especially by sea) and the split between ship and land transport had a strong influence on emissions outcomes. Simulation runs where the assumed distances were higher (e.g., using more circuitous routes or additional transshipment) showed proportionally higher emissions. This reinforces that efficient routing – minimizing detours and unnecessary legs – directly reduces carbon impact. It also implies that efforts like optimizing shipping logistics or choosing nearer refining options can pay dividends in lower emissions.
- Cost sensitivity to fuel and route changes. On the cost side, besides battery content (which dictates how much material is moved), uncertainties in fuel/transport prices and any added tariffs or fees showed a high sensitivity. For instance, a spike in oil prices or new carbon taxes would noticeably increase transport costs. This underscores the economic vulnerability to energy markets and policy; external factors like fuel price volatility or climate regulations can significantly affect supply chain costs.
- Less influential factors. Some variables, such as minor errors in distance estimates (±5%) or small variations in handling fees, had negligible effect on outcomes. This suggests stakeholders can focus on the big uncertainties (like material demand and major route shifts) rather than worrying about fine-tuning minor logistics parameters.

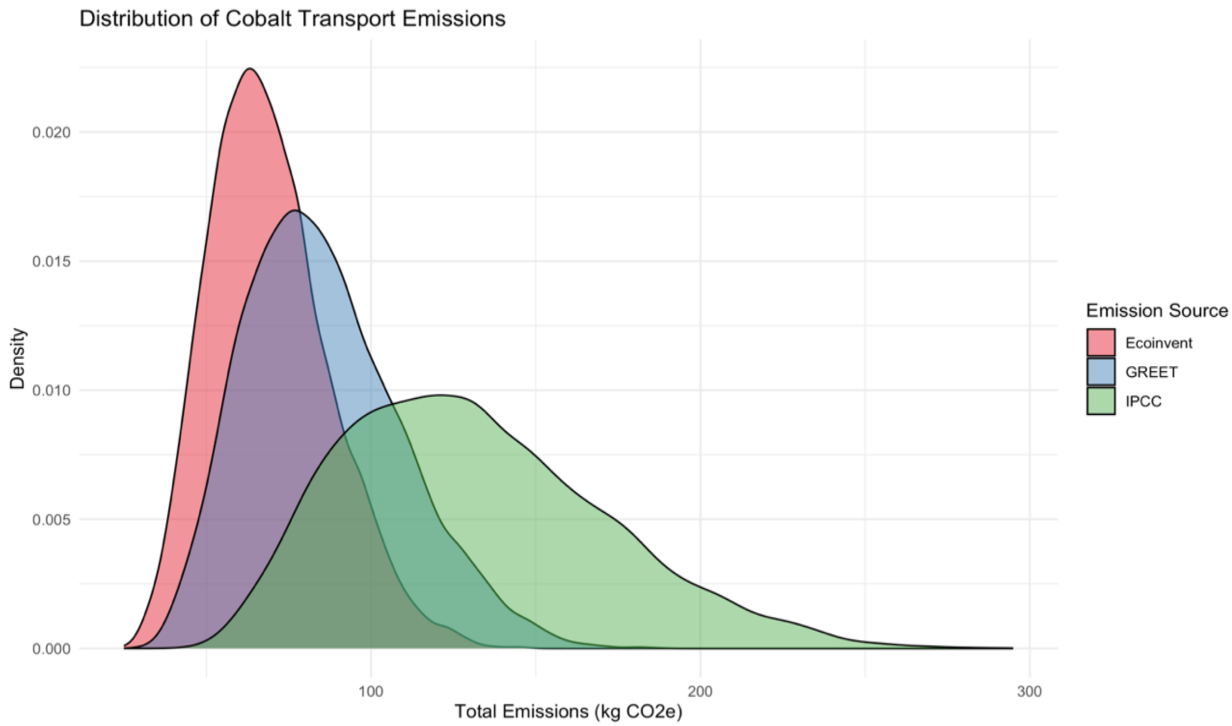

Figure 2: *Probability distribution of cobalt transport emissions (kg CO_2 per EV battery) under baseline uncertainties. Most simulation outcomes fall in the 50–100 kg CO_2 range.*

Overall, the sensitivity analysis confirmed that our earlier conclusions about main drivers are robust. It showed that major shifts in demand or technology (e.g. a new battery chemistry that doubles cobalt use, or conversely a shift to cobalt-free batteries) would have a larger impact on the supply chain's performance than any of the moderate scenario changes we tested. This insight is valuable for strategic planning: it indicates that in addition to scenario planning, watching external trends (such as EV technology evolution) is critical. It also points to the importance of recycling and circular economy approaches – though not explicitly modeled here, recycling could reduce primary cobalt demand and alleviate pressure on the supply chain in the long run.

