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Investigating and Proposing a Framework for Sustainable Supply Chains of Critical Minerals in Electric Vehicle Batteries

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Abstract

The electric vehicle market is positioned for significant growth, driving a major reduction in carbon emissions. A crucial element underpinning this growth is the sustainable management of supply chains for critical minerals essential for electric vehicle battery production, including lithium, cobalt, nickel, and graphite. This research merges principles of economics, engineering, and environmental science to promote a sustainable, competitive, and equitable market environment for critical mineral supply chains. This research proposes a Dynamic Pricing Framework that adapts to governmental incentives, embodies circular economy principles, and leverages technological advancements in artificial intelligence as a solution for sustainable supply chain management of critical minerals.

Keywords
Critical minerals, Lithium Batteries, Dynamic pricing, Sustainable Supply Chain, Circular Economy

1. Introduction
The Electric Vehicle ('EV') market has seen a surge in consumer interest, and sales are expected to reach 45 million by 2030. A concern in the EV battery supply chain is the geographic concentration of critical mineral reserves and supply chain activities. For example, China's dominance over certain stages of supply chain presents a major source of geopolitical risk. Furthermore, the environmental and social impacts of mining activities are profound, leading to human rights violations and environmental degradation as seen in the Democratic Republic of Congo ('DRC') and Indonesia. These necessitate a holistic approach to uphold human rights and ensure environmental integrity, alongside the core objective of securing critical minerals.

The motivation of research in this context is that there is a significant deficiency in the pricing models applied to critical minerals. Criticality of this oversight becomes more acute with geopolitical concentration, and the consistent oversight of environmental and social costs in their pricing. The absence of a pricing framework with widespread stakeholder endorsement presents a significant gap, undermining both the supply chain's resilience and longevity. The effectiveness of advanced pricing strategies in other sectors signals a clear need for innovative methods applicable to the critical minerals domain – a need that has not been adequately addressed by existing research. Dynamic pricing has become imperative for enterprises aiming to harness the full potential of the contemporary commercial environment, driving both immediate returns and sustainable economic growth.

1.1 Objectives
This research aims to develop a Dynamic Pricing Framework ('DPF') intended to promote a sustainable, competitive, and equitable market environment for supply chain management in the EV battery market. The DPF dynamically prices critical minerals by integrating real-time market data, governmental interventions, and sustainability metrics to

promote a balanced and transparent market ecosystem. Through detailed analysis and the introduction of a proposed theoretical framework, this research contributes to sustainable supply chain management in the critical minerals sector.

2. Literature Review

2.1 Critical Minerals Landscape

The transition to sustainable energy and EVs is driving an unparalleled demand for critical minerals such as lithium, cobalt, nickel, and graphite. These minerals are essential for modern energy systems and technologies. The growing demand reflects global efforts to mitigate climate change, expediting developments in electrified transport. Notably, lithium-ion batteries, which are central to this EV transition, rely heavily on these minerals (Kamateros and Abdoli 2023). While China currently leads in lithium-ion capacity, the U.S. is expected to become a major growth market, projected to surpass Europe as the second-largest lithium-ion producer by 2030 (Matt and Buckley, 2023) (IEA 2022). Meeting the demand for these EV batteries will likely require the creation of additional mines, with the IEA estimating the need for 50 lithium mines, 17 cobalt mines, and 60 nickel mines by 2030(IEA 2022).

Indeed, the critical minerals market is facing challenges mainly due to the centralization of mineral reserves and supply chain capabilities in a few countries. China has notably gained a virtual monopoly over rare earth critical minerals. Focusing on graphite, a pivotal component for anode production, China's dominance becomes even more pronounced. With a staggering 80% stake in global graphite mining, it is clear that China holds unparalleled control over the graphite anode supply chain (IEA 2022). On the financial front, China's unmatched economies of scale, intensify the challenges, often discouraging potential entrants. An exception is Lynas Rare Earths Ltd, a Western Australian enterprise, which is the only major rare-earth producer outside China's supply chain (Halton et al. 2023).

From an Environmental, Social, and Corporate Governance ('ESG') standpoint, concentrated production of critical minerals in the DRC, which accounts for around 70% of global cobalt production, exacerbates these geopolitical risks (Liu 2023). A significant portion of cobalt production comes from small-scale mining, which often operates with less adherence to safety standards (Mishra 2022). Moreover, the environmental footprint of cobalt mining is far from negligible. Furthermore, over 70% of DRC's cobalt exports currently go to China, which accounts for more than half of global refined cobalt (Bonakdarpor 2023). The centralized production of essential minerals like nickel in Indonesia amplifies these geopolitical risks. The current landscape of nickel mining and processing in Indonesia is fraught with environmental challenges including deforestation, water pollution, and land conflicts, alongside social issues emanating from poor waste management practices (ABC News 2023).

This concentration of activities in a handful of countries renders the global supply chain vulnerable to disruptions that could affect pricing dynamics and market stability. This complex scenario underscores the need for a comprehensive pricing framework that not only reflects the market dynamics of supply and demand, but also robustly factors in the ESG externalities inherent in mineral production. Such a pricing framework would promote transparency and incentivize responsible practices, thereby contributing to a more sustainable and resilient EV battery supply chain. However, the existing pricing frameworks for these minerals have several major challenges that threaten market stability and transparency.

