Life Cycle Assessment of LFP and NMC battery Production in Nevada, USA

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1. Introduction

"The greatest threat to our planet is the belief that someone else will save it."

— **Robert Swan**, Explorer and Environmentalist

Humans have expanded their horizons to many fields and have proven what was once impossible to be possible. Their curiosity has always made the community advance more than its predecessors. The modern growth in terms of the economy has improved people's lives. Exponentially, a significant number of inventions are emerging each day, but as each coin has two sides, these extraordinary inventions have impacted us and nature as a whole in one way or another. Humans did not realize their torture of the environment until the environment collapsed many of their civilizations. Consequently, to make a balance with nature and sustain their existence on the planet, they started to become aware of the sustainable comparison among the inventions.

Today, the world is facing one of its major challenges, which is transitioning electricity generation from conventional sources, i.e., fossil fuels, to sustainable ones. This shift requires highly efficient energy storage technologies, namely batteries. Despite several impressive advancements in harvesting sustainable energy in recent years, such as photovoltaic cells, wind turbines, and solar panels, there is still significant room for improvement in energy storage devices. Lithium-ion batteries showed significant promise for power storage, especially in the era where EVs are becoming popular. Extensive research has been going on with Li-ion batteries and it is regarded as one of the most prominent achievements of modern electrochemistry due to their thermal stability, prolonged cycle life and eco-friendliness.[1] [1]

In this project, the life cycle of two types of Li-ion batteries will be assessed and compared in the Nevada region of the United States in terms of three distinct sustainability matrices: environmental, economic, and social, along with the perspective of their stakeholders. The two types are LFP (Lithium Iron Phosphate) and NMC (Nickel Manganese Cobalt). Developed in the 1990s, the former is already well-established globally, while the latter, being relatively new, is the proposed alternative sustainable solution for this project.

Description of Geographical Location

LFP Process Geographical Location: Gigafactory (Panasonic), Storey County, Nevada, United States

Gigafactory Nevada is a facility in Storey County, Nevada, USA, producing lithium-ion batteries and components for electric vehicles [2]. The factory began to mass-produce cells in January 2017. Panasonic led the battery cell production portion of the manufacturing and had invested \$3.86 billion in the factory [3]. By 2022, Panasonic had already shipped more than 6 billion battery cells from this factory [4]. Among its key products are the LFP (Lithium Iron Phosphate) based, Model Y Standard Range which became popular due to its economic feasibility, safety and longevity.

NMC Process Geographical Location: Dragonfly Energy, Old Virginia Rd, Reno, Nevada, United States

Founded in 2012, Dragonfly Energy is a leader in energy storage solutions in North America, producing high-quality lithium-ion batteries. One of its specialties is producing traditional manganese cobalt (NMC) batteries, supported by versatile research and development in chemistry, which utilizes various types of LFP raw materials tailored to specific applications.

1.1. Background of Lithium-ion batteries

Metals have always been a cardinal part of new technology, especially for electric vehicles and the renewable energy industry. Iron, cobalt, nickel, manganese, lithium, and phosphorus are some of the important metals or minerals that contributed to this industry for the last few decades. Lithium-ion batteries are one of the most popular and efficient devices that can hold a significant amount of electric energy for electric vehicles. There are numerous methods to extract lithium through mining and there are multiple production methods for electric batteries. In this context, both Lithium Iron Phosphate (LFP) production and Nickel Manganese Cobalt (NMC) are attractive production methods.

In scientific terms, batteries are electronic devices that convert stored chemical energy into electricity within a closed system. An ideal battery requires two electrodes: a cathode and an anode. The storage and the transmission of electricity is highly dependent on multiple factors such as the area of the electron's mass, the volume of the active material and the chemical nature of those minerals and metals. Lithium metal oxides, referred to as positive electrodes, serve as the cathodes in lithium-ion batteries, whereas graphite or lithium titanate are commonly used as the anodes, or negative electrodes. During the charging process, lithium ions move from the cathodes to the anodes, and during discharge, the direction of ion movement is reversed. The cell-arrangement offered by Lithium-ion can function at more than double the potential when compared with any other variety of battery cells such (such as lead acid and nickel cadmium battery. This battery electrode releases the electron and increases the conductivity outside as per requirement. This is an isothermal process that utilizes minimum mechanical and chemical strain. Researchers have been continuously working on improving the thermal stability, battery cycles, performance, and energy density over time. [5]

LFP batteries were invented in the mid-1990s, while NMC batteries were developed in the 2000s. [6] The functional advantages of LFP batteries include better durability, longer cycle life, thermal stability, and lower production costs. On the other hand, the functional advantages of NMC batteries are their ability to sustain in extreme cold temperatures and their higher energy storage capacity per unit weight, making them much better suited for devices that require compact battery designs, such as laptops, cell phones, portable gadgets, and electric vehicles (EVs) [7].

In terms of cost, LFP batteries use affordable raw materials like iron and phosphate, unlike NMC batteries, which rely on expensive and scarce materials such as nickel and cobalt. However, while LFP batteries perform poorly in colder climates, NMC batteries offer higher profitability in the market. [7]

1.2 Production Method of LFP Battery

As the name suggests, LFP batteries include lithium iron and phosphate ions which are in the central part of the battery. The very first stage begins with lithium extraction, where the lithium is leached from the Salt Lake or the rock mining. Here lithium is in complex form such as hydroxide or allied with many other minerals. Similarly, the phosphate and iron are also brought into a complex form separately. Once the LFP powder is produced, it is restructured in a crystal form using carbon nanotubes or buckyballs. Then they are combined using a roller belt and high pressure to make a thin single sheet. These materials are combined to form electrodes which are cathodes in an electrolyte solution. Lithium ions have a huge tendency to hold unpaired electrons within its outer shell. When the electrodes are dipped into the solution it gives the medium to pass through the metal ions and generate electricity as per requirement. [8]

Due to the corrosive nature of iron and the eutrophication issues caused by phosphorus, it became necessary to find alternatives to make lithium-ion batteries.

$4Fe^{3+} + 4H_3PO_4 \rightarrow 4FePO_4 + 6H_2$ – Eq (F)

$2Li_2CO_3 + 4FePO_4 \rightarrow 4LiFePO_4 + 2CO_2 + O_2$ – Eq (G)

<u>The process steps for LFP batteries are listed below</u> [9]

Step 1. Batching Process	**Step 5.** Crushing Process
Step 2. Wet Grinding Process	**Step 6.** Finished Product Post-Processing Process
Step 3. Spray Granulation Process	**Step 7**. Performance Test
Step 4. Sintering Process	

Table 1.1 The process steps for LFP Battery

(The flow diagram with detailed mass balance can be referred in Appendix)1.3 Production Method of NMC Battery

Nickel manganese Cobalt (NMC) batteries are one of the most advanced methods to make lithium-ion batteries. As nickel and Cobalt have a highly conductive nature for electricity, it has become more widely accepted worldwide. As this method does not include phosphorus, the environmental impact due to eutrophication issues is eliminated. Similar to the LFP process, the nickel, manganese and Cobalt are first mined or extracted during the very first stage into a complex form separately. Then these irons were purified with multiple processes before they were cast into an end form. As the NMC process includes metals (Ni, Mn, and Co) with enhanced electrochemical properties, it has higher energy density and higher voltage potential, favoring energy storage capabilities.

