24-643: Electrochemical Energy Storage Systems

Carnegie Mellon University Scott Institute for Energy Innovation

Multi-Criteria Decision Analysis for EV Cathode Material Mining Opportunities

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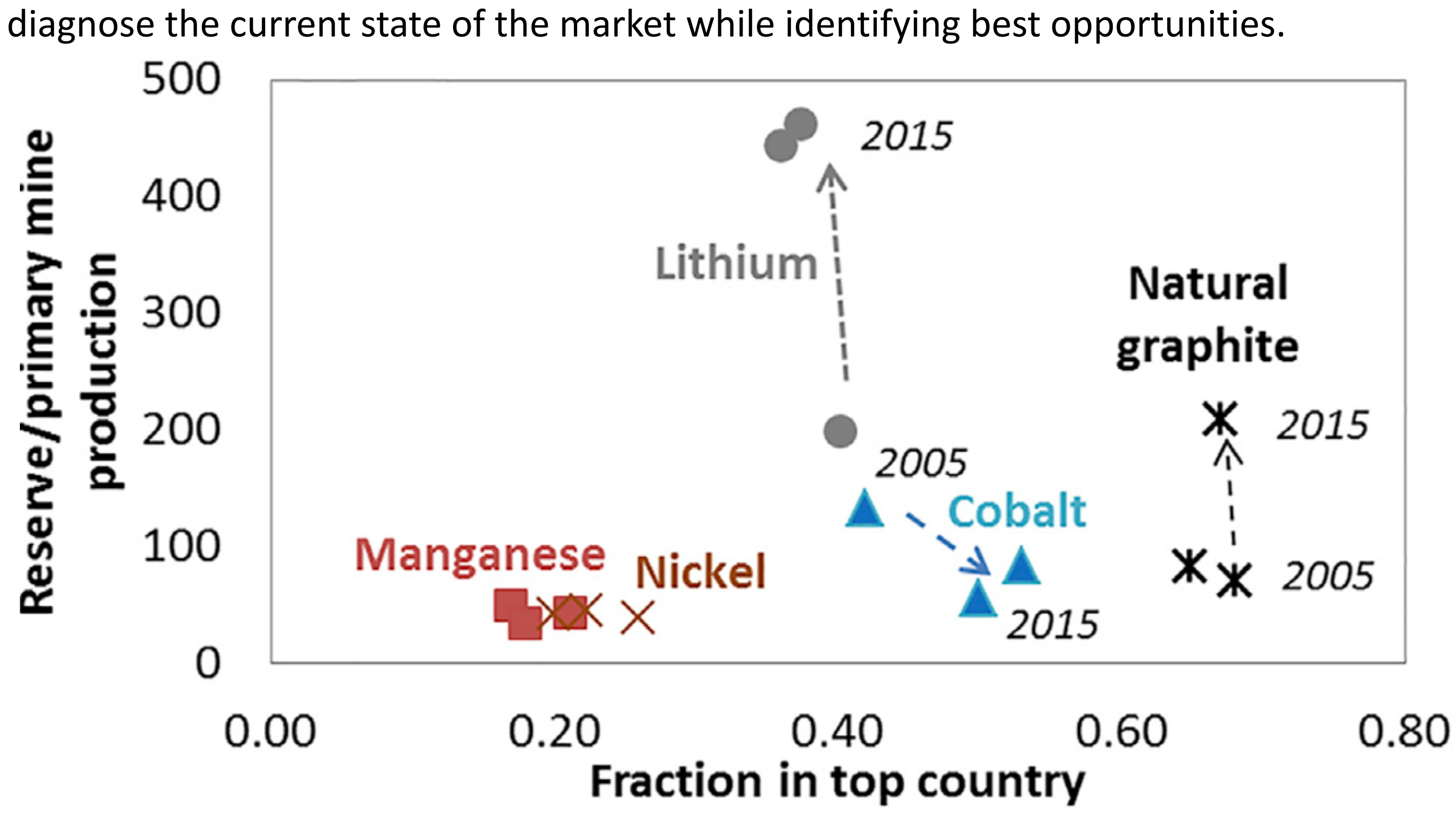
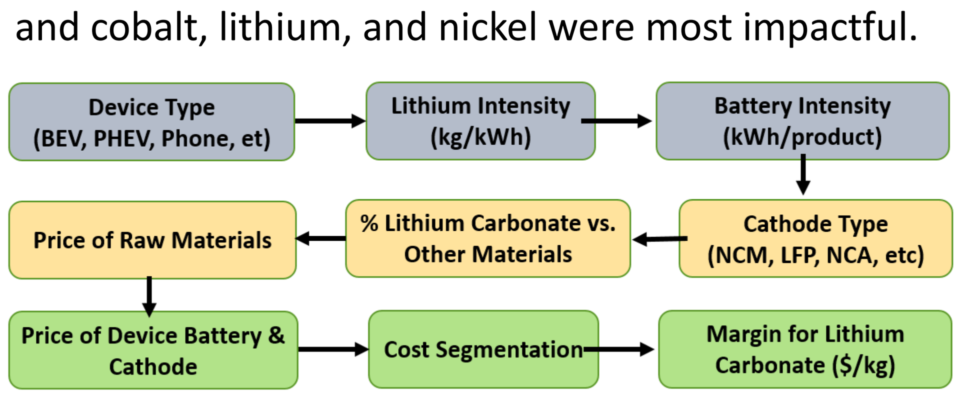
INTRODUCTION

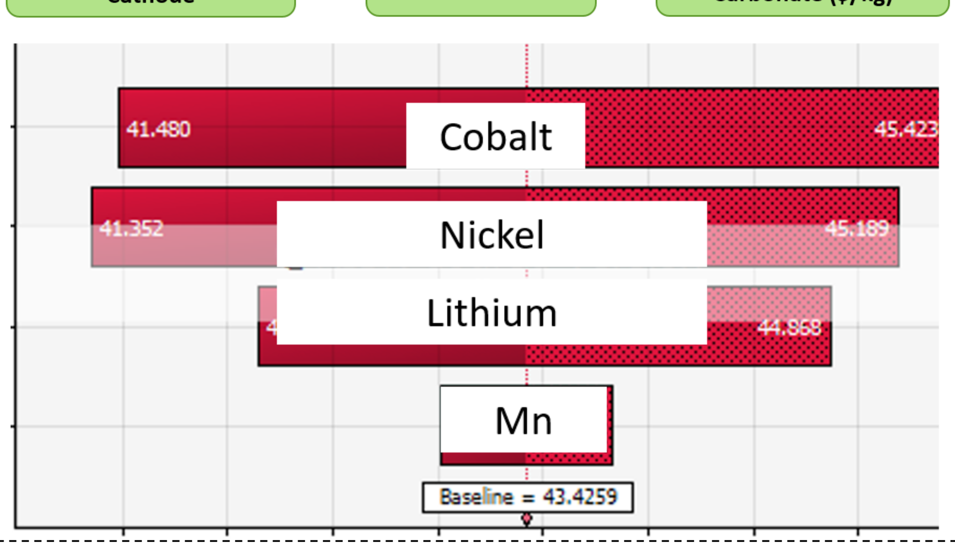
The global rise in electric vehicle demand is impacting the global supply and demand of raw materials used in lithium ion battery cathodes like lithium, cobalt, and nickel. The price of these commodities is of considerable interest to both battery manufactures and mining firms at opposite ends of the supply chain, and this analysis seeks to diagnose the current state of the market while identifying best opportunities.