3. Current Pricing Approaches Shortfall

A notable absence of central spot prices and derivative markets stymies the critical minerals market, resulting in an overall low liquidity scenario, which inhibits the process of price discovery and is significantly exacerbated by the prevalent practice of long-term offtake contracts. Long-term contracts often lock in significant portions of the available supply, leaving only a small portion available for transaction through other modes (State-of-Play 2023).

The prevailing market mechanisms exhibit a lack of standardized trading protocols and regulatory oversight, which further exacerbates the challenge of price discovery. The lack of standardization presents a formidable barrier to product specification discovery, impeding the ability of traders and end-users to ascertain the quality and suitability of the products available in the market. Clearly, this significantly hampers the price discovery process, as the absence of standard specifications makes it difficult to establish benchmark prices. While index pricing services like those provided by Fastmarkets and Benchmark Mineral Intelligence introduces some clarity to critical minerals market, these indices can be inconsistent, lacking the widespread acceptance needed to establish a 'bankable' price that underpins robust financial investment (Krol-Sinclair 2023). The lack of standardization contributes to market fragmentation, with different regions or trading blocs having their own set of specifications and standards. This leads to the creation of regional monopolies, undermining market competition and fostering price volatility.

4. Method: Integrating Concepts with Dynamic Pricing Framework

4.1 Policies

The Inflation Reduction Act 2022 ('IRA') is a legislative advance within the U.S. and its Free Trade Agreement ('FTA') allies, aiming to align the critical minerals market with broader energy transition goals and reduce dependency on 'foreign entities' (Bonakdarpor and Baliey, 2023). The delineation of tax incentives by the IRA serves as an economic impetus, designed to reduce upfront cost barriers associated with EV acquisition and promote consumer adoption.

Table 1 proposes how to incorporate the provisions of IRA and similar legislation with a DPF to contribute to enhanced market efficiency and stability.

Table 1. IRA's Integration within a Dynamic Pricing Framework

Objective	Contribution of a DPF
Demand Stimulation	The DPF can adjust prices in real-time to reflect IRA stimulated demand increases, encouraging participation, investment in mineral technologies
Domestic and FTA Sourcing	Prices within the DPF can be tailored to incentivize sourcing from various countries, in line with IRA mandates, fostering domestic or FTA production.
Ethical and Environmental Standards	The DPF can account for premium placed on minerals sourced in compliance with ethical and environmental mandates of IRA, promoting transparency and sustainable practices.
Market Stability and Efficiency	The DPF ensures prices are aligned with shifts in supply-demand caused by IRA, contributing to market stability and efficient resource allocation.
Geopolitical /Regulatory Navigation	By incorporating IRA regulations and considering geopolitical contexts in pricing, the DPF aids stakeholders in adapting to the complexities of international critical mineral politics and trade.
Stakeholder Collaboration	Transparent/responsive nature of the DPF facilitates dialogue and cooperation among stakeholders and collaborative market governance.
Compliance with International Trade Dynamics	The DPF can reflect international trade dynamics and compliance requirements in pricing mechanisms, ensuring alignment with IRA's goals for global market integration and FTA agreements.

4.2 Circular economy

The prevailing linear economic model, characterized by a 'take, make dispose' approach, leading to a series of challenges including resource depletion, environmental pollution, and geopolitical tensions stemming from resource competition (Xie et al. 2024) (Bahramimianrood et al. 2024). Transitioning towards a circular economy model serves as a viable step to balance the escalating demand for critical minerals with the objectives of environmental protection (Abdoli et al. 2023). In the critical minerals space, this paradigm can be underpinned by three fundamental principles: reducing materials required in manufacturing and usage, reusing products and components, and recycling materials. The circular economy discussion in the realm of critical minerals management is relatively new (Babbitt et al. 2021). The reduced demand strategy is aimed at diminishing the overall demand for critical minerals through promoting the efficient use of materials, minimizing wastage, and repurposing and reusing products (Baars et al. 2021). This strategy would alleviate the pressure on mineral extraction and supply chains. The lifetime extension strategy is centered on prolonging the operational lifespan of products and technologies, thereby retaining the extracted minerals in circulation for an extended period (Smith and Abdoli 2023). The recycling strategy underscores the imperative of efficient recycling processes to recover and reuse materials from end-of-life products and technologies. These strategies aim to create a sustainable cycle that not only reduces reliance on the mining of new minerals, but also ensures that critical minerals are efficiently recirculated within the market rather than being wasted in landfill.

The transition to a circular economy model often requires substantial upfront capital expenditure in new technologies and infrastructure (Nurdiawati and Agrawal 2022). These economic hurdles require the development of new pricing frameworks that can reduce financial risks and enhance the market attractiveness of circular business models. The integration of circular economy principles within a DPF holds the potential to incentivize innovative solutions to the escalating challenges in the critical minerals market. A DPF can further capture the true value and cost of resources, including both environmental and societal ramifications. The integration of circular economy principles with DPF is summarized in Table 2.