$NiSO_4 + 2NaOH \rightarrow Ni(OH)_2 + Na_2SO_4$ – Eq (A)

$MnSO_4 + 2NaOH \rightarrow Mn(OH)_2 + Na_2SO_4$ – Eq (B)

$CoSO_4 + 2NaOH \rightarrow Co(OH)_2 + Na_2SO_4$ – Eq (C)

[10], [11]

To produce the Li-NMC (Li-$Ni_{0.33}Mn_{0.33}Co_{0.33}O_2$) battery, a molar ratio of 1:1:1 of Ni, Mn and Co are required. The equations - Eq (A), Eq (B) and Eq (C) can be represented as:

$NiSO_4 + MnSO_4 + CoSO_4 + 6NaOH \rightarrow 3Ni_{0.33}Mn_{0.33}Co_{0.33}(OH)_2 + 3Na_2SO_4$ – Eq (D) $2Ni_{0.33}Mn_{0.33}Co_{0.33}(OH)_2 + Li_2CO_3 \rightarrow 2LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2 + CO_2 + H_2O + 2H^+$ – Eq (E)

The process steps for NMC batteries are listed below [10], [11]

Chemical Structure of NMC-111 is **LiNi0.33Mn0.33Co0.33O2**

Step 1. Raw Material Preparation • Metal Extraction and refining • Lithium processing (Purification) **Step 2. Precipitation Stage** • Precursor production through co-precipitation **Step 3. Filtration, Washing & Drying**	**Step 4. Calcination with Li Compound** • Calcination and Sintering at High Temperature **Step 5. Assembly and Battery cell Production** • Battery Cell Assembly • LiPF6 Electrolyte Filling and Sealing

Table 1.2 The Process steps for NMC Battery

(The flow diagram with detailed mass balance can be referred in Appendix)

2. Background of the Problem

A remarkable concern of the 21st century is switching to electric vehicles and renewable energy sources, replacing fossil fuels with more sustainable technologies. As mentioned earlier, the two most popular choices among electric automobile companies are LFP and NMC batteries. Both batteries have their merits and demerits with respect to their usage, making selection criteria highly user dependent.

For instance, although LFP batteries are relatively better in thermal stability, have long life cycles, lower production cost, and have less impact on the environment, they have limitations for lower energy density, limited cold weather performance, and bulkier design. There were many incidents also reported such as fires that occurred in many electric vehicles which had LFP batteries in numerous locations around the world. So the comparison of cathode between two processes could be considered via factors Specific Energy, Specific Power, Cost, Safety and Life Cycle. In addition, since a longer energy range is required by electric vehicles, the usage of LFP batteries raises concerns due to their size and weight. As these batteries are heavier in weight it could lead to questions of transportation and other related costs which could increase the carbon footprint in the environment. Due to its low power density, its use in high-power applications is limited. Apart from that, the usage of LFP Process in a high-temperature environment could result in premature aging. [12], [13]

2.1 Advantages of the NMC Process (Alternative Solution)

On the other hand, NMC has the potential of high energy density, and effective performance across a wide range of temperatures, unlike LFP batteries. Despite relatively higher manufacturing costs, NMC batteries provide better profitability. The famously known NMC battery in this regard is NMC111, that is when the cathode combination is one-third each of nickel, manganese, and cobalt. The issue here is that cobalt supply is limited and it's an expensive extractive mineral, so recycling it solves the issue. Furthermore, nickel could make the battery less expensive but a larger portion of nickel could reduce the voltage of the battery. However, the low emission and light weight makes these batteries in account for consideration for the upcoming future.

3. Social, Economic, and Environmental issues accompanying the current situation (the do-nothing scenario)

Electric vehicles are catching people's popularity due to a high level of awareness. People are using electric vehicles at a higher rate compared to previous decades. The LFP process was one of the most used processes in these years but due to its heavy weight, and energy density, people had to consider the other alternative which was NMC. The extraction of nickel and cobalt is highly expensive and less environmentally friendly. Similarly, phosphorus mining is also environmentally harmful. So, to make an environmentally sustainable process it became solely a choice based on consumers' preference. Both processes have similar greenhouse effects. Due to the lack of data available on an NMC process, it became new to the technology, resulting in more confusion about which process is more energy efficient and environmentally efficient. This confuses engineers to do sustainability analysis of both the processes and provide the best solution for the consumer which is affordable and sustainable in all economic, environmental, and social forms. Moreover, the cost competitiveness is higher in NMC batteries and therefore they have better market reach despite the higher production cost then LFP.

As LFP processes are handling ponderous material throughout the process of battery production, the dust particles could affect the company employees and surrounding communities. Apart from that, the processes use extreme amounts of solvent and other chemicals which could affect or harm the workers. If lithium is very reactive when it comes to the contact of moisture it could release some of the byproduct from the process and it could generate a significant amount of waste for commercial batches. Apart from that, lithium, manganese, and cobalt are highly explosive when they contact with air, so it makes the process extremely risky. So only the trained and professional people must be allowed to handle such operations. Similarly, nickel and aluminium could react to each other and Catch Fire, so both raw materials should be kept separated over handle with intense chemical care. The thermal runaway of NMC batteries generates gas which is released during thermal events and is typically a mixture of flammable, toxic, and corrosive volatiles, including carbon di- and monoxide, hydrogen, oxygen, short-chain hydrocarbons (e.g., ethane, methane) and compounds containing fluorine.

4. Analysis of the issues from the stakeholder's perspective

The effective analysis of possible stakeholders and the factors they are affected by is the logical way to evaluate the sustainable capacity of the system. To do so, three factors i.e. environment, social and economic factors are considered for each possible stakeholder. Consequently, how intensive they are affected by each issue is enlisted in the below table.

Issues of LFP production on stakeholders

Stakeholders	Environmental Issues	Social Issues	Economic Issues
Local communities surrounding mining projects	Destruction of biodiversity, water pollution, air pollution (mining) and soil erosion.	Displacement of local tribes from their land. Quality of life is affected. [14],	Increase in house prices due to inflow of skilled workers from other regions.
Manufacturing Industry (management)	Chemical discharge and use of energy wastewater treatment; Energy usage issues	N/A	Treatment/disposal of waste and fulfill the requirements of environmental regulations.
Government and National regulatory agencies	Enforcement of regulations leads to an increase of resources.	Losing support from people due to inadequate implementation of regulations.	Imposing fines for non-compliance by industries; expenses incurred due to enforcement of tighter regulations

NGOs	N/A	Raising community awareness on social justice issues due to mining and production.	N/A
Employees/Workers	Exposure to various toxic chemicals and dust can cause long term health disorders.	N/A	Process runs on demand and supply. Job security is lost when there is low demand.
Automobile companies (retailers)	Companies can unethically sourcing raw materials while greenwashing information.	People perceive greenwashing negatively so the companies' reputation is affected	Cost of sourcing increased due to the requirement of sustainable materials.
Consumers of electric vehicle and other electronic products	May prefer eco-friendly/sustainable products.	N/A	Higher cost of EVs than regular vehicles.
Waste management companies	Recycling issues with harmful materials such as phosphorus, lithium, manganese and cobalt.	N/A	Safe disposal / treatment / processing of waste incurs higher costs
	Mining causes degradation to the environment	Hazardous working conditions (mining)	N/A
Investors	Reluctant to invest in companies that break environmental regulations	N/A	Financial Risk Competitive Risk
Researchers and academic institutions	N/A	N/A	Academic research on improving sustainability LFP processes increases the cost.

[14], [16], [17], [18],

Table 4.1 Issues of LFP Production on stakeholders

5. Detailed Information of alternatives solutions to improve sustainability

LFP batteries had many problems in terms of environmental, economic, and social sustainability, which made the current generation look for alternatives. Nickel Manganese Cobalt (NMC) batteries, which offer many benefits over LFP batteries, can be considered a viable alternative. NMC batteries are more suitable for a wide range of applications, such as electric vehicles and other energy-intensive devices. The environmental, economic, social, and long-term perspectives on NMC batteries are discussed in the paragraph below.

Environmental benefits that could brought by NMC batteries

Here is the corrected version of your paragraph with grammar and spelling errors addressed: As mentioned earlier, NMC batteries have a higher energy density, which makes them more efficient and capable of storing larger amounts of energy within their compact design. Because of the reduced weight and energy consumption for electric vehicles, they directly reduce the carbon footprint on the environment. Despite using cobalt, nickel, and manganese, which might raise environmental and ethical concerns due to mining and require more advanced recycling methodologies, NMC batteries have demonstrated a more sustainable approach throughout their life cycle assessment. In contrast to LFP batteries, which have a larger size and weight that increase transportation and material costs, making them less sustainable overall, NMC batteries offer a viable and improved alternative.