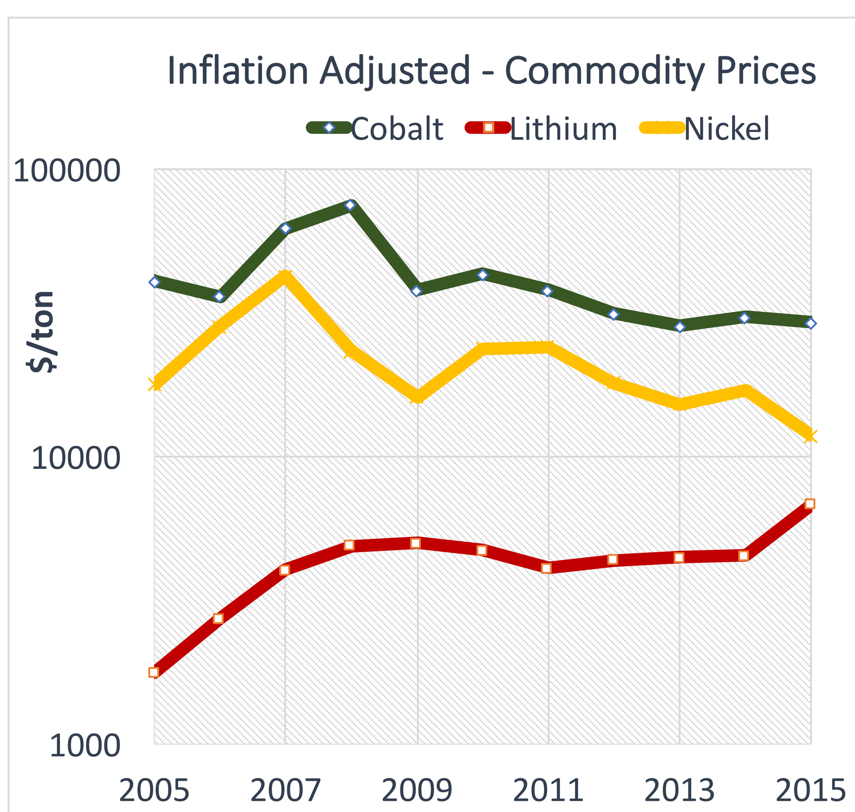


METHODS

First, a simple model was utilized to test the impact of commodity prices on EV cathode $/kWh (mix of NMC & NCA predominately). Historical price distributions and material requirement were input and cobalt, lithium, and nickel were most impactful.

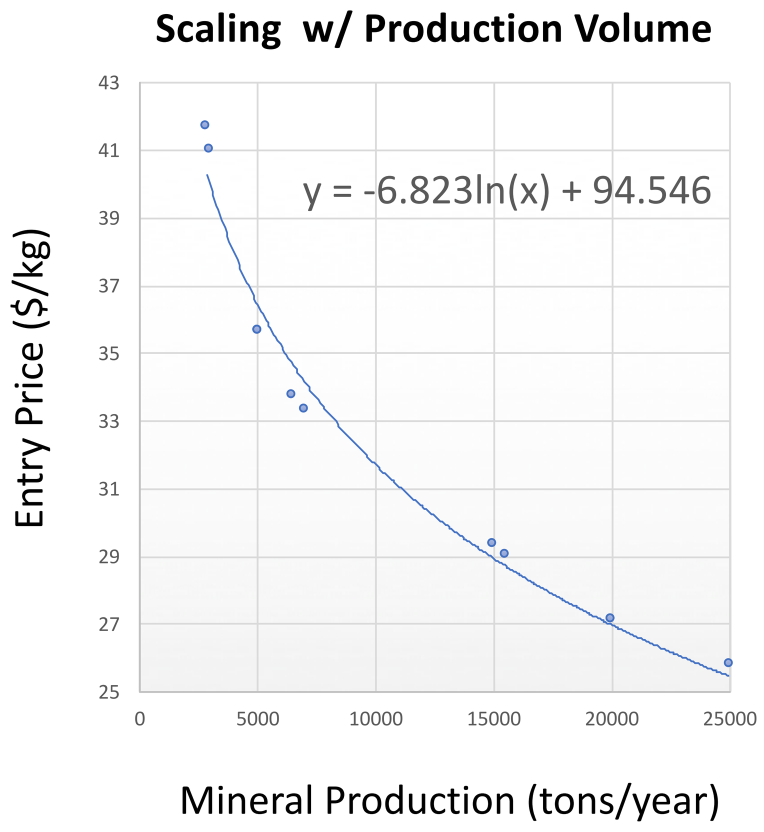






	Cobalt	Lithium	Nickel
Avg Price ($/ton)	30950	6148	15511
Stdev ($/ton)	14673	2005	3356
Range (%)	47%	33%	22%

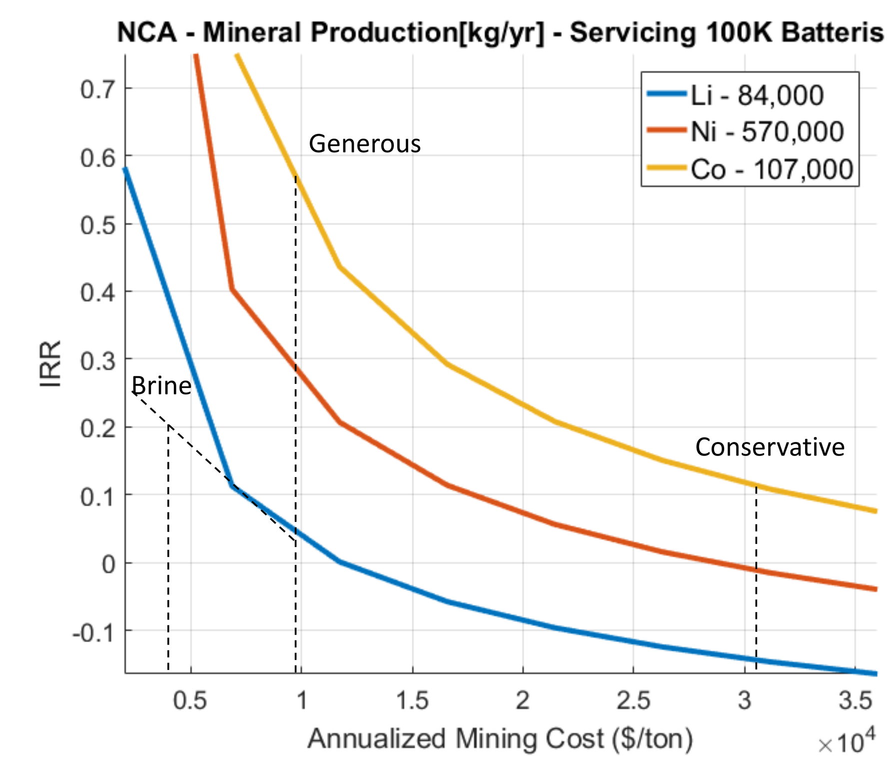
Next, the materials most impactful for EV prices were compared to view the optimal elements to pursue mining either with low production volumes for vertical integration of EV manufacturers or for high production volumes to supply to the whole market.
IRR vs. Cost of mining per ton was evaluated and placed as the criteria carrying the most weight in the multi-criteria decision analysis PROMETHEE.



