

**OPTIMISATION OF ENERGY
CONSUMPTION AND GREENHOUSE GASES
EMISSIONS OF NICKEL IN ELECTRIC
VEHICLE (EV) BATTERIES**

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UNIVERSITI TUNKU ABDUL RAHMAN

**OPTIMISATION OF ENERGY CONSUMPTION AND GREENHOUSE
GASES EMISSIONS OF NICKEL IN ELECTRIC VEHICLE (EV)
BATTERIES**

SEE CHOON MING

**A project report submitted in partial fulfilment of the
requirements for the award of Bachelor of Engineering
(Honours) Mechanical Engineering**

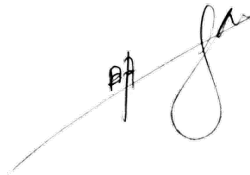
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April 2022

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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ABSTRACT

The sales of electric vehicles have skyrocketed in recent years due to the high demand as gas prices spike coupled with regulations set by the governments around the world. At the heart of the electric vehicle is the lithium-ion battery where the vehicle draws its source of energy for propulsion. Despite its sustainability compared to conventional fossil fuels, the manufacturing process of the battery is always a concern as the processes consume a lot of energy and emit high amounts of greenhouse gases as well. This work analyses the main source of energy consumption and emissions in the manufacturing step by way of Life Cycle Assessment study. Optimisation pathways are subsequently proposed to reduce energy consumption and greenhouse gas emissions. Several models were built and compared based on battery type, country grid, and source of nickel ore. After model was built and analysed, it was found that drying process, N-Methyl-2-pyrrolidone (NMP) solvent drying process, dry room operation and nickel use are the root cause to high emissions and energy consumption. Hence, alternatives were proposed to improve the situation such as the Tesla heat pump for NMP recovery, Cotes dry room technology, replacement of complete renewable energy source, and dry cathode to replace wet slurry cathode. Optimization using Tesla heat pump with our model showed a lower percentage reduction of 2.82 % for GWP and 1.68 % for PED, followed by Cotes' dry room technology reducing GWP by 9.27 % and PED by 3.48 % compared to the conventional desiccant dry room system. Next, dry cathode improved the cell production by reducing the GWP by 25.29 % and PED by 10.62 %. The conversion of non-renewable energy natural gas to solar panel renewable energy as energy source can reduce up to 227.67 % of GWP and 109.60 % of PED. Our models also show that impact to the environment can be reduced by replacing non-renewable energy with renewable energy as the energy source and using dry cathode technology as alternative technology to replace wet slurry cathode.

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LIST OF SYMBOL/ABBREVIATIONS

PHEV	Plug-in Hybrid Electric Vehicle
BEV	Battery Electric Vehicle
EV	Electric Vehicle
LIB	Lithium-ion Battery
NMP	N-Methyl-2-pyrrolidone
NMC	Nickel Manganese Cobalt
NCA	Nickel Cobalt Aluminium
LMO	Lithium Manganese Oxide
LMP	Lithium-ion Polymer
PVDF	Polyvinylidene fluoride
LFP	Lithium Ferro Phosphate
GHG	Greenhouse Gases
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
GWP	Global Warming Potential
PED	Primary Energy Demand

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

Electric Vehicle has become one of the disruptive industries in the recent years, it has brought up a lot of changes in many other aspects (Environmental, Economical, user lifestyle). Regardless of any aspect, the adoption of EV by users are growing in a spontaneous and exponential rate inevitably. Based on the Figure 1.1 below, the sales of plug-in electric vehicle sales have increased exponentially by 173 % of growth rate year-to-year. From the global perspective, the plug in EV market has increased up to 5.4 % for battery electric vehicle (BEV) and 2.8 % for plug in hybrid electric vehicle. (PHEV). As of March 2021, the total sales for this year globally exceed 1.13 million of passenger plug in EV (Mark Kane, 2021b). Based on estimation, Global EV sales are about to exceed the sales of global Internal Combustion Engine (ICE) Vehicle by 2037 (Eric C. Evarts, 2017). In Fact, China, Europe, United States dominate the global EV market followed by California, Germany, Norway and etc.

By looking at sales of 2021 by model globally, Tesla model 3 is the bestselling model with 126,716 units sold across the world year-to-date. This followed by a recent released mini-EV in China, Wuling Hongguang mini-EV with 96,674 units sold mainly in China. This most sold model in China can be explained by its convenient, compact size, free license plate and subsidy by government. License plate was free for small A0-class pure electric car in China, this has attracted China's Gen Z citizens to purchase, but however the license plate is no longer free issued in Shanghai (Phate Zhang, 2021).

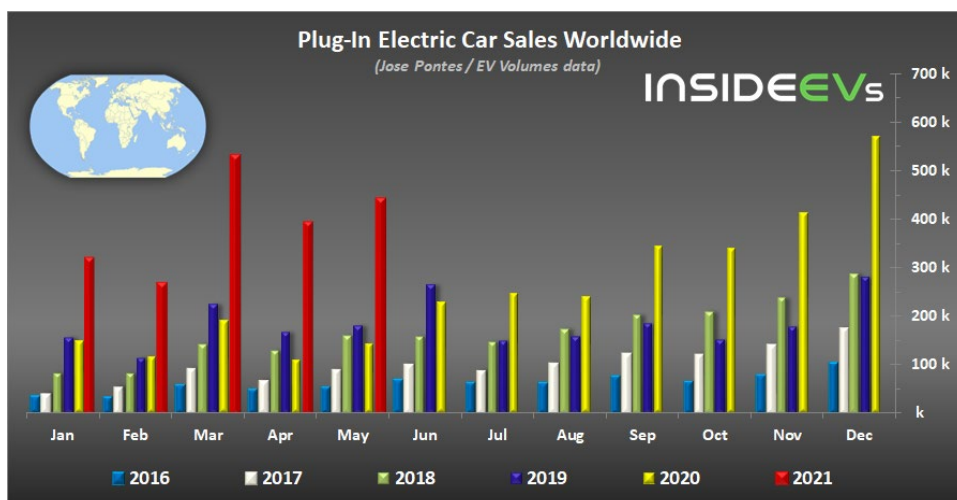


Figure 1.1: Global Plug in EV sales by May 2021 (Kane, 2021b)

In the recent years, lots of regulation and plans proposed has become the catalyst to expedite the growth of EV market. European Union Plans to totally ban the sales of ICE vehicle in their country to promote carbon neutral by 2035. E.U. has even proposed legislation that require 27 E.U. countries to install public EV charging station with interval less than 37 miles in between to provide the convenient for users (Anon., 2021a). U.S. president Joe Biden has allocated 174 billion of dollars to facilitate the adoption of EV in every aspect including domestic supply of material, tax, incentives for EV drivers and charging infrastructure and promised to have 500,000 units of charging network devices installed across entire US by 2030 (Micheal Wayland, 2021).

Furthermore, Joe Biden has signed an executive order to set about 40-50 % of new vehicles sold will be electric by 2030 (Shepardson D. & Mason J., 2021). In the consequences, this could bring U.S. closer to their goals of 51 % of net economy wide GHG emissions reduction far below levels back in 2005. Besides in China, China government imposed an official commission for automakers to make up the sales up to 40 % of all vehicles sold by 2030. EV manufacturers were subsidized by China government to promote the EV sales, but the subsidies have been reduced and eliminated gradually in the recent years after the threshold. EV with range within 250 km to 400 km are entitled for subsidies about 2600 USD while 3600 USD for vehicle range more than 400 km. Aside from electric vehicle, electric buses and trucks are benefited from this policy as well. In medium to long term, electrified vehicle will be significant

for Chinese government's goals to achieve carbon neutral generation. (Electric Vehicles | Guide to Chinese Climate Policy, no date)

Speaking about the sales of electric vehicle, battery accounts for nearly 57 % of entire EV production cost in 2015, to be the most expensive parts for electric vehicle based on the studies of Bloomberg NEF, but the cost of battery has been drastically decreased in the recent years. Based on the projection of ARK investment management, the average price of battery pack is expected to fall below 100 USD per kWh of cell by 2023. At this price point, EV are estimated to be as cheap as the production cost of gasoline powered vehicle (Bhutada, 2021).

Looking further down in details, nickel is one of the important elements in the production of EV lithium-ion battery. Nickel composite are being used by most of the cell manufacturer in their lithium-ion batteries. For example, NCA batteries used by Tesla contained about 80 % of nickel and NMC batteries used by Volkswagen contained about 33 % of nickel. Major key advantages of nickel are that it will carry higher energy density with better storage capacity for cell at a low cost. With this nickel-rich cell, combination of the high energy density and the high storage capacity, electric vehicle can travel a further distance without charging.

Currently, steel production still dominates the nickel demand about 74 % of the market, while batteries only accounts for 5 % to 8 % of the demand. This is expected to change drastically over the next decade. The world's nickel resources are estimated at about 300 million tons with more than 50 % coverage across Australia, South Africa, Indonesia, and Canada. In 2017, nickel usage in batteries are approximately 70,000 tonnes. But according to projection by Bank of America, the nickel demand would surge up to 690,000 tonnes by 2025 with estimation of 13.6 million EV sold. Nickel can be differentiated into two. Class I nickel originated from sulphide ores (70 %) and remaining are from limonite ores with require high pressure acid leaching (HPAL) refining process. While Class II nickel are from saprolites and limonite where is majority of it are being used in stainless steel industries as they are cheap and presence of iron. In the making of stainless steel, both categories of nickel can be used, while batteries need class I clean nickel for manufacturing as the quality of nickel will directly

impact the quality and performance of the batteries made. With the scarcity of nickel sulphide deposits, this has led to shortage of class I nickel in the market (Marcelo, Goffaux and Hoffman, 2020). As of October 2020, With the reference of Adamas Intelligence Critical material research papers, 1837 tonnes of nickel were deployed in NCM 6 series battery cell with 127 % increased over year-to-year, 1,504 tonnes of nickel on NCM 8 series and 1,468 tonnes for NCM 5 series. While for NCA generation-3 is about 1,043 tonnes of nickel deployed in the cell chemistries.