Table 2. Integration of Circular Economy with a Dynamic Pricing Framework

Objective	Contribution of a DPF
Resource Efficiency	The DPF can incentivize efficient use of critical minerals by adjusting prices to reflect scarcity and surplus in real-time, encouraging conservation and innovative use of materials.
Waste Reduction	Through price metrics that factor in cost of waste management and value of recycled materials, the DPF drives adoption of waste-reducing practices.
Supply Chain Sustainability	Prices in a dynamic framework can be adjusted to reflect the sustainability of supply chain practices, rewarding suppliers who adhere to circular economy principles.
Reduction in Environmental Impact	Incorporating environmental costs into the DPF leads to reduction in environmental impact, as higher costs for more damaging practices discourage their use.
Consumer and Stakeholder Engagement	By reflecting the true cost of production, including environmental and social costs, the DPF can engage consumers and stakeholders to make more informed choices that align with circular economy values.

4.3 Technological advancement

Artificial Intelligence (‘AI’), Machine Learning (‘ML’), and blockchain with their inherent capacities for predictive analytics, real-time data processing, and immutable traceability, present a suite of solutions to the complex challenges faced by the critical mineral market. It is important to acknowledge that the exploration of AI, ML, and blockchain in the context of a DPF for critical minerals is relatively new. These capabilities are essential in navigating the complex realms of market dynamics, especially in sectors like critical minerals where the intersection of geopolitical, environmental, and economic factors often leads to a highly volatile market scenario. By examining historical market data, ML algorithms can draw inferences that are instrumental in forecasting market trends (Ji and Abdoli 2023). The integration of these technologies with DPF is illustrated in Table 3.

Table 3. Implications of Technology on a Dynamic Pricing Framework

Implications	Outline
Robust, Accurate/Responsive Framework	The DPF, underpinned by technological capabilities of AI, ML, and blockchain, will be accurate and responsive to market dynamics. Its continuous learning feature informed by real-time data recorded on a blockchain ensures the DPF remains relevant amidst evolving market conditions. The trust engendered by blockchain technology can instill confidence of stakeholders, ensuring that pricing reflects true value and costs.
Enhanced Market Predictability and Analysis	AI and ML offer a robust analytical engine capable of analyzing vast datasets to extract insights regarding market trends, supply-demand dynamics, and price fluctuations.
Improved Supply Chain Transparency	The digitization of supply chain processes on a blockchain significantly enhances the level of transparency across supply chain. From the point of extraction to market use, every transaction and process can be recorded, verified, and analyzed in real-time. This level of transparency provides a solid foundation for the DPF.

5. Dynamic Pricing Framework

Distinctly different from traditional fixed pricing model, dynamic pricing adjusts prices in real-time based on a variety of factors. This adaptability allows businesses to respond promptly to market fluctuations and optimize revenue opportunities. Dynamic pricing has been tried in other areas such as retail production, telecommunications (Fitkov-Norris and Khanifar 2000), the automotive industry, and economics (Biller et al. 2005). The proliferation of dynamic pricing has been propelled by strengthened network connections, enabling more responsive and adaptive pricing strategies (Gupta and Pathak 2014). As a result, pricing algorithms have transitioned to become more adaptable, refined, and discerning in their approach. Such a shift has created a new phase in strategic pricing, deeply influenced by the integration of AI and ML models. Table 4 illustrates notable dynamic pricing methods.

Table 4. Different Forms of Dynamic Pricing

Type	Outline
Competitor-based pricing (Fisher et al. 2018)	Pricing is adjusted in response to competitors' prices. By staying competitive with respect to pricing, businesses can maintain or even enhance their market share, ensuring sustained revenue generation even in highly competitive markets.
Behavior-based pricing (Liu et al. 2018)	Pricing utilizes data on individual customer behavior to tailor pricing to specific customer actions and profiles. This model is a blend of data analytics and dynamic pricing.
Bundle pricing (Tarek and Asadpour 2021)	Pricing that offers set of products together at reduced price, incentivizing larger purchases.
Time-based pricing (Eid et al. 2016)	Pricing adjusted based on specific time frames. Businesses can better manage demand, ensuring a more consistent flow of revenue throughout the day. Time-based pricing help in managing inventory efficiently.
Peak pricing (Guda and Subramanian 2019)	Pricing targets periods of high demand, elevating prices to manage scarcity with the aim to balance the scales of supply and demand, ensuring service availability while capitalizing on high-demand intervals. Peak pricing also serves as an incentive for service providers to offer their services during busy periods.
Segmented pricing (Ruth and Myers 2003)	Pricing that analyses customer behavior and demographics to offer different prices to different segments, adjusting prices for different countries or regions based on prevailing market conditions and economic factors. Segmented pricing allows businesses to better cater to the financial capabilities and preferences of different customer groups

5.1 Common Factors that Influence Dynamic Pricing

Understanding the nuances of consumer behavior is paramount in sustainable development efforts and product lifecycle management (Abdoli 2023). A predominant category is 'myopic consumers', who engage in purchasing activities when they perceive the price as congruent with their immediate valuation, often without contemplation of prospective price declines. However, an increasing segment of consumers are exhibiting 'strategic' purchasing behaviors. Contrary to their myopic counterparts, these consumers engage in a comprehensive analysis, factoring in potential price trajectories and strategically aligning their purchase decisions accordingly. As businesses grapple with these evolving consumer archetypes, it becomes imperative to combine both these behavioral patterns into dynamic pricing models (Aviv and Pazgal 2008).