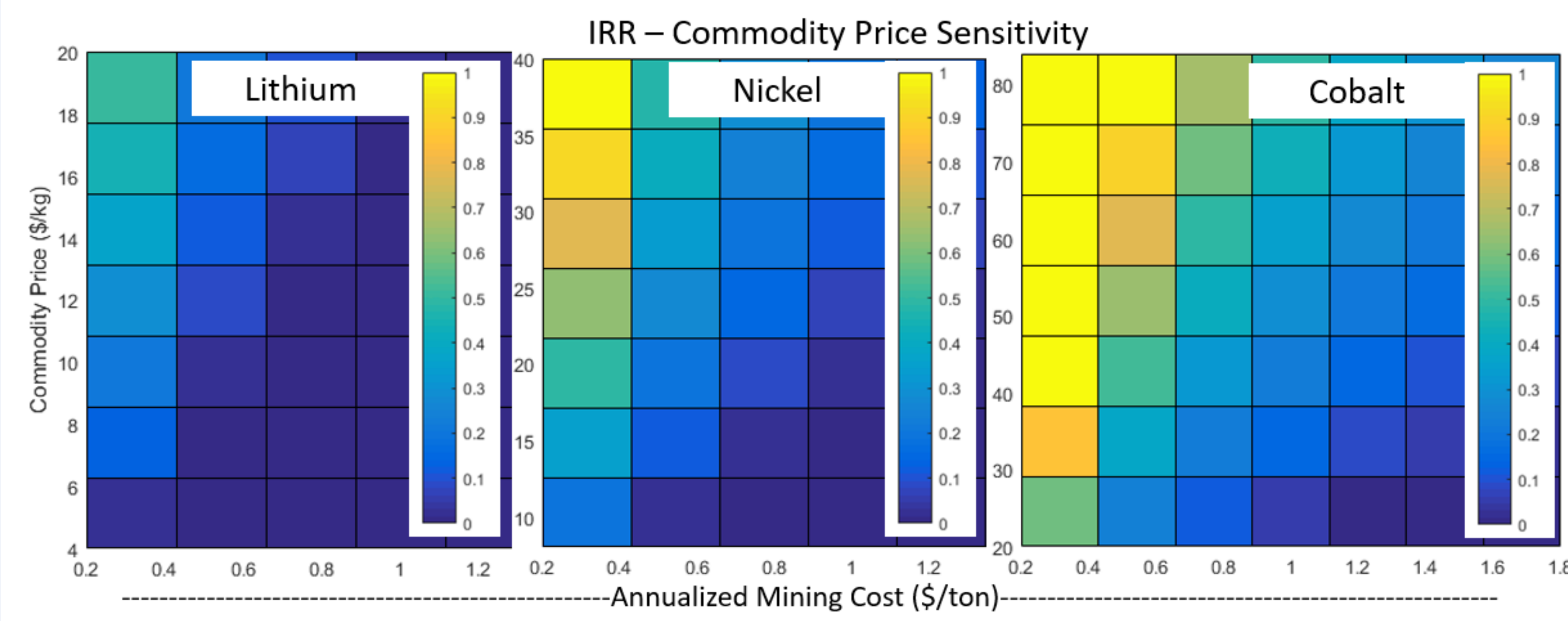
PROMETHEE CRITERIA AND WEIGHT INPUTS

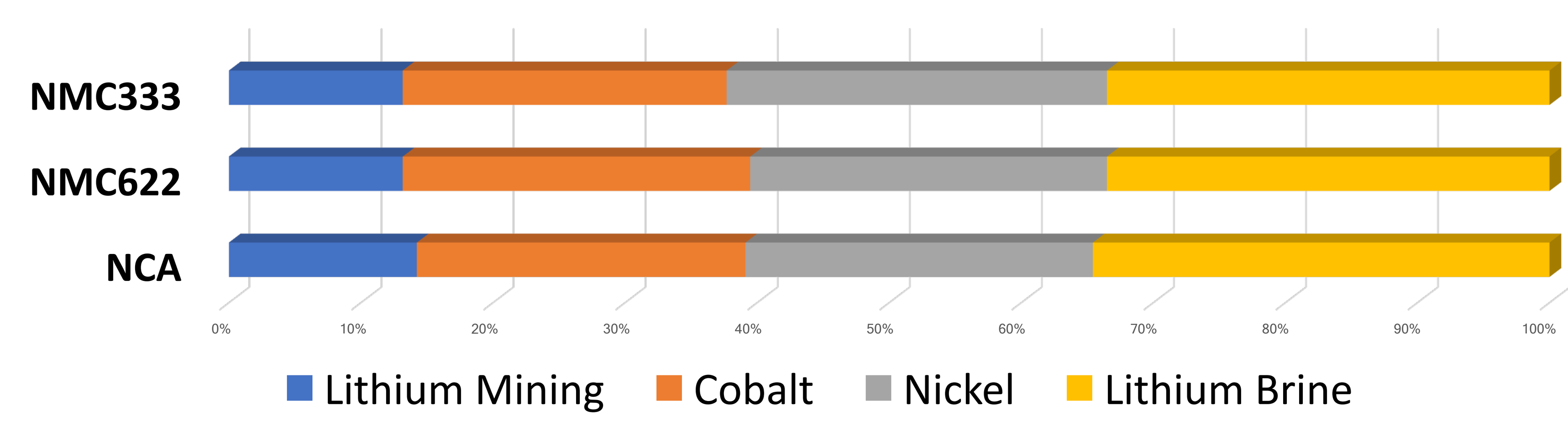
Criterion	Source of Criteria Information	Weights	
		Vertical Int. Scenario	High Volume Scenario
Location	Proximity to the U.S. of the top two element rich countries	2	0
Element Weight per Cathode	BATPAC evaluates element weight per 100,000 battery production	3	0
Price Volatility	Variability in element commodity price over past five years	4 (max)	4 (min)
Humanitarian and Environmental Considerations	The potential negative labor and environmental impacts in mining of element	2	2
Labor Costs	Labor costs in top two countries of element abundance	3	3
IRR	The IRR evaluated by analyzing market costs, operation and capital costs of mining procedures, and production volume	4	4
EV Market Element Dependency	Dependency of EV Li-ion market on Element	1	1

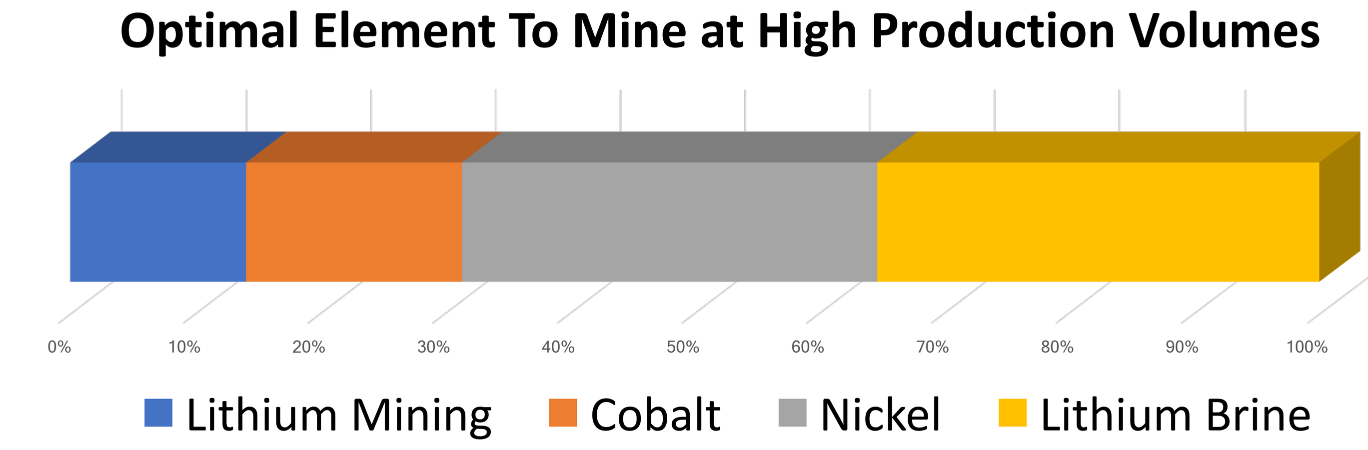
RESULTS



IRR per Element for Low and High Production Volumes		
	Vertical Integration	High Production
Nickel	14%	23%
Cobalt	8%	16%
Lithium Mining	-5%	6%
Lithium Brine	20%	20%







CONCLUSION

- Lithium Brine provides the highest IRR for vertical integration
- Nickel provides the highest IRR for high production volumes
- Mining Lithium brine is the most optimal solution for low and high production volumes

Next steps: Decision makers should now consider locations for mining operations, the heat map to the right provides a starting point for potential lithium exploration. Happy Hunting!

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Multi-Criteria Decision Analysis for Cathodic Material Mining and Sourcing

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1 Abstract

The impacts of material costs on battery manufacturers is growing in weight. In just two years, the percent of material costs in electric vehicle battery packs have shifted from 22 to 51 percent [1]. This increase in material costs weight is rooted in two major aspects, one being the improvements and efficiencies developed in the electric vehicle industry that have been driving overall costs down, and two that the major demand increase for essential cathodic materials have not been met by the supply of these materials.

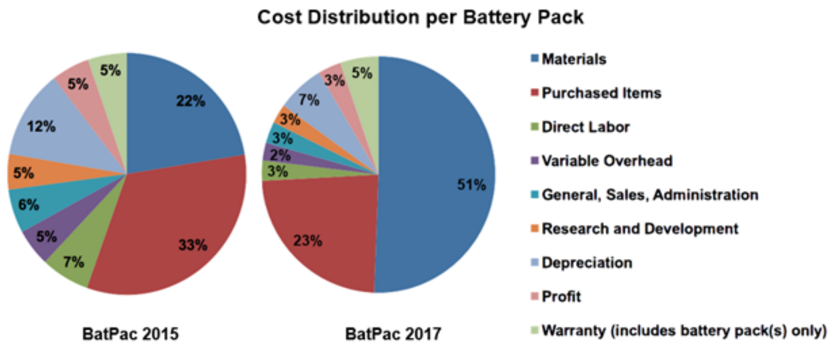


Figure 1: Cost Distribution per Battery Pack

Citing a Bloomberg New Energy Finance projection, electric vehicle sales are expected to reach over 24 million annual sales by 2030 [12]. Lithium-ion battery manufacturers have observed this trend and are quickly moving to add more production capacity [12]. There are several challenges that manufacturers need to address to be well positioned moving forward. For one, they need to be consciences and responsive to automobile manufacturer preferences for which cathode types they will produce.

Furthermore, manufacturers and investors need to be aware of the risks that can challenge adequate profitability. Already, profit margins in the industry are very low and sometimes negative as market share is held at a higher value in certain instances [2]. In this study, cathodic material commodity prices are reviewed, and a sensitivity analysis is done in conjunction with Argonnes Battery Cost Model (BatPac) to determine the resultant impact on manufacturer profit margin.