By the end of February 2021, the metal price in London Metal Exchange (LME) plunged over 20 % in price as the announcement by Chinese steelmaker Tsing Shan regarding the contract of supplying 100,000 tonnes of nickel matte to two battery manufacturers (Emmanuel N. V., 2021). Tsing Shan solved the shortage problem of class I nickel by the replacement of class II nickel. However, this has brought up to the environmental issues whereby the nickel matte provided by Tsing Shan is from the processing of class II nickel into nickel pig iron then into nickel matte followed by the pure nickel which is needed by battery manufacturer. Only about 20-35% of nickel are able to extract from Ferronickel while nearly 8% to 12 % from nickel pig iron. The refining and processing of these class II nickel are not only inefficient and energy intensive, but the process will also be costly and high greenhouse gases (GHG) emission are inevitable.

Besides the fact of processing and refining of nickel require high energy intensity and emits tonnes of GHG, production of battery cell is one of the substantial impact processes to the environment and energy. Jinasena et al. stated that among all the steps in LIB manufacturing process, Dry room and drying of cathode is the most energy intensive process. Drying accounts for 48 % of the entire energy demand and same for dry room as well with about 48 % of the energy demand to produce NMC333 battery cells. This stand was not exactly right as according to Sun et al. (2020), the paper mentioned that about 44.7 % of energy demand are from vacuum drying process which also known as the post drying process while dry room covered 41.2 % of the energy usage. In fact, the energy demand stated includes the coating and drying process. Many existing factors are influencing the values and data obtained by the studies

causing the huge variation on the literature review. Hence, it is important to understand the method of study behind the values obtained and assumption made.

1.2 Importance of study

As the rise of electric vehicle industries, the key component lithium-ion batteries are being widely adopted by most of the EV manufacturer. As the demand of batteries are surging, the manufacturing of lithium-ion batteries becoming a key impact to the industries and environment. This study is to understand the energy consumption and GHG emission of LIB manufacturing, from that optimization will be made to ensure the sustainability of all of the key elements in LIB manufacturing process for example electricity usage, GHG emission, material used, process time period and etc.

Nonetheless, the current studies of related field are having a huge variation among each study. Hence, this study will be using LCA software to determine the estimated figure and optimization to be made to fully understand the major root cause of energy intensive process and major process that release the most GHG emissions. By determining the root cause, recommendation can be made to optimize and reduce the energy demand and greenhouse gas emissions. Subsequently, environmental issues can be mitigated by reducing GHG emission and achieving net carbon emission in the future. Besides, inefficient operation and waste of resources that will become a barrel for business to scale up can be resolved as well. Besides obtaining the energy consumption and GHG emission of the entire manufacturing process, the energy demand and GHG emission of nickel in the manufacturing process will be obtained as well. In accordance with that, optimization of nickel in the manufacturing process can greatly impact the future of sustainable nickel market.

1.3 Problem statement

Energy consumption and GHG emission of lithium-ion battery manufacturing facilities can have a huge standard deviation. Among the available studies, some literature reviews are no longer compatible with the current stage of LIB

facilities energy demand and emission of GHG. The obtained results vary by factors for example annual capacity of factories, conservation of energy technologies, energy recovery system, the electricity grid used, location, types of process and machinery used. All these factors are the major influence of the big variation among the LCA studies. For example, Yuan et al. (2017) uses pilot scale plant which does not reflect the current giga watt hour LIB factory facilities. (Thomitzek et al., 2019) uses simulation model of LIB manufacturing process which results in extreme high value for energy demand. Sun et al. (2020) obtained primary energy data from China with 30 GWh annual capacity, but China electricity grid does have variation with US electricity grid which reflected the difference in the results. Most of the studies are carried out at a different year where the technologies have been rapidly evolved throughout resulting in different approach and assumption made.

To optimise the results obtained, several steps should be taken into consideration for example, primary energy data obtained must be directly from the LIB manufacturing facilities, annual capacity of LIB manufacturing facilities must exceed at least 1 GWh, electricity grid must be standardised, and technologies used to conserve energy must be pointed out clearly. Moreover, this study is conducted as due to the problem happened in Indonesia and China. For instance, class 2 nickel was mined in Indonesia for the purpose of production of stainless steel. However, as the demand of nickel increase caused by electric vehicle industries for the manufacturing of lithium-ion battery, and the limited amount of class 1 nickel, China imports class 2 nickel from Indonesia mine and process the class 2 nickel as known as nickel pig iron into nickel that can be used for lithium-ion battery. Class 2 nickel is known as dirty nickel as the process to generate nickel from class 2 nickel consumed high amount of energy and release greenhouse gas to the environment compared to class 1 nickel. Hence, this issue has to be solved else it will affect the sustainability of nickel used in lithium-ion batteries.

1.4 Aim and Objective

The main aim and objective of this study is to optimize the total energy consumption and GHG emission of nickel in electric vehicle battery

manufacturing process. This aim is to promote a less energy intensive LIB manufacturing process and environmentally friendly to the world. In order to fulfil the aim of this paper, several objectives are needed:

1. To examine existing process of LIB manufacturing process and its distinctive stages.
2. To construct the Life Cycle Assessment (LCA) model of LIB manufacturing using Class I and Class II nickel respectively.
3. To recommend solutions to reduce energy consumption and GHG emissions based on LCA results.

1.5 Scope and Limitation of the study

This study will be focus on evaluate the LCA studies of LIB manufacturing facilities. From that, optimization of work will be made to determine root cause of high energy consumption and GHG emission of the entire manufacturing process. However, limitation exists which put this study to a much difficult level of approach. Limitation of study are:

1. Limited access to primary data (input) from the industries with the latest tech and energy saving method. This could be incompatible with actual case.
2. This study is Gate-to Gate (production of cell material precursor to the end production of battery module and pack) and does not cover the Cradle-to-Grave cycle (resource extraction to disposal).

1.6 Contribution of study

The contribution of this project may help to discover the problem of global warming and issues of limited nickel ore due to the high demand of lithium-ion battery needed by fast growing of electric vehicle industries. Besides, the major contributor to high GWP and high PED will be shown and alternatives solutions to optimize the can be found in this project.

1.7 Outline of the report.

In the report, literature review has been discussed in Chapter 2, while methodology of project can be found in Chapter 3. Moreover, Chapter 4

discussed about the results found using OpenLCA and conclusions has been discussed and presented in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Several papers are being reviewed and studied to retrieve the value on energy consumption and their method of study and assumption made. Detailed review on LCA papers specifically on their global warming potential indicator. Besides, the indicators and energy demand, the entire LIB manufacturing process was studied as well as there is a huge variation between different manufacturer in terms of their manufacturing process and technologies used. This study includes the manufacturing process from nickel sulphate production to NMC precursor, NMC powder production and the final lithium-ion battery cell production. Sensitivity analysis was reviewed to understand the huge gap between the available data. Alternative method of process was studied and review to be used later to replace the current manufacturing process method.

2.2 Types of lithium-ion battery used in electric vehicle

Generally, lithium-ion battery is used as the main driver for most of the pure electric vehicle out there. However, for different lithium-ion battery manufacturer and automotive companies, they have adopted different kind of battery cathode active material composition to suit their usage in their car model. Different type of cathode active material composition has different kind of characteristics and performance itself. As of 2020, there are 4 types of lithium-ion batteries that are being widely adopted by most of the EV companies in the industries which are NMC, NCA, LFP and LMO. According to global sales weighted average (SWA) nickel usage by cell chemistries (Adamas_Intelligence, 2018), the SWA amount of nickel used by NCA generation-2 was 67.7 kg and 47.3 kg for NCA generation-3. While NCM only deployed about 40.2 kg for its 8 series and 34 kg for its 7 series.

Table 2.1: Global EV Sales 2020-2021(May)

2020 Global			2021 Global (Jan-May)		
Vehicle model	Cell type	Amount	Vehicle model	Cell type	Amount
Tesla Model 3	NCA + (MIC)	365240	Tesla Model 3	NCA + (MIC)	172672
Wuling HongGuang	LMP	119255	WLHG	LMP	152667
Renault Zoe	NMC	100431	Model Y	NCA	101674
Tesla Model Y	NCA	79734	BYD Han	LFP	32865
Hyundai Kona EV	NMC	65075	VW ID.4	NMC	26271
VW ID.3	NMC	56937	GW Oraa Black Cat	others	25503
Nissan Leaf	NMC	55724	Hyundai Kona	LMP	24914
Audi E-tron	NMC	47928	Nissan Leaf	NMC	24653
BaojuanE-series	LMP	47704	GAC Aion S	NMC	24540
GW ORA R1/Black cat	others	46796	VW ID.3	NMC	23939

*MIC – Made in China sales (included LFP and NMC cell type)

Based calculation of Table 2.1 among of the best-selling EV cars in 2020 and 2021 YTD (Mark Kane, 2021c), NMC battery is the most used LIB followed by NCA battery, then third is LFP and the least used battery is LMO battery. Each of the cathode material has different chemical properties and performance respectively.