Dynamic pricing is fundamentally anchored to the principle of price fairness (Kelly and Bearden 2006). The real-time price adjustments inherent in dynamic pricing models introduce potential discrepancies in consumer perceptions, where any perceived arbitrariness or exploitation can undermine consumer trust and result in reputational setbacks (Campbell 1999). The intricate relationship between dynamic pricing and price fairness relates to broader consumer-business interactions, brand perceptions, and long-term market sustainability. In essence, ensuring perceived price fairness within dynamic pricing is paramount for fostering trust, maintaining loyalty, and establishing a competitive edge in the rapidly evolving marketplace (Deksnyte and Lydeka 2012).

Lastly, understanding product demand and demand patterns is pivotal. While many view demand in dynamic pricing as somewhat fixed with predictable outcomes, this may not be entirely accurate in practice. These models heavily rely on broad demand signals during pricing but might lack agility in adapting to new market information. Even when new demand data emerges, prices might not adjust swiftly. The main uncertainties come from two sources: the inherent characteristics of products and buyers, and unforeseeable factors such as climate events. Given this uncertainty, it is important for a dynamic pricing model to continuously enhance its understanding of demand over time.

5.2 Dynamic Pricing Model

Here, the proposed model is constructed by translating theoretical concepts into practical applications. The model has been designed to incorporate a targeted array of historical pricing data points to effectively characterize market dynamics. Government policies that directly influence pricing, such as subsidies and tax incentives, serve as quantifiable variables that impact cost structures. Additionally, the model has been designed to integrate circular economy factors, including recycling rates and the financial benefits of waste reduction. The incorporation of ESG metrics, such as emission levels and labor practice, further enriches the model, providing a quantitative measure of sustainability performance. This strategic approach lays the conceptual foundation for future integration of real-time market data, enhancing the model's predictive capabilities.

The stochastic foundation of the model is key in capturing the unpredictable patterns of the critical minerals market, ensuring adaptability in achieving diverse objectives. The model is calibrated to address profit maximization considering upholding sustainability benchmarks, among others. This model serves to capture the complexity of the market while addressing sustainability, risk, and policy factors.

The Objective Function is given in (1).

$$Z = \max_{P_t, \forall t} E\left(\sum_t \left[\pi_t \cdot \left(P_t \cdot D_t(P_t) - C_t(Q_t)\right)\right]\right) \quad (1)$$

Where:

π_t: Profit margin at time t

P_t: Selling price of the mineral at time t, incorporating real-time market indicators and historical data $D_t(P_t)$: Demand forecast at time t, based on historical data and future market indicators

Q_t: Production quantity at time t, influenced by current supply and market indicators

$C_t(Q_t, P_t)$: Cost function at time t, as a function of quantity produced

t: Time period index

The Price Elasticity of Demand is given in (2).

$$D_t(P_t) = D_{t_0}\left(\frac{P_{t_0}}{P_t}\right)^{\epsilon_t} \quad (2)$$

Where:

D_t is the baseline demand

P_t is the baseline price

ϵ_t is the price elasticity of demand at time t.

The Cost Function is given in (3).

$$C_t(Q_t) = c_{variable}(Q_t) + c_{fixed} + \Phi(GP, CE, ESG) + \Psi(MR, SD, GF) \quad (3)$$

Where:

$c_{variable}(Q_t)$ represents variable costs that change with production volume

c_{fixed} represents fixed costs that do not change with production volume,

Φ and Ψ are the penalty and risk functions.

The penalty and risk functions within the objective function are crucial components designed to integrate broader economic, environmental, and social considerations into the pricing strategy for critical minerals. The penalty function Φ imposes additional costs on the overall profit if certain standards or policies are not met. It is designed to ensure that the cost of non-compliance is economically significant and, as a result, discourages neglecting important practices. The risk function Ψ accounts for the potential costs associated with various types of risks. It quantifies the impact of uncertain and often uncontrollable factors on the pricing model, highlighting the need for risk management and diversified sourcing strategies.

The Penalty Function Φ is given in (4)

$$\Phi(GP, CE, ESG) = \sum_p \lambda_p \cdot GP_p + \sum_c \nu_c \cdot CE_c + \sum_s \theta_s \cdot ESG_s \quad (4)$$

The Risk Function Ψ is given in (5).

$$\Psi(MR, SD, GF) = \sum_m \alpha_m \cdot MR_m + \sum_d \beta_d \cdot SD_d + \sum_g \gamma_g \cdot GF_g \quad (5)$$

Where:
GP_p: Impact of policy P on costs, including subsidies, tariffs, and tax incentives
CE_c: Savings or costs associated with circular economy factor c, like waste reduction
ESG_s: Score or cost for ESG metric s, such as emission levels
MR_m: Macroeconomic risk factor m, which could influence prices
SD_d: Supply and demand disruption factor d, reflecting capacity utilization or inventory turnover
GF_g: Geopolitical factor g, quantified through stability indices or risk ratings
λ_p, ν_c, θ_s, α_m, β_d, γ_g: are Weight coefficients for each factor, reflecting their relative importance

The Circular Economy Factor is given in (6).

$$CE_c = CR_r + CI_i - SE_m \quad (6)$$

Where:
CR_r: The difference in costs between using recycled materials and new materials over a given period
CI_i: All upfront and ongoing costs associated with investments made to enable circular economy practices
SE_m: Savings achieved from using materials efficiently, reflected in reduced purchasing and operational costs

6. Validation: Implementation and Case Study

This section demonstrates how the proposed framework, when supplied with relevant data, can promote a variety of long-term benefits. Indeed, the model can justify a premium on targeted material prices by reflecting the true cost of sustainable sourcing. By incorporating subsidies and ESG compliance, among other driving factors, the model ensures that prices account for the added value of responsible sourcing.