5. Discussion

The above results paint a nuanced picture of the cobalt supply chain's trade-offs. There is no single solution that simultaneously minimizes cost, emissions, and supply risk - each approach involves compromises and external considerations:

First, the heavy reliance on the DRC and China represents a clear geopolitical risk with single points of failure. Our mapping and baseline quantification provide concrete evidence of this risk (e.g., ~80% of supply flows through one country's refineries). This aligns with concerns raised in policy forums and industry analyses[9]. Diversifying sources or routes can reduce this dependency and improve resilience, but it tends to incur higher costs (as seen in both the tariff and diversification scenarios). Policymakers must weigh the "insurance value" of a more resilient supply chain against its economic cost. Initiatives like the multinational Minerals Security Partnership[9] underscore the interest in shared approaches to mitigate such risks.

Second, there is an explicit cost–emissions trade-off highlighted by our model. The current supply chain configuration is near the cost optimum (having evolved primarily under cost pressures, favoring DRC mining and Chinese refining). Moving away from that, whether for security or environmental reasons, generally means higher costs. Our analysis quantifies this trade-off: for example, cutting transport emissions by ~10% through route changes raised costs on the order of ~10% in the diversification scenario. This frames the challenge for decarbonization: there is an economic cost to reducing emissions in this supply chain. Policymakers and companies can use this information to decide if the benefits (lower CO_2, reduced risk) justify the costs, or to design mechanisms (e.g., subsidies, carbon pricing) to offset the added costs of a cleaner, more secure supply chain.

Third, technological solutions can alter the equation. The clean transport scenario demonstrates that improvements in transportation technology (electrified trucks, cleaner fuels for ships) can drastically reduce emissions without needing to overhaul the supply network. This suggests a parallel approach: while we restructure supply chains for resilience, in parallel, we should decarbonize logistics. According to climate analyses, reaching net-zero will indeed require such transport sector changes[10]. Encouragingly, our findings show that supply chain sustainability can improve greatly from these external changes alone. Efforts like international shipping efficiency standards, green freight corridors, or electrified trucking could directly benefit critical mineral supply chains. In practice, this means some sustainability improvements can be achieved by broader actions outside the cobalt supply chain itself, which complements internal supply chain reconfigurations.

Finally, the role of demand and innovation must be considered. The sensitivity analysis underscored that if battery technology shifts (for instance, toward low-cobalt or cobalt-free chemistries like LFP), the entire landscape of cobalt risk changes. In such a case, cobalt demand might plateau or decline, making some of these supply chain interventions less urgent. On the flip side, if EV growth accelerates and cobalt-intensive NMC cathodes remain dominant, the volumes (and thus impacts) we examined will scale up, magnifying the importance of these findings. This highlights a need for flexibility in planning: solutions should be robust under different future demand scenarios. It also points to the importance of recycling: incorporating recycled cobalt into the supply (so-called "urban mining") could alleviate some pressure. While we did not model recycling flows, they represent a future avenue to reduce primary demand and increase resilience.

In summary, a combination of strategies is needed to strengthen critical mineral supply chains. No single measure will suffice; rather, a mix of moderate diversification, targeted policy support to absorb cost impacts, aggressive transport decarbonization, and continued innovation in battery technology is recommended. This integrated approach can move the cobalt supply chain toward greater resilience and sustainability simultaneously. Notably, while our analysis centered on cobalt, the insights and modeling framework are applicable to other critical minerals facing similar supply concentration and carbon footprint challenges.

Beyond the quantitative results, there are social and governance dimensions to consider. Sourcing from the DRC entails addressing environmental and human rights standards – an issue highlighted in World Bank reports[8] on the cobalt sector. A truly sustainable supply chain is not only about numbers but also about ensuring ethical practices at the origin. Efforts to improve transparency and standards (such as requiring companies to report the CO_2 per kg of delivered cobalt, or to certify responsibly sourced material) could create incentives to adopt the changes suggested by our model (e.g. shorter routes, cleaner transport, diversified suppliers).

6. Conclusions

This capstone project provided a comprehensive evaluation of the cobalt supply chain's sustainability under various uncertainties. The key insights and contributions are summarized as follows:

- Holistic Mapping: We developed a cradle-to-gate model of the cobalt supply chain for EV batteries, tracing it from mining in the DRC to refining in China (and elsewhere) to battery production. This mapping confirmed critical bottlenecks – notably the heavy reliance on the DRC for raw supply and China for processing – and quantified their implications (e.g., ~80% of cobalt flows through China; on the order of 50–100 kg CO_2 emissions per battery from transport). Such quantification adds depth to concerns raised qualitatively in prior literature, providing a concrete baseline for improvement.