Social benefits that could brought by NMC batteries

NMC batteries require an initial investment cost that is higher than LFP batteries, but they offer superior energy density and longevity, making them a more cost-effective choice over the long term. Due to their smaller design, space and performance can be optimized, and the overall production and design costs can be reduced for large industries such as electric vehicles and other electronic devices. The flexibility to adjust the composition of nickel, manganese, and cobalt allows manufacturers to create different types of conductive materials and battery designs without compromising environmental sustainability.

Social and Practical Benefits

Super social benefits make the current social scenario lean more towards greener and sustainable energy for the long term. Apart from that, because of its higher energy performance, it can work in a diverse range of industries. The logistical challenges have been reduced due to its lighter weight, fostering broader deployment in both rural and urban areas.

Forecast on Future trends

Although LFP batteries excel in thermal stability, NMC batteries are expected to become more advanced in the near future as they are still in the intermediate stage of development. As modern technology moves towards more efficient, compact, powerful, and energy-saving devices, NMC batteries could become the best alternative for the lithium-ion industry. The recycling infrastructure for both types of batteries is under improvement and is expected to evolve into an efficient system, making NMC one of the most energy-efficient storage options for future generations.

6. The proposed methodology for measuring sustainability

To calculate the sustainability of LFP and NMC processes, the data is the first and the most integral part of the process. To calculate the sustainability matrix and the indices real experimental and statistical data are required. Environmental indices such as global warming potential, eutrophication, acid rain, mineral resource depletion are calculated and interpreted. The life cycle analysis except recycling for both the processes is that LFP and NMC are evaluated and all critical parameters are noted. The raw material consumption, energy consumption, manufacturing operation and waste generations are considered. As per the general basis, **cradle-to-gate** metered has been considered. to evaluate economic sustainability raw material and operational costs are considered. The stakeholder perspective has been prioritized. In all of the calculations, financial stability of the company has been considered throughout the years. This data has been acquired from the global financial report, the company statistical report, financial journals, stock market trends, forecasts, the company's image in society, and its future projects. To evaluate social sustainability, the broader data for all stakeholders has been discussed. Health and safety, education, employee wages, training, hazard, natural hazard, toxicity, and all other United Nations social indices are considered.

The chemical nature of minerals, their availability in the earth's crust, the cost and energy required for extraction from or to Pure form, dissipative and non-dissipative nature for recycling, have been considered for both processes. The governmental rules and regulations, the feasibility of the process and stakeholders' interest in the company's sustainable policies have been considered

Based on the above-mentioned information the below data has been considered for LFP and NMC Process.

Category	Environment Sustainability	Social Sustainability	Economic Sustainability
	1. Abiotic Depletion Potential 2. Global warming Potential	1. Health and safety 2. Demography	1. Efficiency 2. Gross Profit

Indicator Analysed	3. Acidification Potential	3. Inequality 4. Cultural tensions 5. Employment 6. Education 7. Economic Development	

Table 6.1 Criteria considered for sustainability measurement in proposed methodology

7. Calculation of Performance Indicators

To measure sustainability, the environment, social and economic indices have been calculated as per below mentioned method.

Overall Environmental Impacts of LFP and NMC processes

Impact	Description	LFP	NMC	Direction
Abiotic Depletion Potential (ADP)	It measures the depletion of abiotic natural resources due to human activities and is expressed in comparison to antimony (kg Sb eq).	15.691 kg Sb eq	9.427 kg Sb eq	– +
Global Warming Potential (GWP)	It is a measure of the amount of greenhouse gases trapped in the atmosphere, expressed in terms of carbon dioxide equivalents (kg CO_2 eq).	348.710 kg CO_2 eq	229.45 kg CO_2 eq	– +
Acidification Potentials (ARP)	It is a measure of the contribution of precursor compounds to acid rain (resulting from harmful NOx and SOx emissions reacting with water in the air) and is reported in terms of SO_2 equivalents.	3.254 SO_2 eq	1.653 SO_2 eq	– +

Table 7.1 The environmental Impact indices for LFP and NMC

Evaluation of Each Social indices

Overall Social Impacts of LFP and NMC Process are mentioned here

Theme	**Sub-Theme**	**LFP**	**NMC**	**Direction**
Health and Safety	Chemical Exposure	Lithium is hazardous if contacted in air, water or high heat. [19]	Lithium can leach out from NMC structure if it accidentally comes in contact with water to react and form LiOH, which could lead to irreversible loss of capacity. [20]	– –
		The use of highly reactive phosphates (especially in humid conditions) in LFP causes the formation of phosphoric acid, which is a corrosive byproduct and poses a potential hazard upon inhalation or dermal contact [21]	The precursors/intermediates of NMC cathode processing are more chemically stable during the production process. [22]	– +

		LFP shows better thermal stability when exposed to higher temperatures [23].	NMC batteries are less thermally stable when exposed to higher temperatures [23].	+ –
	Dust Exposure	LFP cathode materials are processed in fine powdered form. This fine particulate matter can be dispersed in the air, thus subjecting workers to the risk of inhalation, which can cause respiratory disorders such as acute and chronic lung inflammation [24] [25].	Although the mining of nickel and cobalt exposes one to dust, NMC cathodes generally have a greater particle size or are processed in slurry form, reducing the potential for them to become airborne during production [26]	– +
Demography	Displacement	Rising housing cost up to 17% from 2021 to 2023 near Gigafactory putting pressure on low- and middle-class communities to displace. [27]	Mining activities boosted economic opportunities, leading to a population surge and limited housing . This caused housing prices to rise by 83% from 2018 to 2022. However, reduced affordability from the large population influx and higher mortgage rates led to a 14.8% price drop by March 2024 [28].	– +
Inequality	Economic Disparity	Job creation in Highly skilled (ex. Engineers and scientist) and low-wage worker, left middle skilled (administration staff) at disadvantage. [29]	The growth of jobs favors highly skilled people, like scientists and engineers, as well as low-wage workers, while undervaluing middle-skilled jobs, like administrative personnel.	+ +
Cultural Tensions	Indigenous or long time communities and newcomers	Native Americans near the gigafactory showed concern for destruction of their sacred land. They also showed protest and legal actions for lithium mining. [30]	The existence of Indigenous communities and their culture in the Reno-Sparks Indian Colony is at risk due to urbanization and economic pressures, including rising housing costs. Tensions have intensified with immigrants, many of whom are unaware of the region's Indigenous history [31], [32].	– –

Employment	Job creation and Economic mobility	As an industrial hub, the Gigafactory alone created jobs for 10,000 people. production has reduced unemployment rate in Washoe county from 7.5% to 3.4% from 2010 to 2023 [33]	Increased. Companies will add a combined 2,263 new jobs, at a record average wage of $32.67 [34] [34] [35].	++
Education	Skill Development	Truckee Community college has partnered with Gigafactory to offer training programs in advanced manufacturing and clean energy technologies which trained 1000 students who are contributing highly skilled workforce all over Nevada. [36]	Dragonfly collaborated with the University of Nevada, Reno, and undertook initiatives such as EDAWN's Reno Startup, awards, and several others [37].	++
	Environmental Awareness	Because of its extreme focus on energy, the Nevada state as a whole has become a leader in the clean energy sector and aims to achieve 50% renewable energy by 2030 through solar and wind energy. It has influenced the community about sustainability and changed attitudes and local policies [38]	Reno's Sustainability and Climate Action Plan (2019–2025) sets ambitious targets, including reducing emissions by 28% by 2025 compared to 2008 levels and achieving a 40% reduction by 2030 . [39]	++
Economic Development	Community Investment and Infrastructure Development	Gigafactory is large production facility which contributes in Storey county to construct roads, transport system and public service, health care and education [38]	Dragonfly Energy actively participates in a number of regional and national projects, such as assisting new local businesses and working with academic institutions, nonprofits, and veterans' organizations to create positive community impacts [40] [8] [7] [41].	++

[14], [16], [17], [18]

Table 7.2 Social Impacts of LFP and NMC Process

Evaluation of Each Economic indices

1. LFP Battery Production in the USA

Calculation: The energy needed to produce 1kg of LFP battery in Nevada is 65KWh, so based on that **Energy needed for 1000 kg** = 1000 kg×65KWh/kg=65000 KWh [42]