6.1 Data

The data sources used in the implementation of the pricing model include market prices, government reports and industry publications. However, it is important to note that this case study utilized a relatively limited selection of data sources for the purpose of demonstration and validation. In future works and a real-world application, if this pricing model were adopted by a government body or a stakeholder-approved entity, they would have access to a much broader range of sources. This expanded access allows for a more transparent and informed pricing model, benefiting from comprehensive and diverse data inputs. Table 5 captures some of the data sources used for case study parameters.

Table 5. Data Sources for Graphite Case Study

Type	Source
Market Prices	Benchmark Mineral Intelligence (Benchmark, 2024): This resource offers data and tracking monthly deployment of battery metals and materials in EV batteries. Such insights are crucial for understanding the demand dynamics specific to the EV industry.
Government Reports	U.S. Department of Energy (U.S. Department of Energy, 2023): This department provides reports and data on critical minerals, and their role in the energy sector. European Commission (European Commission, 2024) : These guidelines and regulations focus on recycling and reuse of critical minerals, promoting circular economy practices. This data is integral for incorporating circular economy principles into the pricing model.
Industry Publications	International Energy Agency (Interational Energy Agency, 2024): IEA provides policy analysis and recommendations on critical minerals. Their publications offer insights into global trends and policy impacts, which are necessary for validating the sustainability aspects of the pricing model. Tesla (Tesla, 2023): Tesla's reports on their investments in battery recycling facilities and sustainable practices provide practical examples of industry-leading ESG compliance. This helps in quantifying benefits of sustainable and circular economy practices in pricing model.

6.1 Solver

For technical execution, an appropriate optimization solver, namely the L-BFGS-B algorithm, was utilized, which can manage the multifaceted objective function that encompasses the wide range of driving factors. This solver, selected for its performance with complex problems, facilitates iterative refinement of strategic choices and yields solutions that optimize price ranges within a multi-constraint environment. Drawing on best practices from the other markets, the solver ensures the model remains adaptable and responsive to changing parameters and circumstances.

6.2 Uncertainty Analysis

Generally, pricing models and including the proposed approach are subject to data uncertainty and lack of data. This research suggests using a sensitivity analysis approach to address the uncertainty. This helps to investigate the impact of uncertain input data in objective function. This can be done by performing Monte Carlo simulation or variance-based sensitivity analysis using Sobol indices. Sensitivity analysis can be added as an extra step in the proposed pricing framework. In this section some of the input data are varied within a range to perform sensitivity analysis and demonstrate the adaptability of the proposed framework. The integration of scenario analysis also offers deeper market insights, ensuring the model not only delivers profit-optimized strategies but also remains flexible and sustainable amidst a fluctuating market environment.

To calculate the optimized price by considering the uncertainty, this research defined that the lower band and upper band for P_t (as the baseline price) could change withing a range as given below, in which the lower band P_t could reduce to 50% and upper band P_t could increase to 150% of the baseline price.

Lower bound = $P_t \times 0.5$
Upper bound = $P_t \times 1.5$

It is set that the demand and cost can also vary from their baseline values. Hence coefficients for demand and cost are also considered as given below:

Demand variation coefficient = 0.1
Cost variation coefficient = 0.05

To perform the Monte Carlo simulation, normal distribution was chosen for simplicity to generate various cost and demand values for the model. Each of which can be used as a different data input to the model in order to analyze the impact of changing these variables' values on the dynamic pricing results.

The Monte Carlo simulation was carried out by changing the values of the set of input parameters as explained and the results as various profit points were calculated. Each profit point is calculated by taking into the generated data point for price, cost, and demand. The mean value of profit points and the standard deviation is calculated accordingly, which can be used for the decision making on price setting.

6.3 Results

To address a deeper uncertainty analysis, various case studies are also considered which differ in their initially based set values for the input parameters. The input set values for cases studies are demonstrated in Table 6. It is worth mentioning that each case was run separately, and the Monte Carlo simulation was performed on each case as described above.

The rationale behind the selection of specific input parameters for each case was to analyses various potential situations and the suggested optimal price by the proposed framework and the optimal profit in that case/scenario. This helps to understand the future projections and how the proposed framework can optimize the profit by suggesting an optimal price. For example, the choice of variable costs, fixed costs, demand levels, and other economic variables for case 1 is formulated such that projecting a most likely future scenario based on the collected data from the sources given in table 5. On the other hand, the variables for case 2 are valued such that demonstrate an optimistic future scenario where the unit cost is low while the demand is high, still by considering the data collected from sources provided in Table 5 as an initial idea. Case 3 is formulated for the purpose of analyzing the effect of investing on circular economy practices in this context. Purposefully the cost is set higher, and the demand is set lower to analyses, if investment in circular economy can have long term benefit even in a less favorable future scenario.