Additionally, this is an interesting time in the industry that could be conducive of increased cooperation leading to vertical integration strategies up and down the supply chain, from cathodic material mining and production to battery and electric vehicle manufacturing. All at once, electric car companies are driving down costs to achieve vehicle parity, battery manufacturers are being squeezed thin, and additional resource extraction investments are needed to meet growing demand. Through cooperation, the signing of long-term contracts, and investments in new technology a lot of additional value could be realized [12].

Fundamentally, this paper seeks to provide an analytical assessment of the alignment of these interests while identifying best available opportunities present for these stakeholders. Some of the methods utilized include the assessment of commodity price variability, the addition of sensitivity analysis features to BatPac, and the testing of resource extraction project values. All of these factors form inputs into a multi-criteria decision analysis with the objective of determining the most important commodities that mining operations should target and that manufacturers should prioritize. The decision analysis utilized is titled a Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) and allows decision makers to weigh the necessary criteria pertaining to vertical integration or industry entry projects.

To summarize some key takeaways, analysis has identified materials such as lithium, cobalt, and nickel to be of significant importance. The most critical material to secure depends on the type of battery being manufactured, but lithium brine extraction has emerged as a potentially high value venture as lithium prices have grown and new technologies have been developed. From the battery manufacturing perspective, NCA cathode types have shown lower vulnerability to cathodic material price fluctuations and higher profit margins per kWh of battery production when compared to other cathode types used in battery electric vehicles. Additionally, the decision evaluation methodology and the real options framework provides a historically and analytically justified path to assess new ventures in this developing arena.

2 Background

A common tool used in academic and industrial evaluation of electric vehicles, of lithium-ion battery performance, and of manufacturing costs is Argonne National Labs BatPac model. This model stands alone in its robust consideration of manufacturing processes and cell design while accounting for constraints in electrochemical processes and the resulting impacts on energy density and costs [1]. Our efforts began with an observation in BatPac that material costs had increased by a significant amount in terms of total cost proportion for battery pack production (Figure 1). Understanding the growing weight of material costs, our group delved into the commodity markets of key materials so that an understanding of price variability and the resultant impact on EV pack costs could be understood.

To begin, price trends in the commodity markets were viewed for the main cathode materials. These main materials are Lithium, Nickel, and Cobalt. Their commodity market prices were evaluated over a five year period and the volatility in these prices were utilized to test various sensitivity cases via BatPac. There are a number of sources reporting on material prices like cobalt, lithium, nickel, copper, etc. One such source is the USGS Minerals Commodities Summary which publishes annual data on these materials (Figure 2) [9].

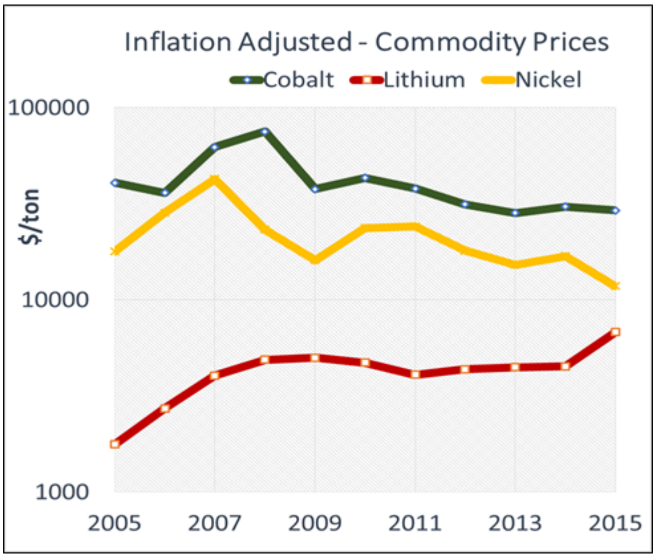


Figure 2: Commodity Price Fluctuations of major Cathodic Materials

Taking a deeper look at Lithium for example: Bloomberg reports the expected demand increase of Lithium to be an equivalent of 35 plants the size of the Tesla Gigafactory being built by 2030. To meet this tremendous increase, total investment in new mining operations for lithium need to grow by $350 billion to 750$ billion [4].

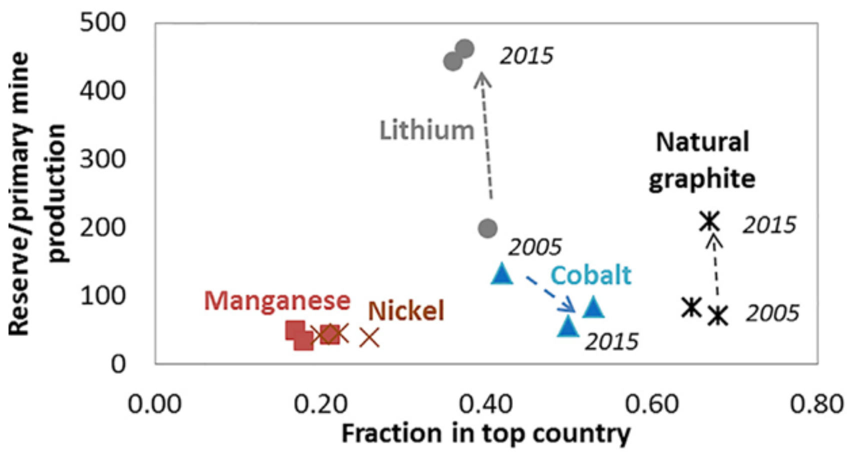


Figure 3: Reserve Rates Comparison

Additionally, a recent figure from Joule illustrates how the reserves for cathodic materials have changed worldwide over the last 10 years [5]. A key takeaway is that cobalt reserves have been decreasing and are lacking in supply diversity (Figure 3). This is a big challenge that must be addressed as cobalt is a key driver of costs for lithium ion battery cathodes. Interestingly, large amounts of lithium have been discovered in brines in locations like the Bolivian salt flats, but the price of lithium has been rising continuously over this time period. This means that the demand and evaluation for lithium has outpaced the additional mining and production capacity that has been added over this time period. Nickel reserve discoveries and, in general, nickel commodity prices have remained relatively stagnant, however due to their large abundance in major cathodic chemistries, namely NCA and NMC, this stagnation may raise a cause for concern for battery manufactures over the long haul.

Due to the scarce nature of this rare earth ore and its requirement to be mined for the growing battery industry, this creates a global scaled incentive for resource rich nations to allow for foreign and domestic investments. The areas of major abundance were viewed and considered as major components within the PROMETHEE analysis. The countries of most abundance are spread across the world for each of these elements. For nickel, the countries of greatest abundance are the Philippines and Canada. Cobalt has a tremendous abundance in the Democratic Republic of Congo as well as some in China, and for Lithium the highest rates of historical production were found in Australia and Chile, and recent advancements in brine have lead Bolivia to becoming a major contributor [5]. Understanding the countries of highest abundance and what benefits or challenges these locations present for investment efforts are very important criteria we considered when analyzing the decision analysis for selection of optimal material pursuits.

Brine resources will be utilized at an increasing rate as prices for the commodity increase. More so, a UBS report finds brine annualized costs between 3,000 and 10,000 dollars per ton yielding possible profit margins over 5000 dollars per ton [11]. These trends are causing significant interest in the development of lithium brine resources in Nevada, United States. On top of traditional lithium carbonate extraction from brine utilizing time intensive evaporation ponds, firms like Tenova SpA, an Italian engineering company, are designing an ion-exchange system that strips lithium and returns groundwater [13]. Another study out of Lappeenranta University of Technology tested a non-traditional method for lithium extraction that has been effective at achieving recoveries of 99.9 percent lithium purity [10]. As stated above, large capital investments in lithium extraction will be needed to meet the growing demand for lithium ion batteries, but these new technology developments show that brine extraction is far from the industrial maturity of its mining counterpart.

3 Methods

Our process for quantifying the impact of cathodic material price increases while identifying solutions is demonstrated via the following flow diagram.