- **Energy Cost** = 6500O kWh×0.06 $/kWh=***$3900*** (Based on the energy rate per kWh for LFP batteries in Nevada) [43]

- **Water Cost:** From the material balance 552.08kg of water is needed to produce 1000kg of LFP battery; Using the density of water of water as 1kg/L, the volume of water needed is 0.55208m3. In addition, the average cost of water for Industries in Nevada is $26 per m3. So, Cost of water = $26 ×0.55208 M3 =***$14.35*** [44]

Base Values:

Raw Material	Mass (kg)	Unit Price (USD/kg)	Total Cost (USD
Lithium Carbonate	234.18	$26.23 [45]	$6,142.54
Iron	354.02	$12.21 [46]	$4,332.34
Conductive Carbon	57.10	$1.98 [46]	$113.06
Phosphoric Acid	621.13	$2.61 [47]	$1621.15
Total			**$12,209.29**

Table 7.3 Base values for LFP economic sustainability calculation

Total cost of Production =Total cost of raw materials + Cost of water + Cost of Electricity

= $12,209.29.14+$(14.35) + $3900 =***$16,123.35/1000 Kg***

The selling price of 1000 kg of LFP Battery in US market is $34769.06. [48]

- ***Efficiency***:=$\frac{Output\ Value}{Input\ Value} = \frac{34769.06}{16123.35} = 2.16$
- ***Gross Profit for 1000 kg of LFP Battery= Selling price (1000 kg)- Manufacturing cost (1000 kg)***
- ***Gross Profit for 1000 kg of LFP Battery= $34769.06- $16123.35 = $ 18,645.71 per 1000 of LFP***

2. NMC Battery Production in the USA

The energy needed to produce 1kg of NMC battery in Nevada is 50-100kWh and **Energy needed for 1000 kg:** 1000kg×100kWh/kg =10000kWh. **Energy Cost** = 10000kWh×0.06$/kWh =*$6000* [43]

Water Cost: From the material balance 1468.55 kg of water is needed to produce 1000 kg of NMC battery, Using the density of water as 1 kg/m3, the volume of water needed is 1468.55m3. In addition, The average cost of water for Industries in Nevada is $26 per 1000 Liters. Cost of water = $26 × 0.14685 [44]. Hence *$3.81823* of water is needed to produce 1000 kg of NMC battery

Raw Material	Mass (kg)	Unit Price (USD/kg)	Total Cost (USD)
Nickel (II) Sulphate	538.0	3.63 [48]	1,952.94
Manganese (II) Sulphate	524.96	1.3 [49]	682.45
Cobalt (II) Sulphate	538.87	8.77 [50]	4,725.88
Sodium Hydroxide	834.38	0.51 [51]	417.19
Lithium Carbonate	385.33	26.23 [45]	10,107.21

Total	**$ 17,885.46**

Table 7.4 Base values for NMC economic sustainability calculation

Total cost of Production =Total cost of raw materials + Cost of water + Cost of Electricity

=$17885.46 + $3.82 +$6000 **= *$23889.28***

The selling price of 1000 kg of NMC Battery in US market is $79477.60. [53]

- ***Efficiency***:$=\frac{Output\ Value}{Input\ Value}=\frac{79,477.60}{23889.28}=3.33$
- ***Gross Profit for 1000 kg of NMC Battery=Selling price (1000 kg)- Manufacturing cost (1000 kg)***
- ***Gross Profit for 1000 kg of NMC Battery= $79477.60 - $23889.28 = $ 55,588.32 per 1000kg of NMC***

8. Calculating the score for the sustainability

Scoring Criteria

- 4: No negative environmental impact
- 3: Minimal Negative environmental impact
- 2: Moderate negative environmental impact
- 1: Substantial negative environmental impact
- 0: Very high negative environmental impact

MS: Material Selection, EU: Energy usage, SR : Solid residue, LR: Liquid Residue, GR: gaseous residue

Scoring LFP Process sustainability

	MS	EU	SR	LR	GR
Pre manufacturing	3	2	2	2	3
Product Manufacturing	2	1	2	1	2
Product Use	3	2	4	4	3
Packaging	2	1	2	1	2
Product Recycling	1	1	1	1	1
	11	7	11	9	11

49 (SCORE); %Score=49/ (25*4) =49%

Scoring NMC Process sustainability

	MS	EU	SR	LR	GR
Pre manufacturing	1	2	1	1	2
Product Manufacturing	1	2	2	1	2
Product Use	3	3	4	4	2
Packaging	2	2	2	2	2
Product Recycling	2	2	2	2	2
	9	11	11	10	10

51 (SCORE); %Score=50/ (25*4) = 51%

9.The impact of the sustainable alternative on the stakeholders

Stakeholders	Impacts of the new system
Local communities surrounding mining projects	• Reduced weight of the battery and support high quality of greener lifestyle
Manufacturing industries, Automobile companies (retailers),	• More compact design reduces raw material consumption and reduce transportation challenges

Raw material suppliers and Investors	• Flexibility in material composition, allow manufacturers to come up with variety of battery types with more features • Enhanced brand reputation and higher profitability for performance
Government and National regulatory agencies, and NGO	• NMC is a more sustainable method which aligns with government's rules and regulations. • NGO supports and promotes more sustainable manufacturing and NMC could get funding for sustainable projects from NGO-led initiatives
Employees/Workers and consumers	• Less toxic chemical environment for employees and workers, more secure job as more advanced and technological approach for manufacturing and recycling. Higher demand for skilled labour. Customer could save for long term battery use
Waste management companies	• Easy waste management methods due to less harmful material usage
Researchers and academic institutions	• Increased funding for research in battery and green technology manufacturing methods

Table 9.1 Impact of sustainable alternative on stakeholder

Conclusion

The report demonstrated how consciousness about using environmentally sustainable products like Electric Vehicles, reshape the demand for alternative solutions such as using NMC batteries over traditionally used LFP batteries. In terms of environmental impacts, the alternative method of NMC battery production produces fewer emissions and has lesser impacts than the LFP method. As far as economic metrics are concerned, although the production cost of the NMC process is higher than the LFP process, the gross profit of the former is considerably higher than that of the latter. The social issues are positively affected by both the processes, as both primarily contribute to positive social impacts such as employment generation in the Nevada region. Therefore, the alternative solution (NMC) process provides a slightly greater positive impact.

Moreover, from the point of view of the stakeholders, they are concerned about all three metrics. The majority of their interest lies in environmental and economic issues. The government enforces strict environmental regulations regarding emissions and waste treatment, which companies must abide by to sustain operations. The NMC process performs better than the LFP process in this regard, as the NMC process occurs in slurry form and causes fewer environmental impacts, while the LFP process produces fine particulate LFP powder, which causes respiratory disorders and greater environmental impacts. Furthermore, it is observed that most local tribes have been affected by mining activities due to both LFP and NMC processes, which also resulted in the displacement of natives. However, around the NMC-producing company, Dragonfly Energy compound, there was an initial increase in house prices, which caused congestion and reduced affordability; consequently, housing prices there gradually declined by 2024. One of the main stakeholders, the workers, massively benefited from both processes due to employment generation and wage hikes by both Gigafactory and Dragonfly Energy in Nevada. Furthermore, NMC is an emerging process and is very popular with EVs, so companies are collaborating with educational institutions and allocating funds for research and development to refine and produce the NMC battery with fewer harmful effects on nature. In addition, through such collaborations, Gigafactory Energy (LFP) trains students to generate a skilled workforce. Dragonfly Energy (NMC producer) went a step further by not only collaborating with the University of Nevada but also investing in several startups to support entrepreneurs.

Overall, with respect to the environmental, social, and economic matrices and the perspective of stakeholders, the alternative process of NMC batteries performed better, addressing the three major problems of LFP batteries by offering higher energy density, smaller pack size, and better performance in extremely cold climates for consumer convenience, showing great promise as a benchmark for sustainable battery production in the future.