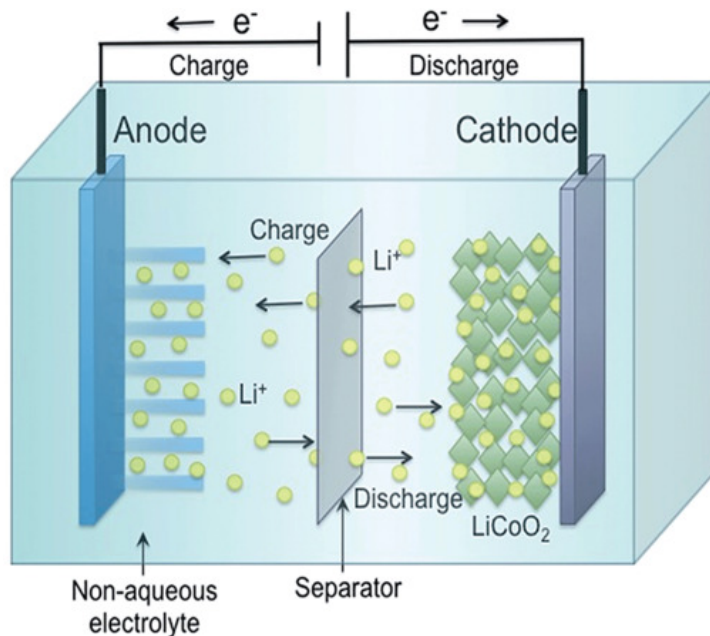


Figure 2.1: Schematic diagram of lithium-ion battery

Despite the chemical composition different for different type of battery, their working concept are almost the same except the material made up in the cathode and anode. Normally anode is made up from graphite while cathode is made up based on the battery type respectively. For example, for NMC, the composition for cathode is nickel, manganese and cobalt with a specific ratio. When a cell is plugged into a device, the charged positive ions move from anode to cathode consequently attracts negatively charged electrons to move towards the cathode side as cathode is now becomes more positively charged than anode. In fact, the movement of the ions through the electrolyte is what causes the electrons to move through which in turns provide the electricity to the device. On the other side, when battery is being recharge, the process is the opposite of the concept when being discharge to the device. The lithium ions now go in the opposite direction which restores the battery for the following use.

2.2.1 Lithium Nickel Manganese Cobalt Oxide battery (NMC)

NMC battery is a combination of Nickel, Manganese and Cobalt. The proportion of each chemistry composition are different for each LIB manufacturer and EV company. There are several types of NMC chemical proportion which is NMC111, NMC622, NMC811 and etc. For example, Volkswagen E-golf uses NMC111 also known as NMC333, Renault Zoe uses

NM 622 for old generation and NMC712 for new generation Zoe, Nissan Leaf uses NMC523 and so on. NMC LIB manufacturers include CATL, LG chem, SK Innovation, Samsung SDI, etc.

Based on the Table 2.2, This type of LIB has a high specific energy, but poor stability. Manganese is used to achieve low internal resistance but however it lowers the specific energy. Hence, the portion of nickel and manganese is closely calculated to results in a best optimal performance of the battery. Most of the companies have switch from NMC111 to NMC622 and now into NMC811 with high nickel composition of about 80 % nickel, 10 % Manganese and 10 % Cobalt.

2.2.2 Lithium Nickel Cobalt Aluminium Oxide (NCA)

This battery are basically lithium nickel cobalt aluminium oxides comprising of metal oxides. The main manufacturer of NCA battery is Panasonic and Tesla. Panasonic cooperate with Tesla to manufacture NCA batteries in Tesla Gigafactory Nevada has more than 35 kWh battery capacity annually. Currently, among the major EV companies in the market, Tesla is the only company that uses NCA battery for their car model. Tesla has used NCA batteries for their Model S, Model X, Model 3 and Model Y since 2012. However, Tesla has gradually start to apply other types of cathode material for their car model for example made in China Model 3 uses NMC and LFP for standard range plus and long-range performance version (Mark Kane, 2021a).

The characteristics of NCA is actually similar to NMC batteries which provides higher specific energy and specific power and longer lifespan, but however it is not the safest among the LIB available in the market. It requires a safety monitoring measure tools in their battery management system to ensure the safety of users.

2.2.3 Lithium Ferro Phosphate (LFP)

Lithium ferro phosphate (LiFePO_4) also a type of cathode active material uses in lithium-ion battery but functioning without cobalt and nickel composition. The main EV company who uses LFP battery for their car model are BYD, and Tesla made in China Model 3 and Model Y and China Xpeng P7 Wing edition.

LFP batteries has great chemical properties with low resistance, high power density, cheaper, less toxic and has wide temperature tolerance range where battery thermal management system is not needed to worry on the thermal runaway issues. But however, it has lower energy density due to lack of space for lithium ion to intercalate and only halve of the energy density compared to NCA cathode material.

2.2.4 Lithium Manganese Oxide (LMO)

Lithium Manganese Oxide batteries (LMO) are being commercialize in 1995. Most of the LMO batteries are normally work together with the Lithium nickel manganese cobalt oxide (NMC) batteries to improve the specific energy and increase the lifespan of batteries. LMO-NMC batteries has been used in the past EV companies, for example Nissan Leaf, Chevy Volt and BMW i3 older generation model. This type of battery has low internal resistance where results in fast charging rate and high current discharging as well as better thermal stability.

2.2.4 Lithium-Ion Polymer (LMP)

In China, due to their restriction and policy, mini-EV has greatly accepted by most of the China citizen due to its small size and convenience especially for the Wuling Hongguang mini-EV model. The battery equipped in Wuling Hongguang is lithium-ion Polymer which is kind of different from the general EV batteries mentioned above.

Lithium-ion polymer also known as lithium polymer battery are relatively safe and light in weight compared to normal lithium-ion battery. It has a comparatively short charging time and able to retain the charge capacity better than lithium ion. But however, the major factors that most of the LIB manufacturer and EV companies are using lithium ion over the lithium polymer is because lithium polymer are about 30 % much expensive than the conventional lithium ion and has very low energy density. These are the factors that are difficult to change while safety of lithium ion can be controlled by adding battery management system and weight are not significant over here. Charging duration can be vary by adjusting the output of charging station.

2.2.5 Comparison of different battery chemistries

In the Table 2.1, it displayed the characteristics of different battery chemistry in terms of nominal voltage, cycle life, charge and discharge current rate, thermal runaway and specific energy. However, this may vary from manufacturer to another as the assumed End of life (EOL) and Depth of discharge (DoD) could be different. Lithium-ion polymer (LMP) is not compared here as the capacity of LMP is very small and normally is being used in electronic device instead of electrical vehicle.

Table 2.2: Characteristic of different battery chemistries

Types of battery chemistry	Nominal Voltage (V)	Cycle (Life)	Discharge current rate (C)	Thermal Runaway (°C)	Specific energy (Wh/Kg)
NMC	3.0-4.2	1000	1.5	210	190
NCA	3.0-4.2	750	1	150	230
LFP	2.5-3.65	2000	1	270	105
LMO	3.0-4.2	500	1	250	125

*Assuming EOL is 80, and DoD is 80 %

In terms of nominal voltage, LFP battery has a higher nominal voltage, which means it's much efficient in delivering the output voltage than the other 3 battery chemistries. LFP battery has a much higher cycle life followed by NMC, NCA and LMO. A higher cycle life refers to how many rounds of a fully discharge and then fully charge battery. Hence, we can conclude that LFP battery can last longer than the others. On the other hand, NMC has higher discharge rate than the 3 other batteries as 1.5 C of discharge current rate means that it required longer time to fully discharge the battery from fully charged one. Thermal runaway's temperature refers to temperature point where the chemical reaction occurs inside the battery and causing an explosion and inflammation. LFP has the highest thermal runaway which means the battery will inflame or explode only when the battery temperature achieves 270 °C, this makes LFP battery much safer than the remaining. Last but not least, NCA also has highest specific energy which means NCA battery chemistries can store a higher amount of energy per unit mass. While LFP has the lowest specific energy, that's the reason that LFP are being used for Tesla Model 3 standard range plus

version (SR+) while NMC battery is used for long range performance model. (Kane, 2021)

2.3 Electrode Material Manufacturing

The NMC synthesis process consists of 2 major stages. First stage is the mixing of nickel, Manganese, and cobalt sulphates to produce the particular precursor. Second stage is mix of the precursor prepared in stage 1 with lithium carbonate or hydroxide to produce the cathode active material powder. The detail steps in each stage could be different for different manufacturer with different scale of production. Production nickel sulphate are the minor steps to obtained nickel sulphate for the production of NMC precursor.