- Integrated Cost–Emissions Analysis: By formulating an optimization framework with both cost and emissions calculations, we showed the inherent trade-off between minimizing cost and minimizing emissions. The current state of the supply chain sits near the cost-optimum. To shift it toward lower emissions or lower risk, some increase in cost is unavoidable. We explicitly quantified this "price of sustainability." This frames the economic challenge of decarbonizing and securing the supply chain. It offers policymakers and firms a basis to decide if the benefits (in CO_2 reduction or supply security) justify the costs, or to find ways to mitigate those costs.
- Scenario Exploration: We simulated realistic what-if scenarios – including tariffs, domestic localization, supply diversification, and transport technology shifts – and found that enhancing resilience (through diversification or localization) can improve security and sometimes reduce emissions, but usually at a moderate cost increase. In contrast, cleaning up transport (electrified/low-carbon freight) can drastically cut emissions with little cost impact (assuming technology maturity or support). The scenario outcomes suggest a combined approach: promote multiple refining hubs (to dilute concentration risk) *and* aggressively pursue transport decarbonization. Notably, we found that diversification need not be dramatically more polluting – with smart planning, it can even reduce emissions by avoiding unnecessary shipping loops.
- Uncertainty and Sensitivity: Through Monte Carlo analysis, we identified which uncertainties matter most. Notably, battery technology (cobalt content per battery) and freight logistics (actual distances and routing) are critical drivers of outcomes. This highlights that solutions can come from both within the supply chain (better routing, smarter sourcing) and outside (innovation in battery chemistry and vehicle technology). Our sensitivity chart (Figure 3) provides a visual guide for decision-makers on where to focus risk management, for example, ensuring shorter routes have a larger impact on emissions than a ±5% change in cost assumptions. It also emphasizes monitoring external trends: an industry shift to cobalt-free batteries would drastically change the context for all these scenario considerations.

In conclusion, our findings indicate that a balanced strategy is needed to strengthen critical mineral supply chains. Stakeholders should combine moderate reconfiguration of supply routes with strong support for clean transportation and continued innovation in material science. By doing so, it is possible to achieve a more resilient cobalt supply chain that meets both economic and environmental objectives.