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Appendix

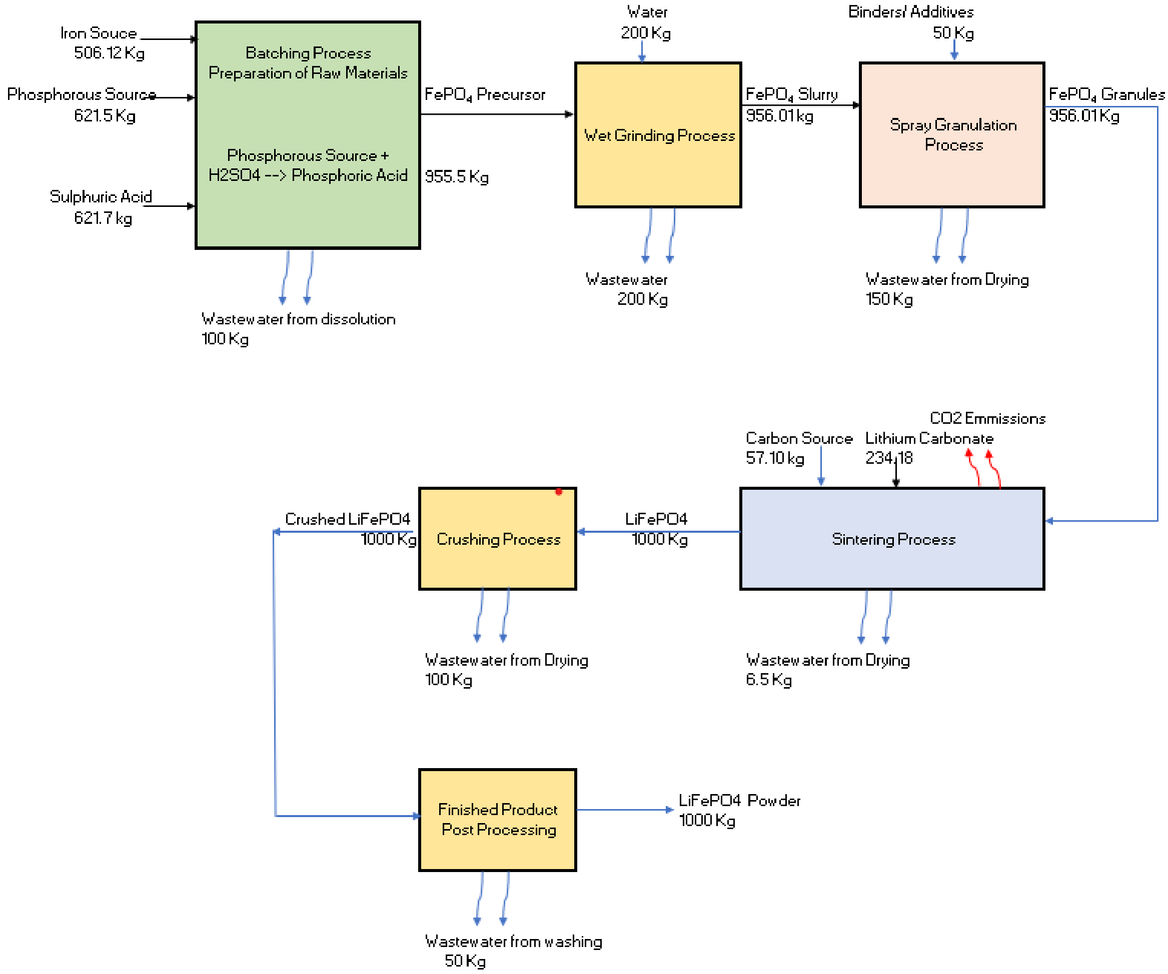

Figure A. Material flow diagram for. Lithium iron phosphate batteries in block flow diagram

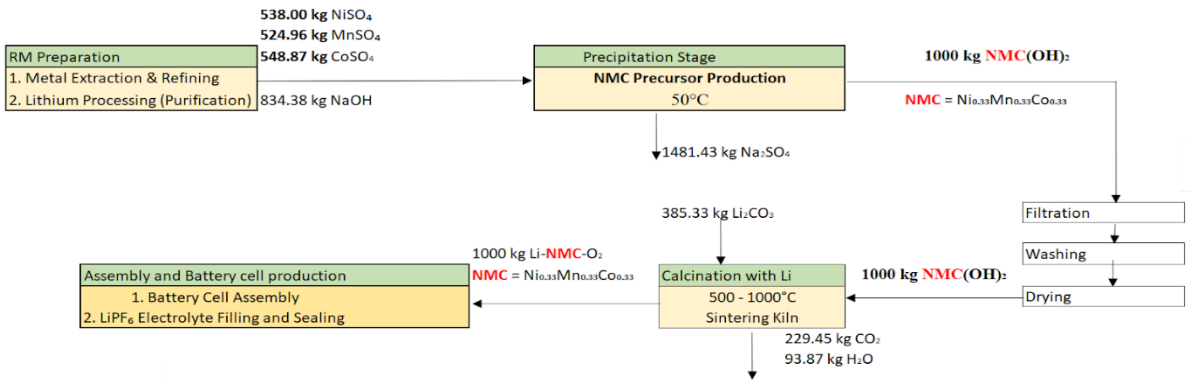

Figure B: Block flow diagram of Nickel, Manganese, Cobalt, and Lithium-ion battery production

A detailed description of production of LFP battery and Mass balance calculation using stoichiometry

From Raw Material

Iron Source:

$$2Fe_2O3 + 3C \rightarrow 4Fe + 3CO_2 \text{ – Eq (A)}$$

$$4Fe + 3O_2 + 6H_2O \rightarrow 4Fe^{3+} + 12OH^- \text{ – Eq (B)}$$

Phosphorous:

$$Ca_5(PO_4)_3F + 5H_2SO_4 + 10H_2O \rightarrow 3H_3PO_4 + 5CaSO_4.2H_2O + HF \text{ – Eq (C)}$$

Lithium:

$$2LiAlSi_2O_6 + 2H_2SO_4 \rightarrow Li_2SO_4 + Al_2(SO_4)_3 \text{ – Eq (D)}$$

$$Li_2SO_4 + Na_2CO_3 \rightarrow Li_2CO_3 + Na_2SO_4 \text{ – Eq (E)}$$

LFP Main Reactions

$$4Fe^{3+} + 4H_3PO_4 \rightarrow 4FePO_4 + 6H_2 \text{ – Eq (F)}$$

$$2Li_2CO_3 + 4FePO_4 \rightarrow 4LiFePO_4 + 2CO_2 + O_2 \text{ – Eq (G)}$$

Assume that 1000 kg of $LiFePO_4$ is formed.

Molar mass of $LiFePO_4 = (6.94) + (55.85) + (30.97) + (16.00 \times 4) = 157.76\ g/mol$

$$\text{Moles of } LiFePO_4 = \frac{Mass}{Molar\ Mass} = \frac{1{,}000{,}000\ g}{157.76\ g/mol} = 6338.74\ moles$$

Based on Eq (G),

Moles of Li_2CO_3 required =>

$$2 \text{ moles of } Li_2CO_3 \rightarrow 4 \text{ moles of } LiFePO_4$$

$$\text{'M' moles of } Li_2CO_3 \rightarrow 6338.74 \text{ moles of } LiFePO_4$$

$$\text{Moles of } Li_2CO_3 \text{ required ('M')} = \frac{6338.74 \times 2}{4} \text{ moles}$$

$$\text{Moles of } Li_2CO_3 \text{ required ('M')} = 3169.37 \text{ moles}$$

Moles of $FePO_4$ required =>

$$4 \text{ moles of } FePO_4 \rightarrow 4 \text{ moles of } LiFePO_4$$

$$\text{Moles of } FePO_4 \text{ required} = 6338.74 \text{ moles}$$

Moles of CO_2 produced =>

$$2 \text{ moles of } CO_2 \rightarrow 2 \text{ moles of } Li_2CO_3$$

$$\text{Moles of } CO_2 \text{ produced} = 3169.37 \text{ moles}$$

Moles of O_2 produced =>

$$1 \text{ mole of } O_2 \rightarrow 2 \text{ moles of } Li_2CO_3$$

$$\text{'N' moles of } O_2 \rightarrow 3169.37 \text{ moles of } Li_2CO_3$$

$$\text{Moles of } O_2 \text{ produced ('M')} = \frac{3169.37 \times 1}{2} \text{ moles}$$

$$\text{Moles of } O_2 \text{ produced ('M')} = 1584.69 \text{ moles}$$

Based on Eq (F),

Moles of H_3PO_4 required =>

Mass of $FePO_4$ = Moles x Molar Mass = 6338.74 moles x $\frac{150.82\ g}{moles} \times \frac{1\ kg}{1000\ g} = 956.01\ kg$