2.3.1 Production of nickel sulphate (NiSO_4)

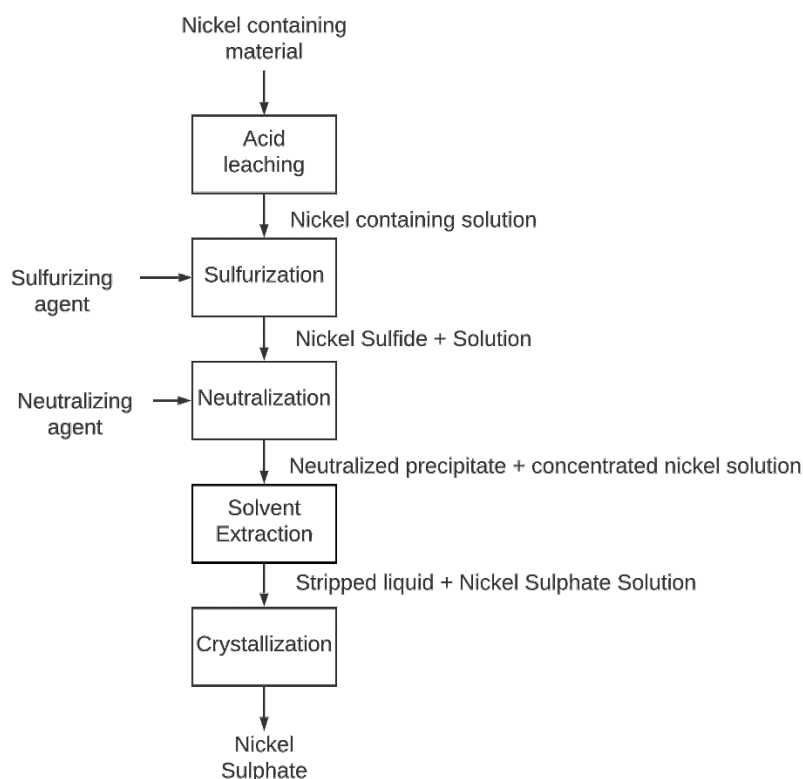


Figure 2.2: Nickel sulphate (NiSO_4) production

Nickel sulphate is an essential element in the production of cathode material precursor on the following steps. Initially, nickel containing material will undergo acid leaching step where will obtain a solution containing nickel

(undiluted acidic liquid). Next, a sulfurization step will happen by adding sulfurizing agent into the solution containing nickel to obtain a precipitate of nickel sulphide with solution. Meanwhile, oxidizing agent is added to the slurry to obtain a concentrated nickel solution. Neutralizing agent will be needed in this step to neutralize the concentrated nickel solution, and product of neutralized precipitate and concentrated nickel solution will be obtained with removal of iron. Solvent is being extracted and obtaining stripped liquid together with nickel sulphate solution. Last, nickel sulphate solution impurities will be removed before crystallization occur to obtain the final product of nickel sulphate.

2.3.2 NMC precursor production (Co-precipitation)

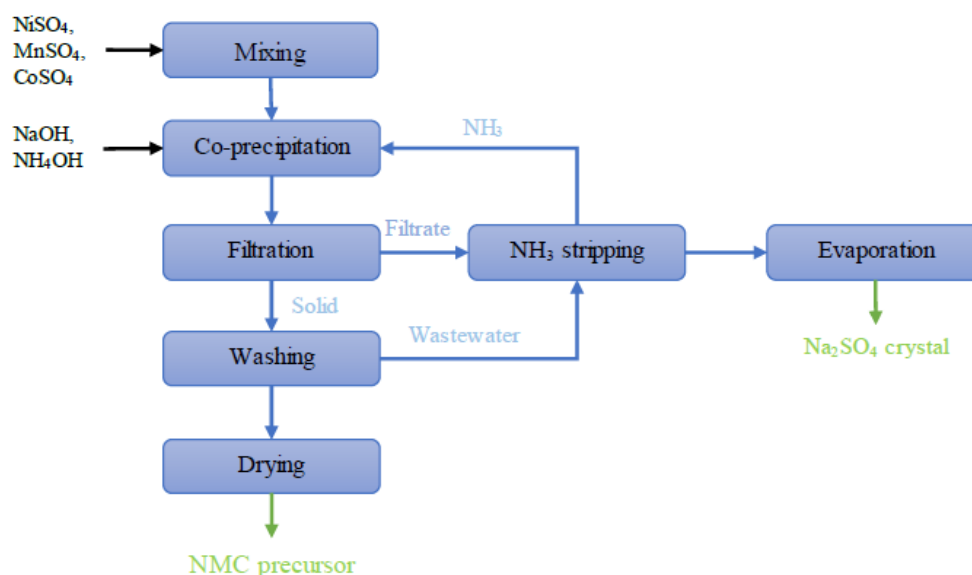


Figure 2.3: NMC Precursor production (Co-precipitation) (Dai et al., 2018)

This process begins with mixing of dissolved stoichiometric ratio of specific sulphate. In this case, nickel sulphate (NiSO_4), manganese sulphate (MnSO_4), and cobalt sulphate (CoSO_4) are mixed together in a reactor tank. After the mixture is ready, sodium hydroxide (NaOH) and ammonium hydroxide (NH_4OH) are added into solution with steam heated at about 50°C , this process is called co-precipitation. During this co-precipitation process, the 3 chemical compositions are being co-precipitated out and form the NMC hydroxide $\text{NMC}(\text{OH})_2$. Next, the NMC hydroxide is then being filtered out and going

through washing and drying process and finally NMC precursor are prepared for next production stages. On the other hand, a by-product of Na_2SO_4 crystal is produced by feeding the filtrate into a process. The excess ammonia is then repelled out from the wastewater in ammonia stripping tower, and later being sent back into the subsequent precursor production line.

2.3.3 NMC cathode powder production from precursor (Calcination)

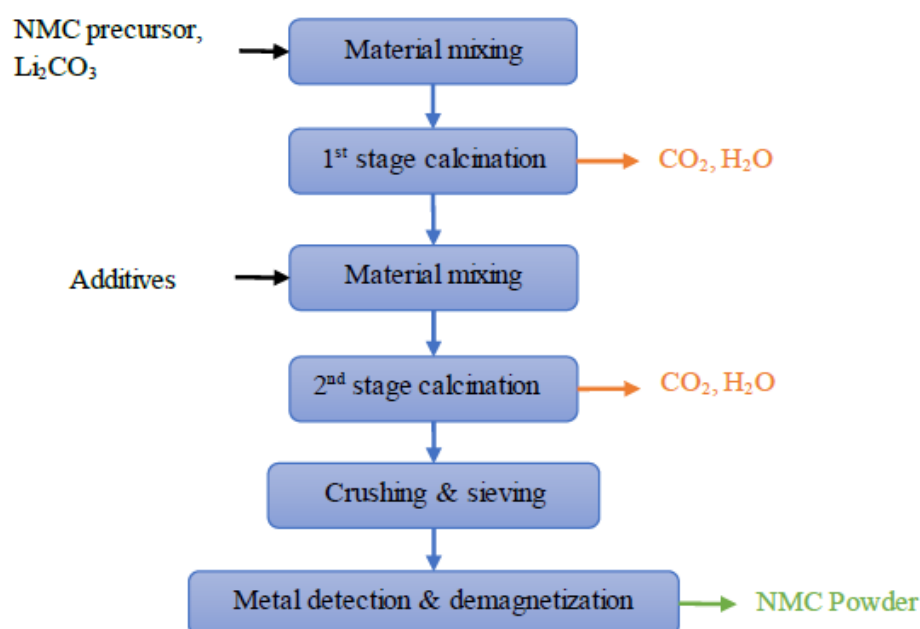


Figure 2.4: NMC cathode powder production (Calcination) (Dai et al., 2018)

After the NMC precursor are done produced from the previous stage, it will be sent here for NMC powder production. The whole process starts with material mixing where NMC precursor, and Lithium Carbonate (Li_2CO_3) or Lithium Hydroxide (LiOH) subject to the final product. Typically, Li_2O_3 is used for NMC111 and NMC622 battery cathode powder production while LiOH is used for NMC811 and NCA cathode powder production. There is a slight difference in the production process in terms of calcination stages required for different cathode material being produced. Cathode material for computer, communication, and consumer electronics (3C) application with low voltage output require 1 stage of calcination. On the other hand, cathode material for traction battery requires about 2 stages of calcination (i.e., NCA and NMC types of battery.). During the production, every intermediate material loss from mixing, crushing and sieving will then be transport

back into the feed stream for reuse. Hence, it has shown the facility can achieve the overall material efficiency close to 100 %.

2.4 General Electric Vehicles (EV) battery manufacturing process

In the EV production lines, every step is basically summing up into 3 main parts, which are electrode manufacturing, cell assembly and cell finishing. Here, we will take lithium-ion battery as the references for the manufacturing process. Despite the process of EV battery manufacturing could have differences among all the manufacturer out in the market, but the general concepts and steps are very similar. However, the differences are particularly in the technology being implemented in their production line. For example, cell design, chemical content, cathode drying technology, HVAC system used to maintain dry room, solvent recovery method and etc.

The entire general process of electrode manufacturing is shown in the Figure 2.5 below.

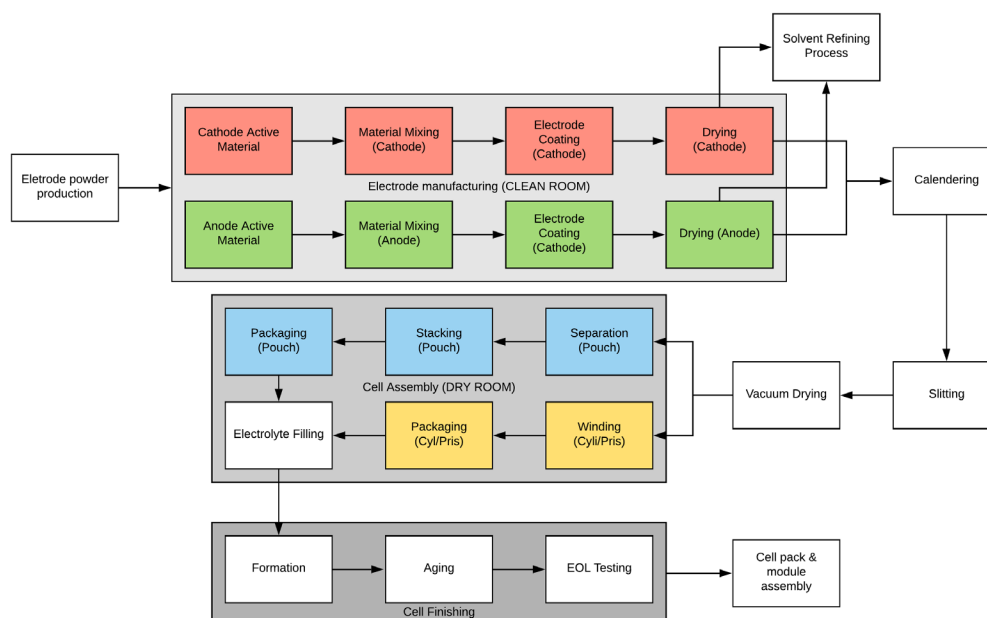


Figure 2.5: General EV battery manufacturing process.