Table 6. Data used for Case Studies

Parameters	Case 1	Case 2	Case 3
Variable cost per unit	\$10	\$9	\$11
Fixed cost	\$10000	\$9500	\$12000
D_t	1000	1100	900
P_t	\$50	\$48	\$52
ϵ_t	-1.5	-1.6	-1.4
Q_t	800	850	750
π_t	0.2%	0.25%	0.22%
P_p (subsidy, tax)	(5, 10)	(15, 8)	(10, 12)
CE_c (recycling rate, lifecycle extension coefficient)	(0.1 ,0.05)	(0.15, 0.07)	(0.12, 0.06)
ESG_s (Emission level, water usage) CO_2-Tones: Tones of emission CO_2 equivalent Lpm: liter per minute	(200 CO_2-Tones, 1000 lpm)	(190 CO_2-Tones, 900 lpm)	(300 CO_2-Tones, 1100 lpm)
MR_m (interest rate, inflation rate)	(0.01,0.02)	(0.01,0.02)	(0.01, 0.02)
SD_d (production delay coefficient, Logistic issues coefficient)	(0.1, 0.05)	(0.1,0.05)	(0.1,0.05)
GF_g (trade tension coefficient, regulatory changes coefficient)	(0.1, 0.2)	(0.1,0.2)	(0.1,0.2)

Figures 1, 2, and 3 respectively demonstrate the optimization results in conjunction with the Monte Carlo simulation on case study 1, 2, and 3. The right-hand side of each figure demonstrates the statistical results of each case due to the implementation of variation on model parameters and applying the Monte Carlo simulation. The discussion on the results of the case studies is provided in the next section.

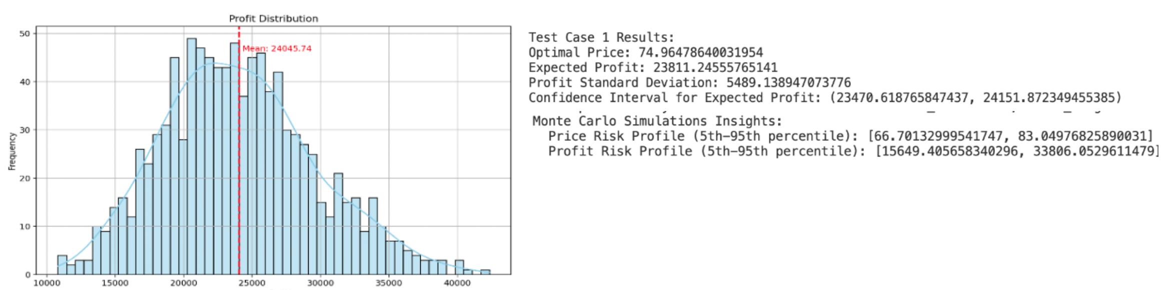


Figure 1. Case study 1 results

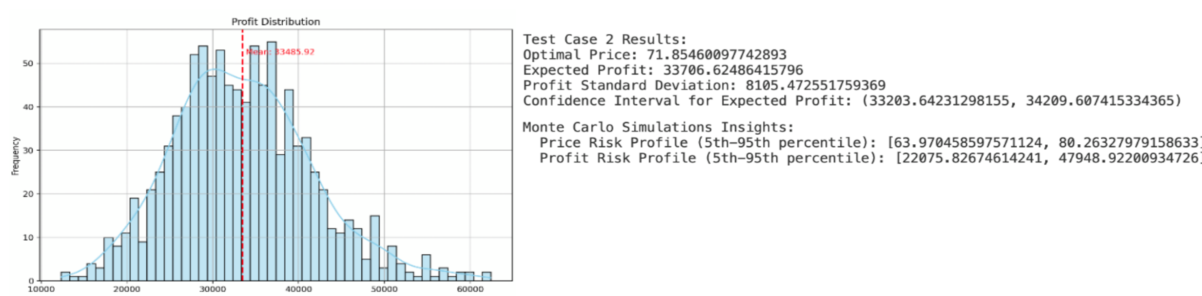
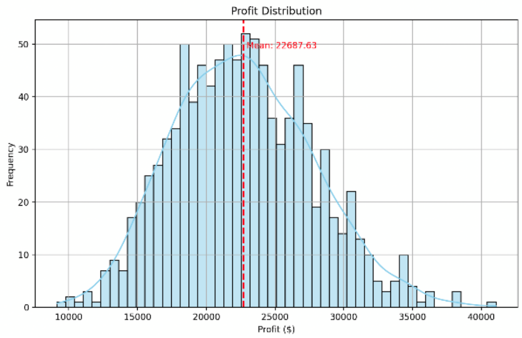


Figure 2. Case study 2 results

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Test Case 3 Results:
Optimal Price: 78.03713387322277
Expected Profit: 22754.007033155784
Profit Standard Deviation: 5075.009278762351
Confidence Interval for Expected Profit: (22439.078927733754, 23068.935138577814)

Monte Carlo Simulations Insights:
  Price Risk Profile (5th-95th percentile): [69.89656962586075, 86.1109727887767]
  Profit Risk Profile (5th-95th percentile): [15057.146500545465, 31591.045646523275]
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Figure 3. Case study 3 results

6.4 Discussion on Results

In case study 1, the optimal price is calculated as 74.96 while the expected profit in this case would be 23811. These values are 71.85 and 3375.62 for case study 2 and 78.03 and 22754 for case study 3. These values mean that for each case study, the framework suggests an optimal price range where profitability is maximized while considering all the inputs such as policies, circularity, and ESG inputs. The provided confidence interval helps in making realistic pricing strategies by providing a range within which the optimal price is expected to fall. The addressed variability in the model is essential for stakeholders to understand as it affects the formulation of realistic and dynamic pricing strategies. The stability and predictability of optimal price are crucial for making informed decisions, especially for the EV industry which drives the demand for natural graphite.