Moles in 956.01 kg of $FePO_4$ = $\frac{Mass}{Molar\ Mass} = \frac{956.01\ kg}{150.82\ g/mol} \times \frac{1000\ g}{1\ kg} = 6338.74\ moles$

4 moles of H_3PO_4 → 4 moles of $FePO_4$

Moles of H_3PO_4 = 6338.74 moles

Moles of Fe^{3+} required =>

4 moles of Fe^{3+} → 4 moles of H_3PO_4

Moles of Fe^{3+} = 6338.74 moles

Moles of H_2 produced =>

6 moles of H_2 → 4 moles of H_3PO_4

'O' moles of H_2 → 6338.74 moles of H_3PO_4

Moles of H_2 produced ('O') = $\frac{6338.74 \times 6}{4}$ moles

Moles of H_2 produced ('O') = 9508.11 moles

For Lithium Process:

Based on Eq (E),

Moles of Na_2SO_4 produced =>

1 mole of Na_2SO_4 → 1 mole of Li_2CO_3

Moles of Na_2SO_4 produced = 3169.37 moles

Moles of Li_2SO_4 required =>

1 mole of Li_2SO_4 → 1 mole of Li_2CO_3

Moles of Li_2SO_4 required = 3169.37 moles

Moles of Na_2CO_3 required =>

1 mole of Na_2CO_3 → 1 mole of Li_2CO_3

Moles of Na_2CO_3 required = 3169.37 moles

Based on Eq (D),

Moles of $Al_2(SO_4)_3$ produced =>

1 mole of $Al_2(SO_4)_3$ → 1 mole of Li_2SO_4

Moles of $Al_2(SO_4)_3$ produced = 3169.37 moles

Moles of $LiAlSi_2O_6$ required =>

2 moles of $LiAlSi_2O_6$ → 1 mole of $Al_2(SO_4)_3$

'P' moles of $LiAlSi_2O_6$ → 3169.37 moles of $Al_2(SO_4)_3$

Moles of $LiAlSi_2O_6$ required ('P') = $\frac{3169.37 \times 2}{1}$ moles

Moles of $LiAlSi_2O_6$ required ('P') = 6338.74 moles

Moles of H_2SO_4 required =>

2 moles of H_2SO_4 → 2 moles of $LiAlSi_2O_6$

Moles of H_2SO_4 required = 6338.74 moles

Phosphorous:

Based on Eq (C),

Moles of $CaSO_4.2H_2O$ produced =>

5 moles of $CaSO_4.2H_2O$ → 3 moles of H_3PO_4

'Q' moles of $CaSO_4.2H_2O$ → 6338.74 moles of H_3PO_4

Moles of $CaSO_4.2H_2O$ produced ('Q') = $\frac{6338.74 \times 5}{3}$ moles

Moles of $CaSO_4.2H_2O$ produced ('Q') = 10564.57 moles

Moles of HF produced =>

1 moles of HF → 5 moles of $CaSO_4.2H_2O$

'R' moles of HF → 10,564.57 moles of $CaSO_4.2H_2O$

Moles of HF produced ('R') = $\frac{10{,}564.7 \times 1}{5}$ moles

Moles of HF produced ('R') = 2112.91 moles

Moles of $Ca_5(PO_4)_3F$ required =>

1 mole of $Ca_5(PO_4)_3F$ → 1 mole of HF

Moles of $Ca_5(PO_4)_3F$ required = 2112.91 moles

Moles of H_2O required =>

10 moles of H_2O → 1 mole of HF

'S' moles of H_2O → 2112.91 moles of HF

Moles of H_2O produced ('S') = $\frac{2112.91 \times 10}{1}$ moles

Moles of H_2O produced ('S') = 21129.10 moles

Iron Source:

Based on Eq (B),

Moles of H_2O required =>

6 moles of H_2O → 4 moles of Fe^{3+}

'T' moles of H_2O → 6338.74 moles of Fe^{3+}

Moles of H_2O required ('T') = $\frac{6338.74 \times 6}{4}$ moles

Moles of H_2O required ('T') = 9508.11 moles

Moles of O_2 required =>

3 moles of $O_2 \rightarrow$ 6 moles of H_2O

'U' moles of $O_2 \rightarrow$ 9508.11 moles of H_2O

Moles of O_2 required ('U') = $\frac{9508.11 \times 3}{6}$ moles

Moles of O_2 required ('U') = 4754.06 moles

Moles of Fe required =>

4 moles of Fe $\rightarrow$ 4 moles of Fe^{3+}

Moles of Fe required = 6338.74 moles

$2Fe_2O_3 + 3C \rightarrow 4Fe + 3CO_2$ – Eq (A)

Based on Eq (A)

Moles of CO_2 produced =>

3 Moles of $CO_2 \rightarrow$ 4 Moles of Fe

'V' moles of $CO_2 \rightarrow$ 6338.74 moles of Fe

Moles of CO_2 produced ('V') = $\frac{6338.74 \times 3}{4}$ moles

Moles of CO_2 produced ('V') = 4754.06 moles

Moles of C required =>

3 Moles of C $\rightarrow$ 3 Moles of CO_2

Moles of C required = 4754.06 moles

Moles of Fe_2O_3 required =>

2 Moles of $Fe_2O_3 \rightarrow$ 3 Moles of CO_2

'W' moles of $Fe_2O_3 \rightarrow$ 4754.06 moles of CO_2

Moles of Fe_2O_3 required ('W') = $\frac{4754.06 \times 2}{3}$ moles

Moles of Fe_2O_3 required ('W') = 3169.37 moles

Summary of Mass Balance

No.	Substance	Molar Mass (g/mol)	Moles	Mass (kg)
1.	Fe_2O_3	159.69	3169.37	506.12
2.	C	12.01	4754.06	57.10
3.	Fe^{3+}	55.85	6338.74	354.02
4.	CO_2	44.01	7923.43	348.71
5.	O_2	32.00	1584.69	50.71
6.	H_2O	18.02	30637.21	552.08
7.	Fe^{3+}	55.85	6338.74	354.02
8.	$Ca_5(PO_4)_3F$	504.31	2112.91	1065.56
9.	H_2SO_4	98.08	6338.74	621.70
10.	H_3PO_4	97.99	6338.74	621.13
11.	$CaSO_4.2H_2O$	172.17	10564.57	1818.90
12.	HF	20.01	2112.91	42.28
13.	$LiAlSi_2O_6$	186.09	6338.74	1179.68

14.	Li_2SO_4	109.94	3169.37	348.44
15.	$Al_2(SO_4)_3$	342.15	3169.37	1084.40
16.	Na_2CO_3	105.99	3169.37	335.92
17.	Li_2CO_3	73.89	3169.37	234.18
18.	Na_2SO_4	142.04	3169.37	450.18
19.	$FePO_4$	150.82	6338.74	956.01
20.	H_2	2.00	9508.11	19.02
21.	$LiFePO_4$	157.76	6338.74	1000.00

A detailed description of production of NMC battery and Mass balance calculation using stoichiometry

Nickel (Sulfide Ore):

Roasting of Sulfide to Oxide

$$\text{Roasting: } 2NiS + 3O_2 \rightarrow 2NiO + 2SO_2$$

$$\text{Leaching: } NiO + H_2SO_4 \rightarrow NiSO_4 + H_2O$$

Moles of NiO required:

$$1 \text{ mole of } NiO \rightarrow 1 \text{ mole of } NiSO_4$$

$$\text{Moles of NiO required} = 3476.57 \text{ moles}$$

$$\text{Mass} = 3476.57 \text{ x } 74.69 = 259.66 \text{ kg}$$

$$2 \text{ moles of NiO} \rightarrow 2 \text{ moles of SO2}$$

$$259.66 \text{ x } 1000 / 74.69 \text{ moles of NiO} \rightarrow ? \text{ moles of SO2}$$