2.4.1 Electrode manufacturing

In the first part of the process consist of several steps like: Mixing, Coating, Drying, Calendaring, Slitting, Vacuum drying.

2.4.1.1 Mixing

In this first step of mixing, active material, additives, and binder are mixed dry into mixing tool with the following steps of solvent dispersion and homogenize. This process is being carried out under the temperature of 20 °C - 40 °C for about 30 minutes to 5 hours inside the clean room operation with vacuum and protective gases. There are few types of mixing process technologies like intensive mixers, planetary mixers, and dispersers. The choice of mixing and dispersing are totally based on the electrode design to be produced. Anode and cathode use separate mixers to avoid cross contamination. Mixture of all these contents is called the wet slurry will later be coated on the current collector in the following processes.

For cathode composition, active materials vary based on the battery to be produced. For example, NCA, NMC, LMO, LFP and so on. The weightage of each cathode active material will be different as well based on the manufacturer. Generally, NMP solvent is used as the solvent for cathode formation and PVDF (5% wt.) is used as the binder. Each of the active materials composition have their own advantages and disadvantages and are being used by different manufacturer. NMC are used by most of the EV cars like Nissan Leaf, NIO ES6, Chevrolet Bolt and BMW i3. NCA are used mostly used in Tesla model cars. However, there is one exception, Tesla model 3 being produced in Shanghai, China Gigafactory is using LFP or NMC as the cathode for their batteries.

On the other hand, anode composition is generally made up of graphite but there is an alternative like silicon. Silicon has number of advantages over graphite including cheap manufacturing and material cost as well as it can store more lithium ion in the anode while being charge. This increases the capacity and energy density of the battery. However, it's yet to be mass adopted by the manufacturer out there.

2.4.1.2 Coating

In this second stage of electrode manufacturing process, the foil as known as current collector is coated with the wet slurry prepared in the previous stage using a tool (e.g., doctor blade, anilox roller or slot die). The process is called wet slurry coating while the top and bottom side of the current collector are

being coated simultaneously with respective slurry. After that, the coated current collector will be transferred to the dryer. Generally, the coating speed are about 35m/min to 80m/min with coating width up to 1500mm. Before entering the drying stage, a laser measurement tools are used to ensure the coating thickness are always in constant.

2.4.1.3 Drying

Moving on to the drying process, the slurry applied on the current collector will be dried in a long drying chamber oven. The wet coated cathode usually undergoes drying process with hot air or thermal radiation then followed by calendaring. This is an important stage where it will influence the electrochemical properties of the cell as well as film adhesion. In fact, the speed of drying can be increased by using larger and longer infrared oven, but this could lead to high demand of energy. In the drying process, NMP wet solvent is being removed from the oven. This wet solvent is toxic and flammable, hence it will be transfer and send to a solvent recovery system or used it for thermal recycling.

Based on Tesla (Tesla, 2018, p.30), Tesla has their own dedicated solvent refining system to convert the NMP solvent back into reusable solvent in a closed loop fashion. This system has been operating since the end of 2017 and has exhibits a 95% conversion of waste solvent.

2.4.1.4 Calendaring

In the process of making, a set of industrial rollers are used to compress the dried electrodes from the previous stage. But right before that, the electrode foil is statically discharged and cleaned. Clean rollers are crucial as it can prevent the foreign particle from interfering the substrate material. The predetermined amount of pressure plays an important role here. If the pressure is set too high, squeezing of the dried electrode will leads to stress cracks which will definitely impact the chemical performance and properties of the produced cells. Calendaring function to decrease the porosity of the electrode by about 20 % to 40 %. By doing so, it can maximize the particles contact with electrode and directly increase its energy and power density. This process is known to affect

the electrode mesostructured which in turns influences the electrochemical performance (Ngandjong et al., 2021).

2.4.1.5 Slitting

The entire mother rolls are fed into the slitting station after the calendaring process. Slitting is a stage where mother rolls are being cut into several smaller electrode foil (daughter roll) according to the size needed. Laser slitting is a type of alternative to the conventional rolling knives. Even though it has better flexibility, but it could damage the active material and contamination might occur.

2.4.1.6 Vacuum Drying (Post Drying)

Vacuum drying also known as post drying, the daughter roll is then being send into special goods carrier which will then be stored in a vacuum oven to remove the residual moisture and remaining solvents. This whole drying process takes about 12 to 30 hours with drying temperature of 60 °C to 150 °C. Evaporation of air at a low temperature result in low total pressure (between 0.07 mbar – 1bar) in the vacuum compartment to reduce the residual moisture and remaining solvents. In additions, the operations of vacuum oven can be used with inert gas to prevent corrosion of electrode. This vacuum drying can be replaced by infrared drying and continuous long oven drying as well, and it's totally based on the preferences of the manufacturer and their limitations.

2.4.2 Cell Assembly

Second main part of production line involves 4 steps, separation, stacking, packaging and electrolyte filling.

2.4.2.1 Separation & Stacking (Pouch cell)

Separation is necessary only for pouch type cell as it separates the cathode anode and separator from the daughter rolls. Normally punching tool is used with shear cutting in a continuous process. After the punching process, it will be sent for stacking. During stacking, the separated electrode sheets are being stacked in repetitive cycle with separator stacked in between anode and cathode and etc. A

classic stacking process is called Z-folding where the current collector is being fold from left to right alternatively with separator involved.

2.4.2.2 Winding (Cylindrical/Prismatic)

Winding however is required for both the cylindrical and prismatic cell types exactly after the vacuum drying. Current collectors and separator are wound together with a winding mandrel (specifically for prismatic cell only), or centre pin (for the cylindrical cell) and the end product is called jelly roll. Comparatively, the machining throughput of cylindrical cell are way faster than prismatic cell speed, which are 30 cells/minutes and 6 cells/minutes.

2.4.2.3 Packaging (Pouch Cell)

In this process, the current collector foils are welded by using ultrasonic or laser welding with cell tabs. Then the insertion process where the cell stacks is then positioned in the pouch foil waiting for sealing. Usually, pouch cells are sealed gas tight on 3 sides of the cells. One side of the cell are left for electrolyte filling in the next process step.

2.4.2.4 Packaging (Cylindrical/Prismatic)

On the other hand, the cylindrical and prismatic cell packaging are totally different from the pouch cell. The wound jelly roll is then inserted into a metal housing in general. For cylindrical cell, the bottom insulator will be inserted first then the jelly roll into the cylindrical housing with anode and cathode welded on respective side. In contrast, the prismatic cell edges are compressed and welded on the contact terminals where it's contacted with the lid of battery. It will then be sealed by a laser welding process.

2.4.2.5 Electrolyte filling (Pouch/Cylindrical/Prismatic)

The process for all types of cells is similar. The cell is filled with electrolyte under vacuum dried condition with a high precision dosing needle. Pressure is then applied to the cell under vacuum dried room or supply of inert gas. Evacuation or partial filling of electrolyte will be needed several times depends on the manufacturer operation. At the end of it, the cell will be sealed.

2.4.3 Cell finishing

For the last part of the process consist of several steps: Formation, Aging, and EOL testing.

2.4.3.1 Formation

The cells will be stored in formation compartment with pins contact for the purpose of charge and discharge based on the predefined values. It can be described as the first charging and discharging process for the battery cell. During the process, a solid electrolyte interface (SEI) protective layer is formed in between the layer of electrolyte and electrode surface. This SEI layer allows the flows of lithium-ions but blocked the flows of electrons which will cause short circuit in battery. The formation normally takes up to 24hours with approximately 0.1 C to 0.5 C specific discharge capacity: State of Charge (SOC) approx. 20 % to 80 %.

2.4.3.2 Aging

Aging is normally called as quality assurance process. During the aging process, the electrochemical properties and performance are constantly being monitored their voltage, capacity of cell and impedance for a period of time. The variation of aging time varies from 1.5 weeks to 3 weeks depending on the manufacturer and cell chemistries. The cell will undergo high temperature aging (30 °C to 50 °C) then normal temperature aging 22 °C. After the monitoring period, if there's no significant change in cell electrochemical properties, that means then cell is fully functional and ready to be delivered.

2.4.3.3 EOL testing

Right before the cells leave the factory for shipping or pack into cell module, the cells will be going through a testing station where here they will be discharged to the State of Charge (SOC) that are suitable for shipping. Aside from this, several testing are carried out as well including pulse tests, internal resistance measurements, optical inspection, leakage test and open circuit voltage (OCV) test. After a series of tests, they will be arranged and sort according to their performance data and grades. Upon completion, the cells will be packed and shipped.

2.5 Energy consumption of EV battery manufacturing process

Energy consumption of EV battery manufacturing process can be divided into 2 stages, one is electrode material manufacturing which is the production of cathode and anode slurry which will be later coated on the current collector while cell manufacturing is the entire production of battery from prepared material to completed unit cell.