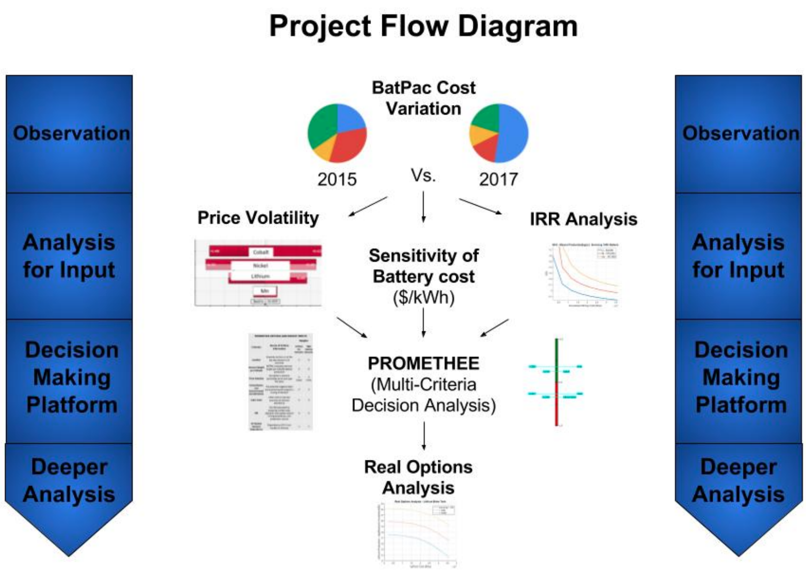


Figure 4: Project Flow Diagram

Walking through these steps, the commodity price volatility shown in Table 1 demonstrates that the assumption for fixed commodity prices utilized in BatPac would be insufficient to describe a full range of outcomes. On the other hand, the historic volatility of these commodities shown below provides reasonable bounds for inputs into a sensitivity analysis feature that was added to BatPac by the group.

Commodity	Range (%)	Low ($/kg)	Estimate ($/kg)	High ($/kg)
Lithium Carbonate	33%	6.70	10.00	13.30
Nickel	22%	17.16	22.00	26.84
Cobalt	47%	23.32	44.00	64.68
Manganese	34%	1.32	2.00	2.68
Aluminum	50%	1.10	2.20	3.30

Table 1: Commodity Price Volatility

The October 2017 version of BatPac has included cost estimates for six cathode types and their active materials. The challenge with adding the new sensitivity analysis tab therefore was getting the total active material price per kg in terms of all the input commodities, therefore we added it onto a separate tab displayed in Table 2.

	NCA-G	NMC622-G	NMC333-G
Equation	LiNi0.80Co0.15Al0.05O2	Li1.05(Ni0.6Mn0.2Co0.2)0.95O2	Li1.05(Ni1/3Mn1/3Co1/3)0.95O2
Cathode Tested	NMC333-G	NMC333-G	NMC333-G
Li g/mol	6.94	6.94	6.94
Ni g/mol	58.69	58.69	58.69
Cobalt g/mol	58.93	58.93	58.93
Manganese g/mol	54.94	54.94	54.94
Aluminum g/mol	26.98	26.98	26.98
Oxygen g/mol	16.00	16.00	16.00
Li mol	1.00	1.05	1.05
Ni mol	0.80	0.57	0.32
Cobalt mol	0.15	0.19	0.32
Manganese mol	0.00	0.19	0.32
Aluminum mol	0.05	0.00	0.00
Oxygen mol	2.00	2.00	2.00
Total g	96.08	94.38	93.93

Table 2: Mass Calculation table for Major Cathode Types

Calling upon a normal distribution of prices based on the above volatility, a value for active material dollars/kg can be generated within a Monte Carlo simulation and can be propagated throughout the results generated within BatPac. Results captured for the three cathode types at every combination of forecasted price ranges include the total price of cathodic material per pack, the total cost of pack, the pack cost per kg, and the pack cost per kWh. The Excel software plug-in called @Risk was utilized to perform and tabulate these results within the added sheet on BatPac. This analysis yields results alluding to the exposure of battery manufacturer profit margins to price volatility and the most critical commodities driving this exposure for each cathode type.

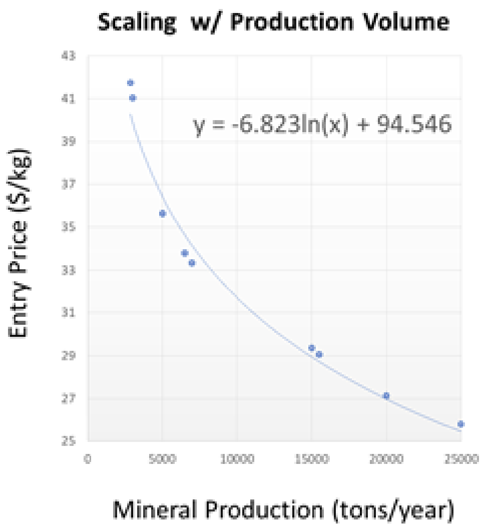


Figure 5: Scaling Costs by Production Volumes

The next step to create a clearer image of the important factors in analyzing mining opportunities was to view the potential profitability of each project. This was done by evaluating the Internal Rate of Return (IRR) based on annualized cost per tonnes produced per year. Resource extraction can take place on a variety of scales from record breaking open-top mining operations to small scale start-ups. For the purposes of this analysis, the small scale will be considered enough to meet the commodity needs for 100,000 battery pack production while the high end will be 25,000 tons per year based on MITs open-top mining estimates for rare earth ore. The assumptions made in the IRR calculations were that the project would be performed over a ten year period and there would be a depreciation at a rate of 10 percent per year. The cost scaling based on production came from a case study performed by MIT [8].

Lastly we considered the other main criteria that decision makers in this space would evaluate. Making the assumption that our decision makers are in the United States, and only considering the locations of the two most abundant countries in each material, criteria were evaluated of location proximity of these countries to the U.S., the labor costs in these countries, and the humanitarian and environmental effects of operating mining procedures in these countries. Other major criteria evaluated were the EV markets dependence on these materials over a ten year time scale and the materials weight per cathode type. The last two criteria considered, and carrying the highest weight, are the inputs from our analysis of potential IRR from each project and the sensitivity of pack costs based on the volatility of material prices.

Establishing weight for these criteria were done by creating a matrix for pairwise comparison between each criteria. If a criteria was deemed more important for the decision maker than the criteria it was compared against then it would receive a preference value of one. For example if Criteria A were compared to Criteria B, and Criteria A were deemed more important than B, the the preference for A would be deemed 1, but if when compared against C and D it is deemed less important, then the total number of preference given to Criteria A would still be one. The total number of preferences that were obtained for each criteria value over another were totaled and the criteria were ordered based off of highest preference values. If a criteria had three or more preference values over the other criteria then the weight would be two points greater than the nearest weight, else the weights would just be one point higher than the criteria below it. We set the lowest preferenced criteria at a weight of one, and the weights and description of the source of information as well as the type of values assigned to these criteria are listed in Table 3.

PROMETHEE CRITERIA AND WEIGHT INPUTS

Criterion	Source of Criteria Information	Value Type	Weights	
			Vertical Int. Scenario	High Volume Scenario
Location	Proximity to the U.S. of the top two element rich countries	9 Point Scale. Score of 9 for closest and 1 for furthest countries to U.S	2	2
Price Volatility	Variation of commodity price for each material over the past five years	The average divided by the standard deviation of commodity prices	3	4
Battery Price Sensitivity	Battery Pack Cost sensitivity based on material Price Volatility	Input from Monte Carlo analysis via BatPac	5	0
Humanitarian and Environmental Considerations	The potential negative labor and environmental impacts in mining of element	5 Point Scale. 5 for the most environmentally friendly and 1 for worst potential impacts	2	2
Labor Costs	Labor costs in top two countries of element abundance	5 Point Scale. 5 for countries of lowest average wages and 1 for highest average wages	3	3
IRR	The IRR evaluated by analyzing market costs, operation and capital costs of mining procedures, and production volume	Input from IRR vs. Levelized mining cost analysis	4	5
EV Market Element Dependency	Dependency of EV Li-ion market on Element	5 Point Scale. 5 for element of highest EV long term dependency and 1 for lowest	1	1

Table 3: PROMETHEE Methods and Weights

The two test cases considered were that of low production volume with the idea of the battery manufacturer as the main decision maker, and of high production volume with a broadening of the decision maker to any entity looking to enter the mining and refining industry for these materials. For low production volumes, we assumed the manufacturers would produce on a scale of 100,000 battery packs per year. This is consistent with the estimates of production volume in BatPac which we used as a major form of our sensitivity analysis. The high production volume test case isnt cathode type specific as we assumed the materials are normalized across all cathode types and the production value of this case is 25,000 tons/year.

The criteria listed in Table 3 have both quantitative and qualitative values. These values were determined for each of the material extraction methods we viewed; Lithium mining, Lithium brine, Nickel mining, and Cobalt mining. For the test case at high production, all the criteria analyzed were measured once as a representation for all electric vehicle cathode material supply. For the test case at low production, all criteria remained the same for different cathode types except for Sensitivity of Price Volatility, as these values depend on the proportion of total material each element accounts for in the cathode type.

The platform for analyzing these criteria is called Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) and is used to achieve the objective of selecting the optimal material for vertical integration or production at high volumes for each cathode type. There is a multitude of literature related to the analysis method PROMETHEE [14,15]. The optimal selection of alternatives have been made utilizing this method for a great number of energy sector issues such as geothermal systems [16], electricity generation [17], and transportation systems [18]. PROMETHEE works on the basis of making pair-wise comparisons of alternatives depending on the criteria selected for one or multiple objectives [19].