Case 2 demonstrates the highest expected profit with the highest standard deviation. On the other hand, Case 3 demonstrates lower standard deviation in profit profile compared to case 1 and 2. This means case study 3 offers lower financial risks compared to other cases.

The profit distribution of all three cases illustrates a relatively narrow spread, likely due to the law of large numbers, indicating higher predictability and replicability in results. This reliability is essential for creating dependable and effective pricing models, especially when proving the bankability of companies.

The proposed sensitivity analysis approach allows analyzing the influence of specific factors on the pricing model, providing an itemized view of how each parameter affects costs and pricing strategies which can be expanded upon in future iterations. Case 3 has better circular economy initiatives compared to case study 1. While in case study 1 the variable cost and fixed cost is lower, and demand is higher which is a more favorable situation. The better values for circular economy, although might lead to additional costs but result in long-term savings via sustainable practices. To cover the initial costs associated with the circular economy practices the optimal price is calculated higher for case study 3. This highlights not only the costs incurred but also the significant improvement in the company's market reputation and investor confidence.

7. Conclusion and Future Work

The dependence on limited and potentially geopolitically unstable regions for critical mineral supplies exacerbates supply chain vulnerabilities and threatens the security of supply. This work proposed a framework with DPF as a solution to this challenge, fulfilling the stated research objective. The strategic depth of this approach is reinforced by the model's implementation and validation, which paves the way for future developments, including the integration of real-time market data. Such expansion can significantly enhance the model's predictive capabilities and its adaptability to dynamic market conditions.

The preliminary outputs of the model serve as a platform for devising dynamic pricing strategies that encapsulate the true fair value of critical minerals extracted through diversified, sustainable practices. The model's capacity for data integration positions it to conduct thorough assessments of ESG compliance and evaluate macroeconomic and geopolitical risks, emphasizing the strategic advantage of diverse sourcing methodologies. The proposed approach can support diversification by reducing reliance on single sources, particularly from geopolitically unstable regions, which enhances supply chain resilience and stability, ensuring a consistent supply of natural graphite. This diversification can be further supported by the bankability of new critical minerals production companies. The proposed approach can cover the implications of various scenarios simulated through different scenarios; indeed, the standard deviation analysis of optimal prices and profits signifies predictable outcomes and lower financial risks.

References

ABC News, Indonesia's Electric Vehicle Battery Nickel Rush, 2023. Available:https://www.abc.net.au/news/2023-10-22/indonesias-electric-vehicle-battery-nickel-rush/102862362, Accessed on October 22, 2023.

Abdoli, S., A framework for analysing the environmental impact and support decision making in sustainable development context. Environment Systems and Decisions 43, no. 2, pp. 281-297, 2023.

Abdoli, s., Xie, S., Bahramimianrood, B., Malaibari, M., Stringer, T., A Methodological Framework for Analysis and Theorization of Circular Supply Chain at the System Context Level. *ESSN: 2701-6277,* pp. 382-392, 2023.

Abdallah, T., Asadpour, A., Large-Scale Bundle-Size Pricing: A Theoretical Analysis. *Operations research,* pp. 1158-1185, 2021.

Aviv, Y. and Pazgal, A., Optimal pricing of seasonal products in the presence of forward-looking consumers. *Manufacturing & service operations management,* pp. 339-359, 2008.

Nurdiawati, A. and Agrawal, T.K, Creating a circular EV battery value chain: End-of-life strategies and future perspective. *Resources, Conservation and Recycling*, 106484, 2022.

Baars, J., Domenech, T., Bleischwitz, R., EricMelin, H., and Heidrich, O., Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. *Nature Sustainability,* pp. 71-79, 2021.

Bahramimianrood, B., Xie, S., Malaibari, M., and Abdoli, S., Reviewing Circularity Indicators for a Sustainable Transition to a Circular Economy. *Procedia CIRP*, 1065-1070. 2024.

Benchmark. Natural Graphite Price Assessment, 2024. Available: https://www.benchmarkminerals.com/price-assessments/natural-graphite/, Accessed on June 14, 2024.

Biller, S., Chan, L.M.A., Simchi-Levi, D., and Swann, J., "Dynamic pricing and the direct-to-customer model in the automotive industry.". *Electronic Commerce Research 5*, no. 2, pp. 309-334, 2005.

Bolton, R.N. and Matthew B. Myers, M.B., Price-Based Global Market Segmentation for Services. *Journal of Marketing,* pp. 108-128, 2003.

Bonakdarpor, M., Baliey, M., Inflation Reduction Act: Impact on North America metals and minerals market. S&P Global. 2023.