2.5.1 Energy consumption of electrode material manufacturing

In this process, it includes two main process which is co-precipitation and calcinations for both precursor production and powder production respectively. Dai et al. (2019) has obtained the energy consumption values from world's top five NMC powder suppliers. The industry primary data is shown in the table 2.3 below.

Table 2.3: Energy consumption of electrode material manufacturing

Electrode material production	Total energy (MJ)
NiSO ₄	27.07
CoSO ₄	55.96
MnSO ₄	3.06
Li ₂ CO ₃	16.23
NaOH	27.37
NH ₄ OH	2.40
Co-precipitation	46.97
Calcination	52.23
Total	(113.5 Wh_e/Wh_c) 231.28

According to the paper published by (Dai et al., 2019). The total energy consumption of electrode material manufacturing is about 231.28 MJ per 1 kg of NMC powder. Based on this study, a functional unit of 23.5 kWh of NMC 111 battery is used with 41.52 kg of NMC 111 powder for a battery pack. With this, we can equate that 231.28 MJ of energy consumption per kg of cathode powder is equivalent to 113.5 Wh of electricity per 1 Wh of battery pack capacity. The co-precipitation process consumes about 46.97 MJ of heat energy to produce 1 kg of NMC111 powder whereas the calcination process consumes

52.23 MJ of electricity per 1 kg of NMC111 powder. However, in comparison with (Majeau-bettez, Hawkins and Strømman, 2011) co-precipitation doesn't incur any energy inputs while calcination process only consumed 0.55 MJ/kg of NMC111 powder. There are several reasons behind the energy difference. First, pilot scale plant by Majeau-Bettez et al. (2011) may not represent the actual industrial scale process. Second, industrial scale of production required multistage of calcination process rather than single-stage calcination used in pilot scale plant. Furthermore, waste treatment process is normally not considered in pilot scale plant but it's necessary for industrial scale plant to follow the rules and regulation set by government. In co-precipitation step, ammonia is being removed in the stripping tower from wastewater. This entire wastewater treatment consumed up to 45 % of the process heat demand. Besides, cathode powder production raw material cost about 50 % of the production cost while the utilities cost is nearly negligible. Due to the higher cost of raw material, producer would rather choose to maximize the usage of the material than improving energy efficiency.

Looking back into table 2.3, the material composition also accounts for 57% of the total energy consumption. Cobalt sulphate is the highest among material with 55.96 MJ/kg followed by nickel sulphate and sodium hydroxide. The energy consumption for different material composition will have slight difference as their proportion ratio for nickel, manganese, cobalt, and aluminium are different. For example, NCA cell has lowest energy usage, NMC811 has slightly higher energy consumption than the other NMC composition cells (Jinasena, Burheim and Strømman, 2021). Despite the total energy consume varies among each other, but the energy breakdown of each step is similar in proportion.

2.5.2 Energy consumption of cell manufacturing

Several literature reviews are studied to understand the difference among their analysis, and their assumption made. The full summarized energy consumption breakdown is listed in the. Sun et al. (2020) has retrieved and evaluate the primary data collected onsite from 2 leading LIB suppliers from China with annual capacity of about 30 GWh from 2017 to 2019. The cathode used for this study is NMC622. In this study, the major player that contribute to the highest

energy consumption is dry room (includes coating and drying process) consumed about 25.2 MJ of electricity and 17.0 MJ of steam equivalent to 7.0 Wh/Wh and 4.72 Wh/Wh. The total energy consumption including both electricity and steam energy is 28.4 Wh/Wh.

On the other side, Dai et al. (2019) uses primary data was from a leading LIB manufacturer from China in 2017 who was one of top automotive LIB suppliers as well. During the visit, they were told that electricity is mainly to power up total of 11 dehumidifiers and 4 industrial chillers while steam was used for dehumidification and drying purpose. The energy consumption by remaining equipment and process is negligible (Dai et al., 2019). Moreover, the manufacturer assumed that if the factory is operating at 75% of the capacity, the energy consumption for electrode drying is between 15.6 to 19.7 Wh/Wh and dry room is about 17.5 to 26.9 Wh/Wh of cell. Summing up the electricity needed to fully charge the battery at formation step took about 1.11Wh/Wh. Hence, Dai et al. (2019) estimate that the energy intensity for entire cell production step is 170 MJ/kWh which equivalent to 47.2 Wh/Wh with 30 MJ of electricity and 140 MJ of steam. Schunemann et al. (2015) had come up with a calculation model with energy consumption for LIB manufacturing process included with the annual capacity of 0.7 GWh. Based on the calculation model, coating and drying process and vacuum drying consumed the most electricity followed by dry room operation and stacking. The annual energy consumption is about 34.31 Wh/Wh of cell produced.

Table 2.4: Energy Consumption of battery manufacturing process by different authors.

	Sun et al. (2020)	Dai et. Al (2019)	Schunemann et al. (2015)	Yuan et al. (2017)	Pettinger and Dong et al. (2017)	Thomitzek et. Al (2019)	Asanthi et. al (2021)	Kurland et al. (2020)	Average %
Annual Capacity	Primary data from china factory (30GWh)	Primary data given (2GWh)	Calculation model (0.7Gwh)	Pilot scale (18.2MWh)	Production plant SOVEMA (76kWh)	Simulation based (48kWh)	Benchmark (2GWh)	Assumed electricity usage (35GWh)	
Cathode Chemistry	NMC 622	NMC 333	No data	LMO	No data	No data	No data	NCA	
Mixing	1.00		0.15	0.88	2.64	10.50	0.10	-	1.75%
Coating /	-	15.60-19.70	11.44	51.2	15.42	133.60	21.60	-	32.11%
Drying	-	-	0.15	3.04	5.97	20.70	0.002	-	2.76%
Calendaring	-	-	1.17	6.16	5.97	1.40	-	-	3.28%
Stacking	-	-	16.57	-	5.97	6.00	-	-	15.36%
vacuum drying	12.70	-	0.88	4.72	1.53	8.70	0.001	-	1.71%
drying	-	-	0.88	0.56	2.92	26.10	1.47	-	4.15%
filling	3.00	1.11							
formation									
Dry room	11.70*	17.50-26.90	2.56	31.20	-	448.70	21.31	-	34.64%
Other	-	-	-	-	5.56	88.90	-	-	3.43%
TOTAL	28.40	34.20 - 47.20	34.31	106.24	45.98	744.60	34.20 - 60.26	65.00	100.00%

Moving on, Yuan et al. (2017) has reported the manufacturing energy analysis of LMO-graphite LIB from real industries process annual capacity of 18.2 MWh pilot scale plant by Johnson Control. It was found out that coating and drying of cathode is the most energy intensive process followed by dry room operation which is 51.2 Wh/Wh of cell produced and 31.2 Wh/Wh respectively. This pilot scale plant has averagely higher energy consumption than other assumption available which is 106.24 Wh/Wh. Proceed to next, Pettinger and Dong et al. (2017), they have presented the data from the production plant by SOVEMA battery manufacturer with annual capacity of 76 MWh. The main energy intensive contributor is the coating and drying process whereas the remaining processes has the similar proportion of energy consumption to each other. This sums up to 45.98 Wh/Wh of cell of energy consumed yearly. The following assumption is the outlier among all with simulation-based model of 48 kWh annual capacity. Thomitzek et al. (2019) simulated the process and was found that the total energy consumption is 744.6 Wh/Wh with 295.9 Wh/Wh by process machining and 448.7 Wh/Wh by Technical Service Building (TBS) which is responsible for maintaining the factory building especially dry room condition control (Thomitzek et al. 2019)

In Jinasena et al. (2020) published paper, author has benchmarked the energy usage from several assumption studies available due to high variation on these studies available. The generalized process is chosen and selected by simplified several steps together. 2 GWh of capacity per year was used and has concluded with standard deviation of $(47.23 \pm 13.03 \text{ Wh/Wh})$. This benchmark model shown that coating/drying, formation and dry room is the most energy intensive process, which is similar to the available data mentioned above. Last, Kurland et al. (2020) has calculated the energy usage of Tesla Gigafactory in Nevada by calculating its assumed electricity usage. By using 6.8 U.S. cents per kWh of electricity in Nevada and assuming 1% of franchise fee. This equals to 65k Wh/Wh per cell produced (Davidsson Kurland, 2020) but however this paper doesn't include any calculation on particular steps in the LIB manufacturing.

Most of the literature studies were carried out in the early commercialization step where industry data is not fully disclosed. Moreover, some of the studies are based on approximations, theoretical calculation,

secondary data, or even model-based simulation. According to Dunn et al. (2015) as cited by Dai et al. (2019) mentioned that the earlier pioneer LIB manufacturer might not yet to fully discovered or implement any energy conservation technologies in and their annual capacity. The energy intensities measured from these LIB manufacturer facilities are said to be overestimates and doesn't reflect the existing commercial scale LIB facilities. For example, dry room are operating 24 hours a day for 365 days a year despite of the facilities operating capacity. In fact, the energy consumption of dry room for smaller scale LIB facilities are inefficient comparing to larger commercial scale LIB facilities as the same amount of energy intensity is being utilized by more cell at a time.