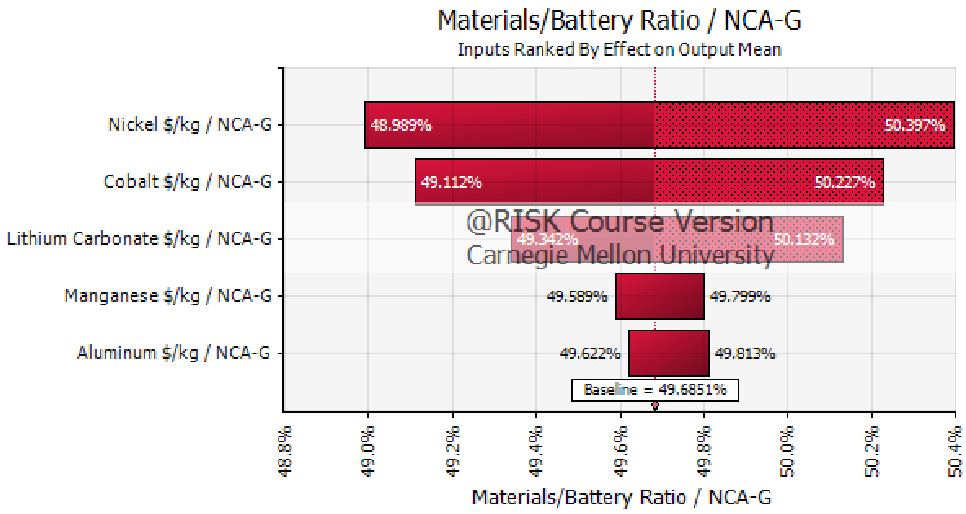
Having concluded from the background that lithium brine extraction could be enhanced by new technology and production ventures, we wanted to set up a framework by which investments in this space can be analyzed for financial viability. Real options theory is an appropriate analysis technique to assess the size such an investment.

$$d_1 = \frac{\ln(S/E) + (R + \frac{\sigma^2}{2})T}{\sigma\sqrt{T}} \longrightarrow d_2 = d_1 - \sigma\sqrt{T} \longrightarrow C_0 = S \times \mathrm{N}(d_1) - Ee^{-RT} \times \mathrm{N}(d_2)$$

In the equations above, S represents the present value of all future revenue. E is representative of the present value of all costs inquired to engage in the project. R is the risk free interest rate, sigma is the standard deviation of cash flows, and T is the time until project execution. C represents the value of investment opportunity today. Because investments in new technologies give the patent holders the right to scale up the size of their operation or not depending on outcome success, real options theory can find greater value in projects with high uncertainty than would analysis utilizing traditional discounted cash flows.

4 Results Discussion

Sensitivity Analysis: To begin, the estimated prices for cathodic material inputs as well as their volatility ranges were input into the BatPac sensitivity analysis. A Monte Carlo simulation was ran for each cathode type, and the results presented below demonstrate the resultant impact that occurred for parameters of interest. The first output shown is a Tornado Plot showing the impact that each commodity type had on the total material price/total battery price ratio for NCA. For NCA, nickel prices were the most impactful given their likely price distribution. Next was cobalt and lithium. At its highest value, all else held constant, Nickel prices alone could raise the total material price/battery price ratio by about 1 percent. This may not sound like a lot, but for reasons discussed below, the combined effect of material price fluctuation could pose a challenge to the industry.



Price Volatility Average Impact on Total Material Price (%)			
Cathodic Input	NCA-G	NMC622-G	NMC333-G
Lithium Carbonate $/kg	0.40%	0.43%	0.48%
Nickel $/kg	0.70%	0.47%	0.37%
Cobalt $/kg	0.56%	0.78%	1.29%
Manganese $/kg	0.11%	0.13%	0.15%
Aluminum $/kg	0.10%	0.11%	0.09%
Averages———————>	0.37%	0.38%	0.47%

Table 4: Price Volatility Impact on Total Material Price

The summary table above aggregates the results of the Tornado sensitivity plot for all three cathode types, and it can be observed that NMC 333-G is the most sensitive to likely commodity price fluctuations. Additionally, the most impactful commodity varies between cathode types. Unlike NCA, the most impactful commodity for NMC622 is cobalt rather than nickel, and for NMC333, cobalt is of very high weight with lithium also taking precedence over nickel supply for battery producers of this cathode type.

Next, the key metric being driven down within the battery production space is the price per kWh. At a baseline scenario of todays commodity spot prices, BatPac runs profit calculations that are generally descriptive of battery production at a 100,000 pack per year rate. So, both the cost of the battery and the profit are known in terms of $/kWh.WhentheMonteCarlosimulationisran,thechangeinbatterypackprice($/kWh) can be shown in every scenario, and the probability of commodity prices reaching a point that absorbs current profit margins can be determined.

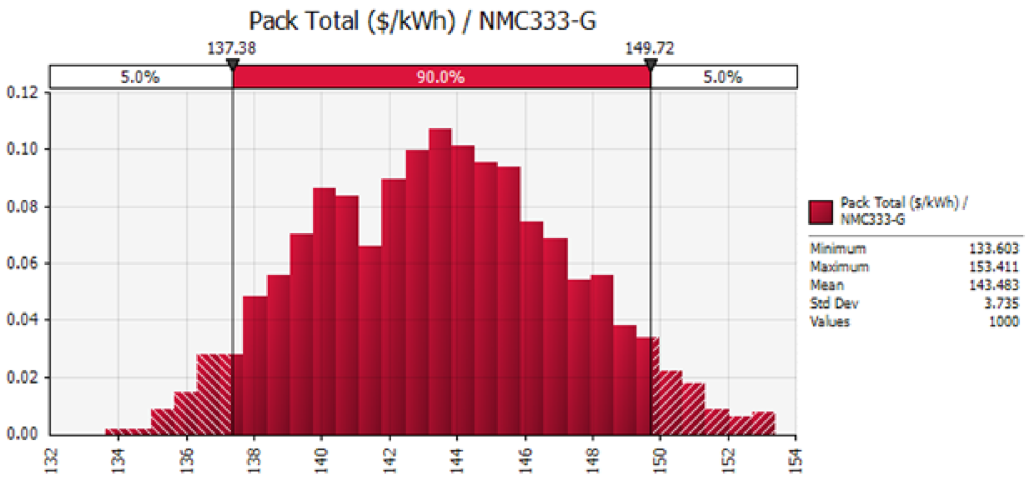


Figure 6: NMC333 Price/kWh Distribution

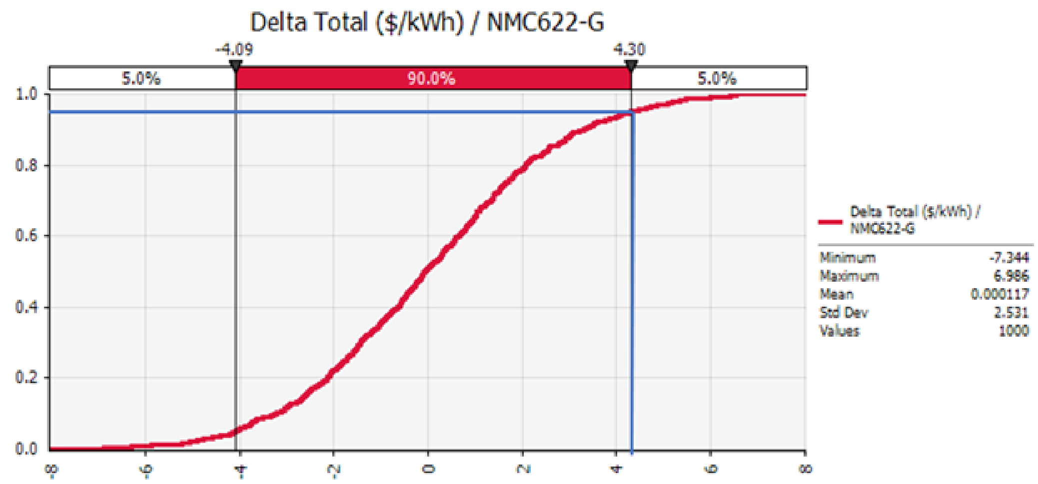


Figure 7: NMC633 Cumulative Probability Distribution

Prices ($/kWh)	NCA	NMC622	NMC333
Max	189.025	158.03	153.411
Mean	181.667	151.313	143.483
Variation	4.05%	4.44%	6.92%
Delta	7.358	6.717	9.928
Profit ($/kWh)	5.88	4.33	3.62
High End Loss ($/kWh)	1.48	2.38	6.30
Probability of Reaching Profit Margin	<5%	5%	15%