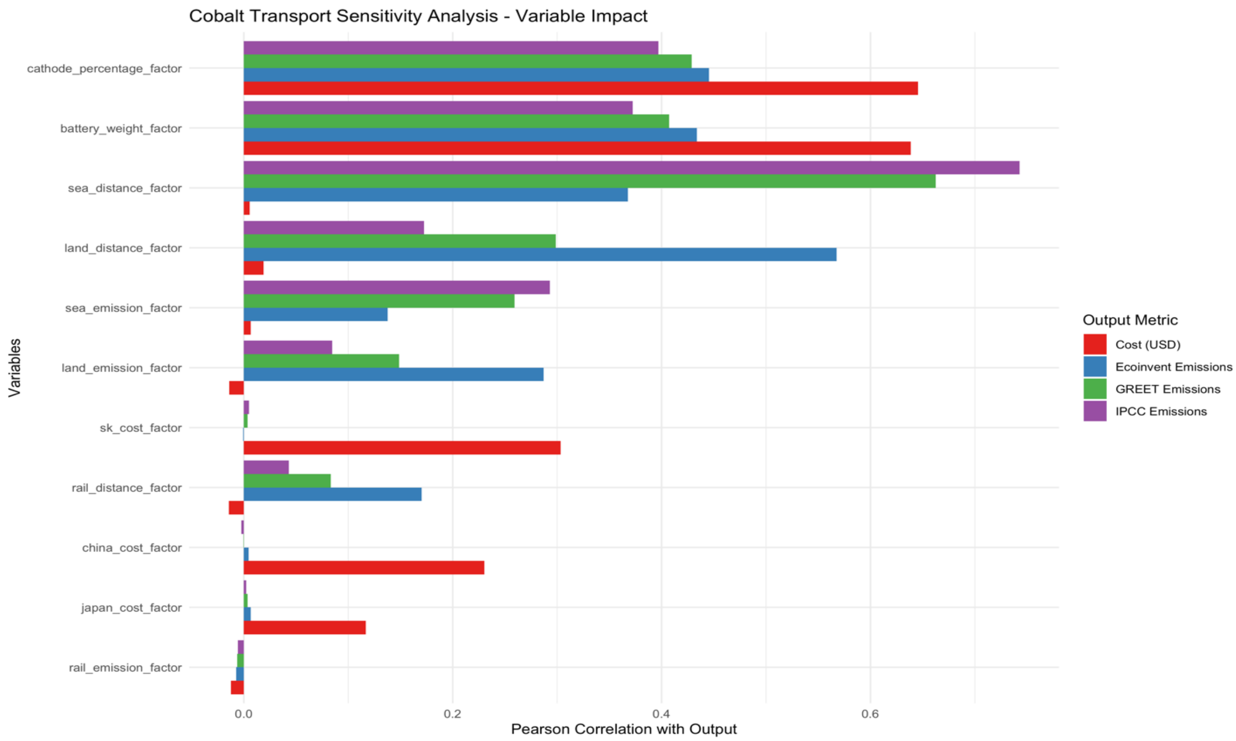

Figure 3: *Sensitivity analysis results – Pearson correlation of uncertain input variables with output metrics (transport cost and emissions). Variables with larger bars have a stronger influence on outcomes.*

7. Recommendations

Based on the analysis, we recommend the following actions for industry and policymakers to improve the sustainability and resilience of cobalt (and other critical mineral) supply chains:

1. Diversify Refining and Encourage Regional Processing: Take steps to decentralize the midstream. For example, incentivize investment in refining capacity across multiple regions (Southeast Asia, North America, Europe, and within Africa) to reduce over-dependence on any single country. Even a partial shift (as our scenarios show21ed) can shorten some supply lines and improve resilience. Governments can facilitate this through public–private partnerships or by supporting countries like Indonesia or Zambia in expanding value-added processing of their resources.

2. Green the Transport Network: Collaborate with logistics providers to decarbonize freight for critical minerals. This includes piloting electric or hydrogen-powered trucks for regional transport and adopting low-carbon fuels (or even wind-assisted ships) for ocean shipping routes. Additionally, explore shifting more freight to rail where feasible (and electrifying rail lines). Our results show that cleaner transport directly cuts emissions without requiring supply rerouting – a win-win for sustainability. International cooperation on shipping efficiency and green corridors will accelerate this transition.
3. Enhance Transparency and Standards: Implement and enforce supply chain sustainability standards. For instance, require battery manufacturers to report the transport CO_2 emissions per kg of cobalt (and other materials) used. Such transparency creates reputational incentives to optimize logistics and choose cleaner options. Similarly, promote certifications for responsibly sourced and delivered minerals. If companies and consumers can distinguish products by the sustainability of their supply chains, it will drive competition on metrics beyond cost alone, encouraging the adoption of the above strategies.

By pursuing these recommendations, stakeholders can begin to mitigate the identified risks in cobalt supply chains. A more diversified, low-carbon, and transparent supply chain will be more robust against disruptions and better aligned with climate goals, helping to secure the critical materials needed for a clean energy future.

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Appendix A: Work Breakdown Structure

This appendix presents the Work Breakdown Structure (WBS) used to manage the project. The below WBS outlines the tasks, subtasks, timelines, deliverables, status, and responsible team members, ensuring a systematic approach to data collection, modeling, analysis, and reporting.

Schedule of Project Tasks and Work Assignments				
Task	Status	Timeline	Deliverables	Responsible
Data Collection and Cleaning	Completed	Weeks 1-4	Clean dataset, validated with secondary sources	All
Optimization Equations Development	Completed	Week 4	Development of equations for Cost and Emission	Sachi Massimo Vidyullatha
Base Model with Emission and Cost Integration	Completed	Weeks 5 - 7 Posit Cloud Space	R-based supply chain model with LCA outputs	Vidyullatha
Scenario Definition	Completed	Weeks 8 - 10 File	Scenario descriptions and simulation framework	Sachi
Expert Elicitation	Completed	Weeks 8 - 10	Input from industry experts	All
Sensitivity Analysis	Completed	Weeks 9 - 12 Posit Cloud Space	Impact assessment on emissions and costs using Monte Carlo simulations	Vidyullatha
Scenario Simulation	Completed	Week 10 - 12	Simulation outputs	Sachi Vidyullatha
Shiny App for Visualisation	Completed	Weeks 10 - 12	Data visualizations and insights	Ife
Project Report	Completed	Weeks 11-12	Comprehensive report with insights and recommendations	Ife Sachi Vedanth
Project Presentation	Completed	Week 12	Prepare slides for the final presentation	Massimo