As of January 2021, there are about more than 600 GWh total annual production capacity are being announced by 24 different LIB manufacturer (Roland Zenn, 2021). For example, Tesla are to announce their Gruenheide, Berlin production line ramping up to 100 GWh, LG Chem currently has 15 GWh but ramping up to 65 GWh. Hence, measurement by pilot scale plant or low-capacity plant are not compatible with current LIB facilities energy consumption. In a nutshell, general trend of these data will be reduced as the annual capacity increases for reason that industrial scale plant is designed for optimized profit and energy with consideration of energy recovery and saving method. On the other hand, pilot scale plant is meant for research purpose where objective is to produce high quality of cell over energy consumption (Jinasena, Burheim and Strømman, 2021)

By looking at the general major proportion of energy intensive from all assumption made, it can be observed that coating/drying, vacuum drying, and dry room are the most energy intensive process. Calculation on the right has shown, averagely coating and drying process consumed about 32% of the entire cell manufacturing process, while vacuum drying about 15% and dry room is 34% of the overall process. All of them have the similarity of drying. In fact, parameters such as air flow rate, humidity, dew point and temperature of the dry air effect influence the energy intensity greater than the drying temperature and rate of drying (Jinasena, 2021). In coating and drying process, NMP solvent in cathode is the main reason of high energy and time demanding in this process (Liu et al., 2021). According to (Bryntesen et al., 2021), Lab scale electrode production uses one stage drying with no air-flow, while industrial scale of

drying uses continuous multistage web coating process. Based on this, it's obvious that lab scale consumed multiple times higher energy than industrial scale as one stage drying with no airflow doesn't promote forced convection which is less efficient for drying. (Bryntesen et al., 2021) has mentioned that removing the remaining 10% of the NMP solvent could take half of the total drying time due to limitations of mass transfer in the electrode porous structure.

On the contrary, vacuum drying as known as post drying in general has high energy intensity because cell will need to undergo extreme high temperature between 60 °C to 150 °C for about 12 to 30 hours to achieve lowest water content as possible. This drying process dried the initial non-post dried cell of 336 ppm to dried cell of about 136 ppm. (Ahmed, Nelson and Dees, 2016) stated there are several equipment are energy intensive, which is blowers and refrigeration, discharge air heating for zeolite wheel regeneration. Furthermore, process of heat removal and 3 cooling stations consumed high level of energy as well. Particularly in the dry room, the heat generated required energy as well as it need to ensure the inlet air temperature at 14 °C and outlet of air leaving dry room to be specified 25 °C. In general, the energy needs for a dry room operation dependent on the mass of air flows that need to be managed on top of the volume of dry room.

2.6 Greenhouse gases (GHG) emission of EV battery manufacturing process

In assessment of life cycle phase of the entire cradle to gate EV battery manufacturing process, it can be divided into 3 sections: Battery material production (including cell material production as well as battery components), battery production, and others. Others have included several factors which is amount of carbon dioxide equivalent release by transportation of battery, battery management system, battery module and pack production. In accordance, several literature reviews are studied to determine their source of data and figure. A summarized table are listed in the Table 2.4 below.

Table 2.5: General GHG emission data from different authors

Authors	Majeau-Bettez 2011	Ellingsten 2014	Dai 2019	Sun 2020	Kim 2016	Emilsson 2019 (IVL)	Shu 2021	Shu 2021	Hao 2017	Hao 2017
Battery production stages	NCM	NCM 26.6kWh	NCM	NCM	LMO + NCM	NCM	NCM	LFP	LFP	NCM
(Cell material + battery components)	143	65	51.53	105.47	28	59			103.80	99.90
Cell production	54	107	13.38	19.01	65		92.85	46.43	5.50	4.10
Others*	-	1	7.5	-	47	47	-	-	-	-
TOTAL	197	172	72.87	124.48	140	106	92.85	46.43	109.30	104

*Others included: Transportation + BMS + Thermal management + enclosure + pack manufacturing

First, Majeau-Bettez et al. (2011) has employed literature proxy values measured for small scale stationary battery manufacturing (Kim et al., 2016). According to (Ellingsen et al., 2014), Majeau-Bettez and colleagues based their energy data and statistics on industry reports from Hitachi Maxwell (2003, 2005), Saft (2008) and Rydh and Sanden (2005). Among all the literature review studied, Majeau-Bettez et al. (2011) has shown the highest amount of GHG emission. Top down approach applied by Majeau-Bettez et al. (2011) has inclusion of complete relevant activities but often clumped together consequently results in lacking of details, this could be the reason that the LCA has overestimated the GHG emissions data. (Aichberger and Jungmeier, 2020) mentioned that, in comparison with top-down approach and bottom-up approach, GHG emissions for top-down approach has a significant higher result even excluded the outlier values. The reason is because top-down approach starts with the energy intensity of the entire manufacturing facilities and allocate them to each of the production process and steps. In the contrary, bottom down approach relied on calculation and measurement of each industry process and combined them into total energy consumption (Aichberger and Jungmeier, 2020). With that said, bottom-up approach normally underestimates the energy intensity. Another reason for high GHG emission could be the assumption of polytetrafluoroethylene (PTFE) binder for anode which researchers said to generate high GWP and Ozone depletion potential (ODP) impact.

Next, Ellingsen et al. (2014) uses real world commercialized pilot scale production data (<1GWh annually) for cell manufacturing and battery design. It assumes that 100% of electricity is used from East Asian Mix with 46% of coal. Ellingsen et al. (2014) estimated about 172 kg CO₂-eq released per kWh cell produced for lower bound value (LBV), 240 kg CO₂-eq/kWh for asymptotic value (ASV) and 487 kg CO₂-eq/kWh for average value (AVV). However, Ellingsen et al. (2014) mentioned that LBV is more likely to reflect the large-scale production capacity of LIB production. Kim et al. (2016) said that the difference is significantly caused by big amount of non-cell battery material is used in the studies which is using real industrial battery design compared to literature review or software simulation by the other studies. It is about 30 % of difference between Ellingsen et al. (2014) and other studies.

In accordance with that, Kim et al. (2016) uses Ford Motor car battery with about 24 kWh capacity as the reference of studies in estimating the GHG emissions. The lithium-ion batteries are produced by LG chem in South Korea. The amount of GHG emitted by the assumption of Kim et al. (2016) 140 kg CO₂-eq/kWh. This amount of carbon dioxide equivalent is considerably high among the studies here. This author disclosed that as the data is retrieved from Ochang plant of LG chem in South Korea with approximately 3 to 4 GWh production capacity annually, the plant is underutilized. In fact, the manufacturer chooses to shut down some production line to save operational cost when the demand is low. Despite of the run down or throughput of production line, operation of dry room is inevitable. Hence, this could lead to overestimation of energy intensity as well as the consequent GHG emission values. With the fact that Ellingsen et al. (2014) has large amount of battery enclosure material, Kim et al. (2016) LCA has excluded these components from the studies which includes the GHG emissions from enclosure, electronic components, battery management system (BMS) and thermal management system.

As mentioned above, Dai et al. (2019) uses primary data was obtained in 2017 from a LIB manufacturer in China. Similarly, Dai et al. (2019) and Ellingsen et al. (2014) retrieved their source of data from publication's literature review and secondary LCI data which doesn't reflect the actual commercial scale LIB production. In contrast with Ellingsen et al. (2014), Dai et al. (2019) assume US electricity mix with about 32.7 % of coal. However, Dai et al. (2019) assume 18 % energy demand from electricity and 82 % of energy demand from heat generated by natural gas. This has lowered down the influence of electricity mix on GHG emissions later on. In Dai et al. (2019) studies, about 72.87 kg CO₂-eq/kWh of GHG is produced with NMC battery cell chemistries. The major contributor to this environmental burden is the production of NMC111 powder to the extent of 39.1 % of GHG emission.

On the other side, Emilsson et al. (2019) uses Dai et al. (2019) model and recalculate the model by changing the electricity grid. Two scenarios were listed as heat generated by electricity, renewable mix, fossil fuel rich mix, and heat generated by natural gas with boiler efficiency of 80 % calculated from

(EIA, 2016) cited by (Emilsson and Dahllöf, 2019). The initial scenario was chosen. The variation in GHG emission only affect the cell production, where the battery material upstream value remains 59 kg CO₂-eq/kWh. The calculated range for cell production is from 61 to 106 kg CO₂-eq/kWh. Emilsson et al. (2019) stated the reason for choosing top range is that fully automated production will be used instead of manual human labour, this will be added up to the electricity demand. While the reason for choosing lower range is that sources of heating can be renewable fuel and electricity grid varies from local to non-local sources. It's important to understand the system boundaries as it could potentially reduce the GHG emissions (Emilsson, 2019).

(Sun et al., 2020) has gotten their cradle-to-grave primary LCI data from 6 leading lithium-ion battery factories with market shares of about 75 % as of 2018 in China and another 5 materials manufacturers from 2017 to 2019. The inventory data is taken from GREET model which is used by Dai et al. (2019) as well. However, Sun et al. (2020) mentioned that Dai. et al. (2019) uses old fashioned technology in China while they are using the current latest technology behind the LIB manufacturer. This study has an average value among the studies available, which is 124.48 kg CO₂-eq/kWh. The material production stage has accounts the highest GHG emissions caused by the NMC622 cathode material production with about 105.47 kg CO₂-eq/kWh. Nonetheless, the GHG emission of battery usage on the road is not included as could incur a lot of uncertain parameters.