Table 5: Profit Margin Impacts from Worst Case Commodity Prices

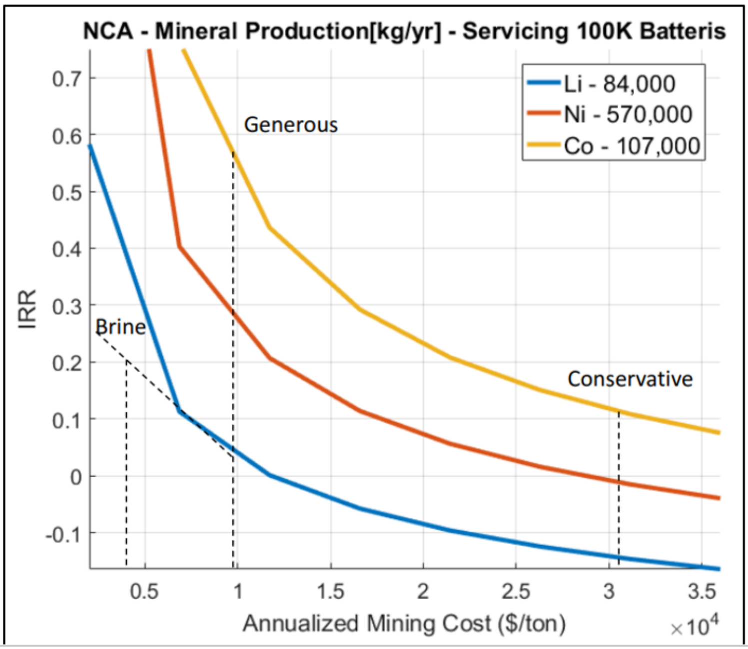
For the histograms generated for each cathode type, the expected high and low pack costs are observed and tabulated in the table above. Although NCA has the highest cost per kWh of the three, the range of upward variation its price could observe is the smallest (4.05 percent) while NMC333 is the highest (6.92 percent). Then using the cumulative probability distributions above, it is shown that NMC333 has a much higher probability of losing its profit margin at current sales prices than does NCA or NMC622 given the volatility of input commodities.

Cathode Metrics	NCA-G	NMC622-G	NMC333-G
Energy per mass (kWh/kg)	0.16	0.17	0.16
Energy per volume (kWh/L)	0.254	0.285	0.295
Density (kg/L)	1.61	1.69	1.80
Profit ($/kWh)	5.88	4.33	3.62

Table 6: Profit/kWh of Different Cathode Types

Relating the preferences of electric vehicle and battery manufacturers, Table 6 shows some key metrics that these stakeholders may value. From the electric vehicle perspective, a high energy content per given weight and volume are desirable, and that seems to favor the NMC variations. However, density could also be a criteria worth considering (kg/L) where a trade-off exists between vehicle weight, available energy, and the resulting vehicle range depending on the design goals for a vehicle. From the battery manufacturing perspective, there is a clear benefit for the production of NCA batteries which afford a higher profit margin and less risk exposure to price volatility.

Mining IRR Determination: Next, the analysis transitions to assess the commodity market from the lense of resource extraction. Again, the goal is to identify optimal elements to pursue mining in cases of both low production volumes for independent or vertically integrated operations and for high production operations supplying a greater percentage of the market.



IRR per Element for Low and High Production Volumes		
	Vertical Integration	High Production
Nickel	14%	23%
Cobalt	8%	16%
Lithium Mining	-5%	6%
Lithium Brine	20%	20%

Mining IRR Determination: Next, the analysis transitions to assess the commodity market from the lense of resource extraction. Again, the goal is to identify optimal elements to pursue mining in cases of both low

production volumes for independent or vertically integrated operations and for high production operations supplying a greater percentage of the market. The x-axis on the plot in Figure 8 represents the annualized cost of mining. Pinpointing this number is challenging due to the variations in variables for different mining locations and project specifics, however approximations were made on rough averages for these values based on sources from MIT and UBS [8, 11]. Depending on the commodity being produced, the cash flows depended on the sale prices of minerals shown earlier in this paper.

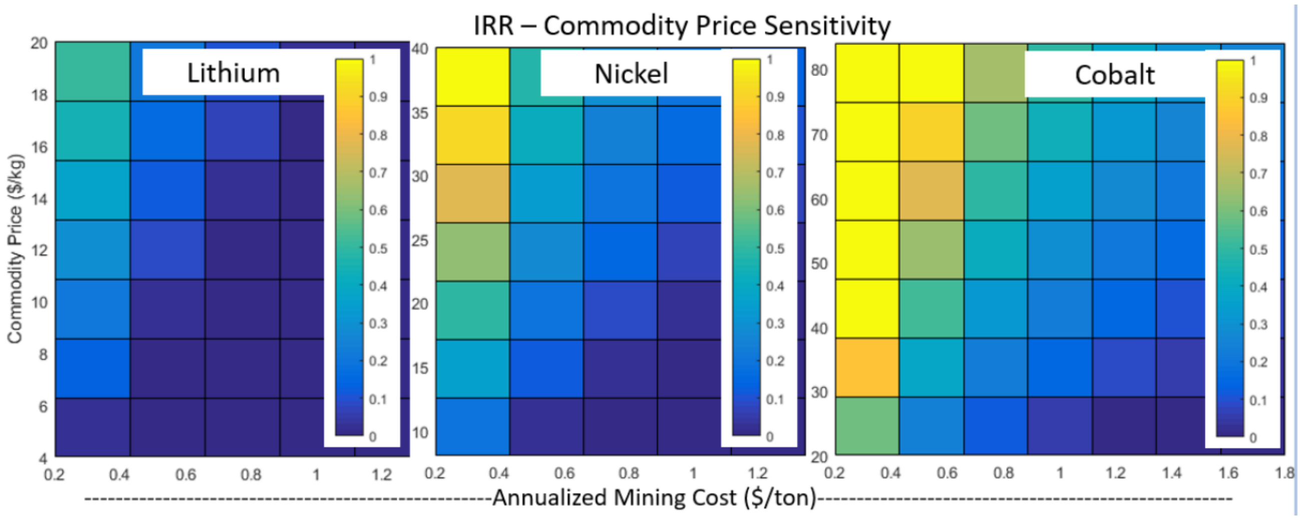


Figure 8: IRR Analysis Results

At a small scale of production, this analysis predicts that lithium brine would offer the highest rates of return on an investment. At higher production volumes, large nickel mining operations would offer the highest rates of return at our estimated annualized mining cost. These values are subject to high levels of uncertainty but can provide guidance to those who have more certain project costs already evaluated. Additionally, the heat map in Figure 8 depicts the impact that commodity price fluctuations have on the attractiveness of these exploration projects. For instance, if cobalt prices rose and the annualized cost of mining were lower than our estimate, the attractiveness of this venture would grow rapidly in value as the yellow indicates scenarios with possible high IRRs.

	Location	Volatility	Hum & Env	Labor	IRR		Dependence
Value Type	9 Point	Value	5 Point	5 Point	Low Production Value	High Production Value	5 Point
Lithium Mining	6	33	4	2	14	23	5
Nickel	5	22	3	3	8	16	4
Cobalt	2	47	1	5	-5	6	2
Lithium Brine	7	33	5	4	20	20	5

Table 7: PROMETHEE Analysis Values

Decision Analysis: The above sensitivity analysis and the IRR calculations were then used as important inputs into a decision analysis that identifies commodities that should be prioritized in the supply chain and pursued in extraction ventures. Sensitivity of pack prices based on price volatility carried the most weight of all the criteria in our decision analysis, and the IRR inputs provided the second most weight. Holistically combining all of the above results into a platform for decision makers to analyze optimal options was done via the PROMETHEE method with the criteria and weights provided in Table 3. The values for each extraction procedure, both quantitative and qualitative, that remained consistent amongst cathode types are defined in Table 7. The values input into PROMETHEE for the sensitivity of price volatility that adjusted based on cathode type is listed in Table 4.