Callie, B., Shahana, A., Rios, C., Bilec and Graedel, M., The role of design in circular economy solutions for critical materials. *One Earth*, pp. 353-362, 2021.

Campbell, M. C., Why did you do that? The important role of inferred motive in perceptions of price fairness. *Journal of Product & Brand Management*, pp. 145-153, 1999.

Deksnyte, I., and Lydeka, Z., Dynamic pricing and its forming factors. *International Journal of Business and Social Science,* 2012.

Eid, C., Koliou, E., Valles, M., Reneses, J., and Hakvoort, R., Time-based pricing and electricity demand response: Existing barriers and next steps. Utilities Policy, pp. 15-25, 2016.

Fitkov-Norris, E. D, Khanifar, A, Dynamic pricing in mobile communication systems. *in First International Conference on 3G Mobile Communication Technologies,* London, 2000.

European Commission. European Critical Raw Materials Act, 2024. Available: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/green-deal-industrial-plan/european-critical-raw-materials-act_en, Accessed on July 22, 2024.

Fastmarkets, Graphite, 2024. Available: https://www.fastmarkets.com/insights/category/commodity/graphite/, Accessed on June 22, 2024

Fisher, M., Gallino, S., and Li, J., Competition-Based Dynamic Pricing in Online Retailing: A Methodology Validated with Field Experiments. *Management Science*, 2496-2514, 2018.

Guda, H., Subramanian, U. Your Uber Is Arriving: Managing On-Demand Workers Through Surge Pricing, Forecast Communication, and Worker Incentives. *Management Science,* pp. 1995-2014, 2019.

Gupta, R., and Pathak, C., A machine learning framework for predicting purchase by online customers based on dynamic pricing. *Procedia Computer Science,* pp. 599-605, 2014.

Haws, K.L. and Bearden, W.O., Dynamic pricing and consumer fairness perceptions. *Journal of consumer research,* pp. 304-311, 2006.

Halton, B. and Beazley AC. K., AUKUS and critical minerals: hedging Beijing's pervasive, clever and coordinated statecraft. Retrieved from ASPI, 2023: Available: https://www.sustainalytics.com/esg-research/resource/investors-esg-blog/cobalt-esg-risks-threaten-electric-vehicle-supply-chain, Accessed on June 22, 2023.

IEA, Electric vehicle sales by region, 2022-2030. Available: IEA, Paris: https://www.iea.org/data-and-statistics/charts/electric-vehicle-sales-by-region-2022-2030, Accessed on April 2023.

IEA, Global Supply Chains of EV Batteries. Available: https://www.iea.org/reports/global-supply-chains-of-ev-batteries, Accessed on July 18, 2023.

International Energy Agency. Global Critical Minerals Outlook 2024.

Ji, X., and Abdoli, S., Challenges and Opportunities in Product Life Cycle Management in the Context of Industry 4.0. *Procedia CIRP*, pp.29-34, 2023.

Kamateros, G. and Abdoli, S., Automated Disassembly of Lithium Batteries; Methods, Challenges, and a Roadmap. *Procedia CIRP*, 119, pp.1216-1221, 2023.

Krol-Sinclair, M. J., Bring Commodities Market Regulators into the Critical Minerals Discussion. CSIS, Center For Strategic & International Studies, 2023. Available: https://www.csis.org/analysis/bring-commodities-market-regulators-critical-minerals-discussion, Accessed on November 12, 2023.

Liu, K., Li, W., Jia, F. and Lan, Y., Optimal strategies of green product supply chains based on behaviour-based pricing. *Journal of Cleaner Production*, pp. 130288, 2018.

Mishra, S. The Cobalt Conundrum: Net Zero Necessity vs Supply Chain Concerns. Harward Law School Forum on Corporate Governance, 2022 Available: https://corpgov.law.harvard.edu/2022/10/18/the-cobalt-conundrum-net-zero-necessity-vs-supply-chain-concerns/, Accessed on November 1, 2022.

Pollard, M. and Buckley, T., A VALUE-ADDED CRITICAL MINERALS BILATERAL AGREEMENT FOR AUSTRALIA AND SOUTH KOREA. *Climate Energy Finance.* 2023.

Smith, B. and Abdoli, S., Scenarios Of Glass Disposal In Australia From Circular Economy And Life Cycle Assessment Perspective. *ESSN: 2701-6277*, pp.893-902, 2023.

State-of-Play. Critical Minerals: Developing Price Transparency, 2023. Available: https://stateofplay.org/download/2023-critical-minerals-developing-price-transparency/, Accessed on October 21, 2023.

Tesla, Tesla Impact Report, 2023.

U.S. Department of Energy. Critical Materials Assessment, 2023.

Xie, S., Bahramimianrood, B., Malaibari, M., Abdoli, S., Dietrich, F., (Navigating Complexities In Closed-Loop Supply Chains: A Review Of Objectives, Uncertainties And Decision Variables. *Proceedings of the CPSL 2024. Hannover,* publish-Ing. pp. 753-765, 2024.

Zoe Liu, Z., Critical Minerals and the New Cold War. Available: THE DIPLOMAT, 2023: https://thediplomat.com/2023/09/critical-minerals-and-the-new-cold-war/, Accessed on October 1, 2023.

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