Moles of H_2SO_4 required:

$$1 \text{ mole of } H_2SO_4 \rightarrow 1 \text{ mole of } NiSO_4$$

$$\text{Moles of } H_2SO_4 \text{ required} = 3476.57 \text{ moles}$$

Moles of H_2O produced:

$$1 \text{ mole of } H_2O \rightarrow 1 \text{ mole of } NiSO_4$$

$$\text{Moles of } H_2O \text{ required} = 3476.57 \text{ moles}$$

Moles of SO_2 produced:

$$2 \text{ moles of } SO_2 \rightarrow 2 \text{ moles of NiO}$$

$$\text{Moles of } SO_2 \text{ produced} = 3476.57 \text{ moles}$$

Moles of O_2 required:

$$3 \text{ moles of } O_2 \rightarrow 2 \text{ moles of NiO}$$

$$\text{'X' moles of } O_2 \rightarrow 3476.57 \text{ moles of NiO}$$

$$\text{Moles of } O_2 \text{ required ('M')} = \frac{3476.57 \times 3}{2} \text{ moles}$$

Moles of O_2 required ('M') = 5214.86 moles

Moles of NiS required:

2 moles of NiS → 2 moles of NiO

Moles of NiS required = 3476.57 moles

Manganese: (From Carbonate Ores):

$MnCO_3 + H_2SO_4 \rightarrow MnSO_4 + CO_2 + H_2O$

Moles of CO_2 produced =>

1 mole of CO_2 → 1 mole of $MnSO_4$

Moles of CO_2 produced = 3476.57 moles

Moles of H_2O produced =>

1 mole of H_2O → 1 mole of $MnSO_4$

Moles of H_2O produced = 3476.57 moles

Moles of H_2SO_4 required:

1 mole of H_2SO_4 → 1 mole of $MnSO_4$

Moles of H_2SO_4 required = 3476.57 moles

Moles of $MnCO_3$ required:

1 mole of $MnCO_3$ → 1 mole of $MnSO_4$

Moles of $MnCO_3$ required = 3476.57 moles

<u>Cobalt Extraction: (Either)</u>

USA: From imported intermediates

Roasting: $2CoS + 3O_2 \rightarrow 2CoO + 2SO_2$

Leaching: $CoO + H_2SO_4 \rightarrow CoSO_4 + H_2O$

Moles of CoO required:

1 mole of CoO → 1 mole of $CoSO_4$

Moles of CoO required = 3476.57 moles

Mass = 3476.57 x 74.69 = 259.66 kg

2 moles of CoO → 2 moles of SO2

259.66 x 1000 / 74.69 moles of CoO → ? moles of SO2

Moles of H_2SO_4 required:

1 mole of H_2SO_4 → 1 mole of $CoSO_4$

Moles of H_2SO_4 required = 3476.57 moles

Moles of H_2O produced:

$$1 \text{ mole of } H_2O \rightarrow 1 \text{ mole of } CoSO_4$$

$$\text{Moles of } H_2O \text{ required} = 3476.57 \text{ moles}$$

Moles of SO_2 produced:

$$2 \text{ moles of } SO_2 \rightarrow 2 \text{ moles of } CoO$$

$$\text{Moles of } SO_2 \text{ produced} = 3476.57 \text{ moles}$$

Moles of O_2 required:

$$3 \text{ moles of } O_2 \rightarrow 2 \text{ moles of } CoO$$

$$\text{'X' moles of } O_2 \rightarrow 3476.57 \text{ moles of } CoO$$

$$\text{Moles of } O_2 \text{ required ('M')} = \frac{3476.57 \times 3}{2} \text{ moles}$$

$$\text{Moles of } O_2 \text{ required ('M')} = 5214.86 \text{ moles}$$

Moles of CoS required:

$$2 \text{ moles of } CoS \rightarrow 2 \text{ moles of } CoO$$

$$\text{Moles of CoS required} = 3476.57 \text{ moles}$$

Cobalt: From intermediates
[https://miningconnection.com/surface/news/article/first_cobalt_produces_battery_grade_cobalt_sulfate/]

$$CoOOH + H_2SO_4 \rightarrow CoSO_4 + 2H_2O$$

$$NiSO_4 + 2NaOH \rightarrow Ni(OH)_2 + Na_2SO_4 \text{ – Eq (A)}$$

$$MnSO_4 + 2NaOH \rightarrow Mn(OH)_2 + Na_2SO_4 \text{ – Eq (B)}$$

$$CoSO_4 + 2NaOH \rightarrow Co(OH)_2 + Na_2SO_4 \text{ – Eq (C)}$$

To produce 1000 kg of Li-NMC (Li-$Ni_{0.33}Mn_{0.33}Co_{0.33}O_2$), a molar ratio of 1:1:1 of Ni, Mn and Co are required. The equations - Eq (A), Eq (B) and Eq (C) can be represented as:

$$NiSO_4 + MnSO_4 + CoSO_4 + 6NaOH \rightarrow 3Ni_{0.33}Mn_{0.33}Co_{0.33}(OH)_2 + 3Na_2SO_4 \text{ – Eq (D)}$$

$$2Ni_{0.33}Mn_{0.33}Co_{0.33}(OH)_2 + Li_2CO_3 \rightarrow 2LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2 + CO_2 + H_2O + 2H^+ \text{ – Eq (E)}$$

Molar Mass of Li-$Ni_{0.33}Mn_{0.33}Co_{0.33}O_2$ = $(6.94) + (0.33 \times 58.69) + (0.33 \times 54.94) + (0.33 \times 58.93 + 2 \times 16.00) = 95.88\ g/mol$

Moles of Li-$Ni_{0.33}Mn_{0.33}Co_{0.33}O_2$ = $\frac{Mass}{Molar\ Mass} = \frac{1{,}000{,}000\ g}{95.88\ g/mol} = 10429.70\ moles$

Molar Mass of $Ni_{0.33}Mn_{0.33}Co_{0.33}(OH)_2$ = $(0.33 \times 58.69) + (0.33 \times 54.94) + (0.33 \times 58.93 + 2 \times 16.00 + 2 \times 1.00) = 90.95\ g/mol$

Based on Eq (E),

Moles of $Ni_{0.33}Mn_{0.33}Co_{0.33}(OH)_2$ required =>

$$2 \text{ moles of } Ni_{0.33}Mn_{0.33}Co_{0.33}(OH)_2 \rightarrow 2 \text{ moles of } LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$$

$$\text{'X' moles of } Ni_{0.33}Mn_{0.33}Co_{0.33}(OH)_2 \rightarrow 10429.70 \text{ moles of } LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$$

$$\text{Moles of } Ni_{0.33}Mn_{0.33}Co_{0.33}(OH)_2 \text{ required ('X')} = \frac{10429.70 \times 2}{2} \text{ moles}$$

Moles of $Ni_{0.33}Mn_{0.33}Co_{0.33}(OH)_2$ required ('X') = 10429.70 moles

Amount of Li_2CO_3 required =>

1 mole of Li_2CO_3 → 2 moles of $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$

'L' moles of Li_2CO_3 → 10429.70 moles of $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$