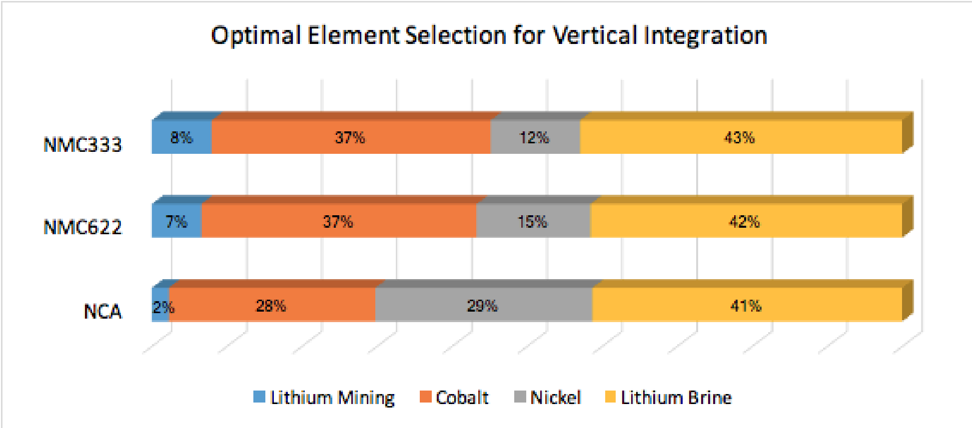


Figure 9: Optimal Element Selection for Vertical Integration

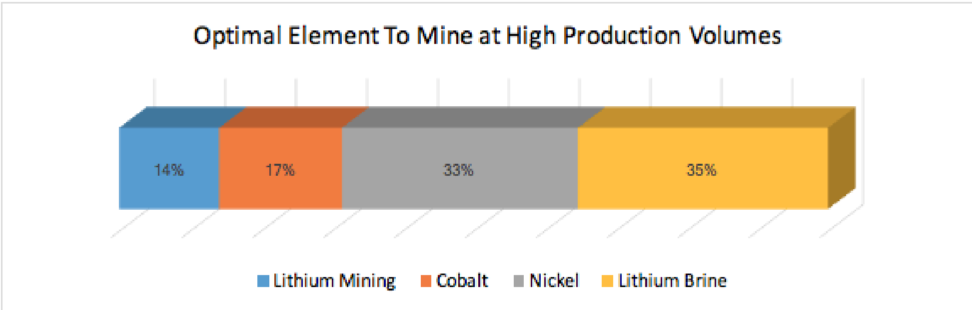


Figure 10: Optimal Element Selection for High Production Volumes

The results defined in Figure 9 represents the optimal element selection for vertical integration for each cathode type. This ordered representation displays the alternative extraction procedures by percentage of optimality in relation with one another. For NCA for example, Lithium Brine is the optimal decision by a significant margin, but Nickel and Cobalt and very close to one another for second best extraction consideration. Figure 10 represents the optimal element selection for the high production volume test case. Here we also find that Lithium Brine is the optimal extraction method considering the criteria analyzed, with nickel as a very close second opportunity to consider further.

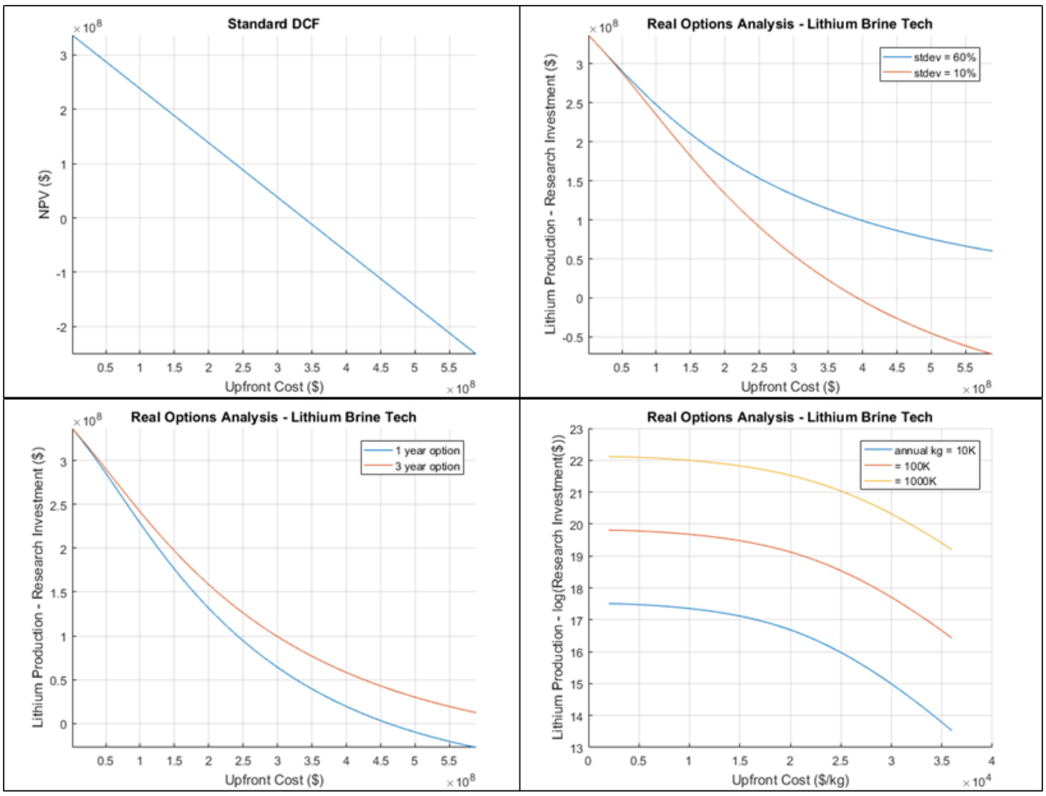


Figure 11: Real Options Analysis

Looking at the discounted cash flow plot from Figure 11 in the top left, we can see that there is a cost of production on the x-axis where the present value of the opportunity goes to zero. The use of real options theory allows more value to be captured because early investments upfront give the developer the right to walk away from the opportunity if the market or technology performance fail to materialize. So, the uncertainty in the outcome increases the value of the option because there is a greater window of positive outcomes to be realized if full commitment is realized down the line. The top right plot demonstrates that, in fact, real options analysis finds value in a venture where DCF analysis does not. Additionally, this plot shows that greater standard deviations around the certainty of the inputs lead to a higher assessment of investment value. Additionally, the longer the right to engage in project commitment belongs to the owner of the option, the greater the value of the initial investment as shown in the bottom left. Finally, the value also depends on the quantity of production or market share of lithium production that an entities utilizing this new technology believes can be captured. This scaling in value is shown in the bottom right plot.

These plots can be utilized as a tool to assess investments that fit the given constraints. Additionally, the investment should be made only if the annualized cost of production is far enough below existing technology that the marginal benefit gained is enough to recapture the marginally greater investment cost associated with developing the new technology. Future work on this subject could take a deeper dive into emerging technologies to find where their value fits along these curves.

5 Conclusions and Future Work

The production of lithium resources from brine appears to provide the highest internal rate of return for low production volume projects most suitable for vertical integration strategies with battery manufacturers. This is becoming increasingly feasible in areas like California and Nevada where battery manufacturing and lithium extraction are occurring in close proximity. At high production volumes, Nickel mining remains a viable industry as demand for the commodity grows with battery vehicle uptake. Canada has a high reserve base of nickel relative to other nations and could provide a good source for U.S. battery production. The analysis also revealed that not all cathode manufacturing opportunities are of equal value to manufacturers. For instance, NMC333 has the highest probability of losing profit margins or raising prices given likely commodity price volatility in the future. NCA on the other hand preserves the highest profit in terms of dollars per kWh and has advantages for electric vehicle use due to the cathodes low density in a given volume when compared to NMC.

We conclude thus far that it is essential to have an easily integrated system for process evaluation for the booming industry that is lithium ion battery manufacturing. The numbers are staggering for the increase in demand expected over the next decades for electric vehicles and it is critical to have models that demonstrate process based cost evaluations to give manufacturers an understanding of what to expect before entering the market. Our efforts have provided the initial steps for creating a framework for manufacturers and resource producers to utilize when evaluating their key sensitivities to commodity price fluctuations and investment opportunities. Once again, this is a unique time in history where there exists strong alignment between industrial interests up and down the battery supply chain, and this is needed to incentivize the increased cooperation that will inevitably alter the global energy landscape.

While this analysis has been based on sound research on the electric vehicle market that promoted our assumptions for the PROMETHEE analysis, one element of this analysis that we look to hone in on further in the future is the establishing of weights for each criteria. We trust that our selection of criteria are an accurate representation of the considerations decision makers would take into account when deciding on best alternatives for vertical integration and element extraction, however we would like more confidence on the weight we evaluated for these criteria. This would be done by having representatives from top battery manufacturers sit down with us and run through the weight creation procedure that we did for each of these criteria. We will also look towards communication with representatives from major mining companies to do the same thing and better establish weights for the high production volume test scenario. This will further validate our findings and help bring a clearer image to what decision makers place their highest value within.

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