Moles of Li_2CO_3 required ('L') = $\frac{10429.70}{2}$ moles

Moles of Li_2CO_3 required ('L') = 5214.86 moles

Based on Eq (D),

Moles of $NiSO_4$ required = >

1 mole of $NiSO_4$ → 3 moles of $Ni_{0.33}Mn_{0.33}Co_{0.33}(OH)_2$

'Y' moles of $NiSO_4$ → 10429.70 moles of $Ni_{0.33}Mn_{0.33}Co_{0.33}(OH)_2$

Moles of $NiSO_4$ required ('Y') = $\frac{10429.70 \times 1}{3}$ moles

Moles of $NiSO_4$ required ('Y') = 3476.57 moles

Moles of $MnSO_4$ required = >

1 mole of $MnSO_4$ → 1 mole of $NiSO_4$

Moles of $MnSO_4$ required = 3476.57 moles

Moles of $CoSO_4$ required = >

1 mole of $CoSO_4$→ 1 mole of $NiSO_4$

Moles of $CoSO_4$ required = 3476.57 moles

Moles of NaOH required = >

6 moles of NaOH → 1 mole of $NiSO_4$

'M' moles of NaOH → 3476.57 moles of $NiSO_4$

Moles of NaOH required ('M') = $\frac{3476.57 \times 6}{1}$ moles

Moles of NaOH required ('M') = 20,859.42 moles

Moles of Na_2SO_4 produced = >

3 moles of Na_2SO_4 → 1 mole of $NiSO_4$

'N' moles of Na_2SO_4 → 3476.57 moles of $NiSO_4$

Moles of Na_2SO_4 produced ('N') = $\frac{3476.57 \times 3}{1}$ moles

Moles of Na_2SO_4 required ('N') = 10429.70 moles

The Calcination Stage produces CO_2 emissions and H_2O – wastewater, which potentially contributes to environmental impact. Therefore, their amounts are needed to be calculated in order to quantify and evaluate their impact.

Based on Eq (E),

Moles of CO_2 produced,

1 mole of CO_2 → 2 moles of $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$

'M' moles of CO_2 → 10429.70 moles of $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$

$$\text{Moles of } CO_2 \text{ produced ('M')} = \frac{10429.70 \times 1}{2} \text{ moles}$$

Moles of CO_2 produced ('M') = 5214.85 moles

Moles of H_2O produced,

1 mole of H_2O → 1 mole of CO_2

Moles of H_2O produced = 5214.85 moles

Summary of Mass Balance

No.	Substance	Molar Mass (g/mol)	Moles Required	Mass (kg)
1.	$NiSO_4$	154.75	3476.57	538.00
2.	$MnSO_4$	151.00	3476.57	524.96
3.	$CoSO_4$	155.00	3476.57	538.87
4.	NaOH	40.00	20,859.42	834.38
5.	Li_2CO_3	73.89	5214.86	385.33
6.	$Ni_{0.33}Mn_{0.33}Co_{0.33}(OH)_2$	90.95	10429.70	948.58
7.	$LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$	95.88	10429.70	1000.00
8.	Na_2SO_4	142.04	10429.70	1481.43
9.	CO_2	44.00	8691.42	229.45
10.	H_2O	18.00	15,644.56	1468.55
11.	NiS	90.76	3476.57	315.53
12.	O_2	32.00	10,429.72	333.75
13.	NiO	74.69	3476.57	259.67
14.	SO_2	64.06	6953.14	445.42
15.	H_2SO_4	98.08	10,429.71	1022.95
16.	$MnCO_3$	114.95	3476.57	399.63
17.	CoS	91.00	3476.57	316.37
18.	CoO	74.93	3476.57	260.50

Detailed calculation of Environmental Indicator for LFP method

ADP Calculation of LFP process:

1) Mass of Iron = 354.02 kg

ADP factor = $1.66 \times 10^{-6}\ kg\ Sb\ eq/kg$

Iron ADP = $Mass\ \times ADP\ factor = 354.02\ kg \times \frac{1.66 \times 10^{-6}\ kg\ Sb\ eq}{kg}$

Iron ADP = 0.0006 kg Sb eq

2) Mass of Lithium raw material = 1179.68 kg

ADP factor = $1.33 \times 10^{-2}\ kg\ Sb\ eq/kg$

Lithium ADP = $Mass\ \times ADP\ factor = 1179.68\ kg \times \frac{1.33 \times 10^{-2}\ kg\ Sb\ eq}{kg}$

Lithium ADP = 15.690 kg sb eq

Total = 0.0006 + 15.690 = 15.691 kg Sb eq

GWP Calculation of LFP:

1) Mass of Carbon Dioxide Released = 348.71 kg

GWP of Carbon Dioxide = 1 kg CO_2 eqv

Impact = $Mass \times GWP = 348.71\ \ kg \times \frac{1\,kg\,CO_2\,eq}{kg}$ = 348.71 kg CO_2 eqv

Acid Rain Potential of LFP:

1) Sulfuric Acid:
Acidification: $\eta_i = \frac{\alpha_i\,moles\ of\ H^{+} \times 1}{MW_i}$
Acidification of H_2SO_4: $\eta_{H_2SO_4} = \frac{2\,moles\ of\ H^{+} \times 1}{98.08} = \frac{1}{49.04}$
Acidification of SO_2: $\eta_{SO_2} = \frac{2\,moles\ of\ H^{+} \times 1}{64.06} = \frac{1}{32.03}$

Acid Rain Potential of H_2SO_4, ARP = $\frac{\eta_{H_2SO_4}}{\eta_{SO_2}} = \frac{\frac{1}{49.04}}{\frac{1}{32.03}} = 0.653$

2) Acid Rain Potential of SO_2 = 1

3) Hydrogen Fluoride:
Acidification: $\eta_i = \frac{\alpha_i\,moles\ of\ H^{+} \times 1}{MW_i}$
Acidification of HF: $\eta_{H_2SO_4} = \frac{1\,moles\ of\ H^{+} \times 1}{20.01} = \frac{1}{20.01}$
Acidification of SO_2: $\eta_{SO_2} = \frac{2\,moles\ of\ H^{+} \times 1}{64.06} = \frac{1}{32.03}$
Acid Rain Potential of HF, ARP = $\frac{\eta_{HF}}{\eta_{SO_2}} = \frac{\frac{1}{20.01}}{\frac{1}{32.03}} = 1.60$

Detailed calculation of Environmental Indicator for LFP method

ADP Calculation of NMC process:

1)Mass of Nickel = 315.53 kg

ADP factor = $4.18 \times 10^{-3}\ kg\,Sb\,eq/kg$

Nickel ADP = $Mass\ \times ADP\ factor = 315.53\ kg\ \times \frac{4.18 \times 10^{-3}\ kg\,Sb\,eq}{kg}$

Nickel ADP = 1.319 kg Sb eq

2.)Mass of Manganese = 399.63 kg

ADP factor = $2.35\ \times 10^{-5}\ kg\,Sb\ eq/kg$

Manganese ADP = $Mass\ \times ADP\ factor = 399.63\ kg\ \times \frac{2.35 \times 10^{-5}\,kg\,Sb\,eq}{kg}$

Manganese ADP = 0.009 kg Sb eq

3) Mass of Cobalt = 316.37 kg

ADP factor = $2.56 \times 10^{-2}\ kg\,Sb\ eq/kg$

Cobalt ADP = $Mass\ \times ADP\ factor = 316.37\ kg\ \times \frac{2.35 \times 10^{-5}\ kg\ Sb\ eq}{kg}$

Cobalt ADP = 8.099 kg Sb Eq

GWP Calculation of NMC:

1) Mass of Carbon Dioxide Released = 229.45 kg

GWP of Carbon Dioxide = 1 kg CO_2 eqv

Impact = $Mass\ \times GWP = 229.45\ kg\ \times \frac{1\ kg\ CO_2\ eq}{kg}$ = 229.45 kg CO_2 eqv

Acid Rain Potential of NMC:

1) Sulfuric Acid:
   Acidification: $\eta_i = \frac{\alpha_i\ moles\ of\ H^+ \times 1}{MW_i}$
   Acidification of H_2SO_4: $\eta_{H_2SO_4} = \frac{2\ moles\ of\ H^+ \times 1}{98.08} = \frac{1}{49.04}$
   Acidification of SO_2: $\eta_{SO_2} = \frac{2\ moles\ of\ H^+ \times 1}{64.06} = \frac{1}{32.03}$

   Acid Rain Potential of H_2SO_4, ARP = $\frac{\eta_{H_2SO_4}}{\eta_{SO_2}} = \frac{\frac{1}{49.04}}{\frac{1}{32.03}} = 0.653$
2) Acid Rain Potential of SO_2 = 1