(Shu et al., 2021) uses SimaPro 9.0 simulation based to estimates both LFP and NMC batteries which is the most common used batteries in EV today. 28 kWh of cell capacity for both cell chemistries are used as reference with assumption that service life of EV is about 200,000 km. LCA is carried out by using software SimaPro 9.0 to assess the impact of two different chemistries cell. Results show that the total amount of GWP released for LFP is 46.43 kg CO₂-eq/kWh which is relatively low compared to NMC about 92.85 kg CO₂-eq/kWh. Each cell has different GWP due to the differences of cathode materials, production method and end of life recycling method. Finally, (Hao et al., 2017) adopts BatPac Model of Argonne National Laboratory of US but however the investigation is carried out of the EV market in mainland China. The analysed

GHG emissions of the entire cycle of LFP are provided by Lu Qiang from Jilin University. The major contributors of GHG emissions are the production of cathode materials and wrought aluminium. 103.8 kg CO₂-eq/kWh is being released by production of LFP cell material and components and 99.9 kg CO₂-eq/kWh for NMC cathode material production. It has accounts up to 95 % of the entire cradle to gate GHG emissions. According to Hao et al. (2017) in China average electrical structure contribute to higher GHG emissions and aluminium forging consumed significant amount of energy which results in high GHG emissions consequently. Moreover, the uncertainties came from different sources. For example, for this studies BatPac model is used which by default reflecting the condition and factors in US but is being used to simulate the composition in China. There will be a deviation between US condition and China.

Among the literature reviews available, combined battery production and material production has more available data in compared with emission data for each production stage or even each material and components (Aichberger et al., 2020). With the lack of detailed value and explanation from the sources, assumption is used instead leading to huge deviation in evaluation. Despite the limited data available per component or stages, Dai et al. (2019) and Sun et al. (2020) has the details emission for each component and stages for LIB manufacturing. Complete list of LCA model from cradle to gate for 1kg of NMC111 powder are shown in the Appendix A below. Based on those given values, we observed that CoSO₄, NiSO₄ and the two major process of co-precipitation and calcination accounts for higher GWP. The entire cathode powder manufacturing process emitted about 16.11 kg CO₂-eq per 1kg of NMC111 cathode material composition produced. The root cause of high GWP for the processes is the multi-stage calcination is needed for cathode material manufacturer instead of single-stage reported in studies of Majeau-Bettez et al. (2011) which have been mentioned above.

In the studies of Dai et al. (2019) and Sun et al. (2020), they have listed the detail breakdown of cell material production and battery component. In the Appendix C, NMC111 powder production and wrought aluminium are both the major contributor to GWP with about average of 50.67 % and 29.54 %

respectively. This is incompatible with what was mentioned in Shu et al. (2017) studies. Regardless of the total values of GHG emissions released, the percentage calculated are similar for both cases, but even so, the total GHG emission retrieved from Sun et al. (2020) is 105.36 kg CO₂-eq nearly double the emission data from Dai et al. (2019) is 51.53 kg CO₂-eq/kWh. The big variation can be explained by the scarcity of primary data. The estimation of GHG emission in the LIB manufacturing is the most difficult aspect of studies with the existence of uncertainties along with the advancement of technologies. Generally, electricity mixes vary from country to country. For example, European country and US has less fossil fuel shares in the electricity mixes while China has high coal shares in their grid. Hao et al. (2017) mentioned that this could be a reason of huge variation behind the studies.

2.7 Alternative solution for current EV manufacturing process

There are several alternative ways to replace the current manufacturing process steps in the production line. The alternative ways are believed to be able to reduce either in energy consumption, greenhouse gases emission or both. Some of the alternative solutions are yet to be applied on the current manufacturing technology of the LIB manufacturing process, but they have successfully proof of concept in the pilot scale plant or lab experimental scale. For example, in LIB manufacturing process, Maxwell dry cathode to replace the entire wet slurry coating and drying process, Argon purging process to replace the current vacuum drying right before the cell assembly process, heat pump for solvent recovery to reduce the energy consumed in recovering the solvent, water jet based direct recycling to replace hydrometallurgy of indirect recycling and etc.

2.7.1 Dry Cathode Technology

Dry cathode is a solventless dry battery electrode coating technology where it is meant to replace the current conventional wet slurry coating and drying process in the LIB production line. In 2019, Tesla has acquire Maxwell technologies company for 218 million USD. Tesla CEO Elon Musk said dry cathode technology could bring a “very big impact” to their batteries business (Fred Lambert, 2020). In the figure 2.5 below, the highlighted frame (blue) is

the process replaced by dry cathode technology. The coating technology and drying process is not needed anymore as dry powder coating is used for dry cathode coating. Furthermore, solventless dry cathode means it doesn't need solvent in the wet slurry anymore. Hence, the entire solvent refining process will be eliminated as well.

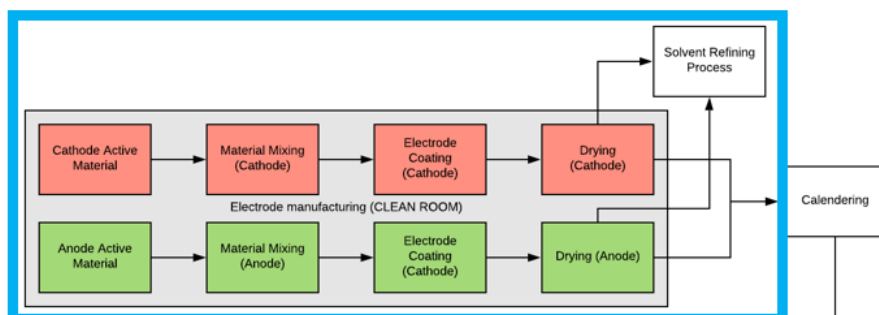


Figure 2.6: (Highlighted) frame were replaced by dry cathode coating technology.

From the start, dry powder (active material, conductive agent, binder) is mixed to come out with a final mixture of powder consisting active material needed for dry coating process. The powder mixture is then calendared to form a continuous dry cathode film in a rolled form.

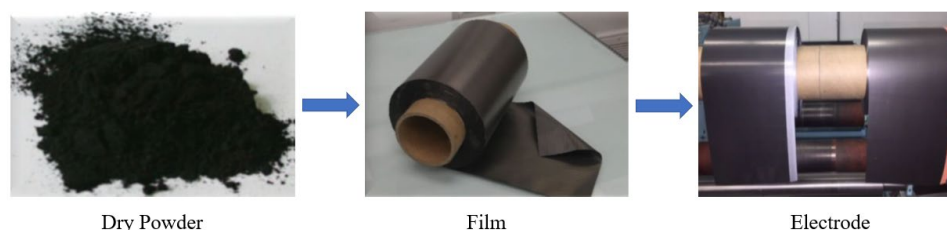


Figure 2.7: The formation of dry powder into electrode (Duong, Shin and Yudi, n.d.)

Once the dry cathode film is ready, it is then double sided laminated onto the current collector, and it will be vacuum dried at about 120 °C overnight to remove any residue moisture before being assembled into cell. In this solventless process, the polymer binder used in the dry powder will not dissolved results in the binding structure has better playroom for lithium ions to have better access to reach the active material particles. This has brought up the

advantages for high-rate performance in high energy density electrodes, and the comparison chart is shown in Figure 2.8 for both dry cathode and wet cathode with the same NMC 111 performance under low constant current discharge rate. The results are obvious that dry cathode delivered higher power and better capacity retention rate than wet cathode.

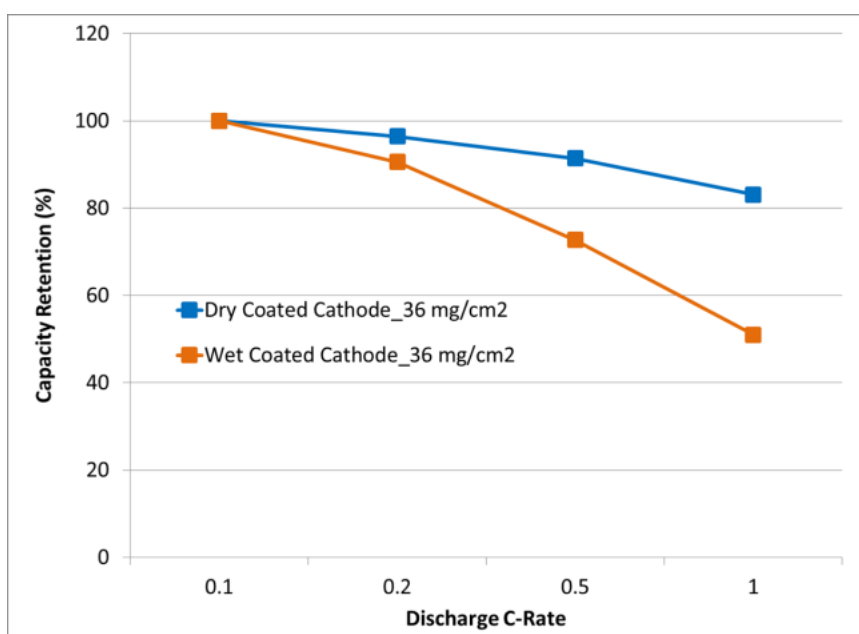


Figure 2.8: Discharge rate performance of dry cathode vs wet cathode (Duong, Shin and Yudi, n.d.)

In the recent published Tesla impact report 2020, the papers mentioned that the conventional wet cathode process required large ovens which are energy intensive. However, with the new dry cathode electrode, it has eliminated the process of drying with large energy intensive ovens results in reducing energy consumption overall. This could bring a total of at least 70 % energy reduction for cell manufacturing process based on Tesla analysis (Tesla, 2020).

2.7.2 Tesla closed loop heat pump for solvent refining

NMP solvent recovery process could be energy intensive based on some studies. Ahmed et al. (2016) estimated about 10 kWh of energy demand for producing 1 kg of NMP solvent. Yuan et al. (2017) on the other hand estimated about 8.5 kWh/kg of energy needed for industrial scale plant and 55 kWh/kg for pilot scale. Despite, Dai et al. (2019) stated that as the consideration of cost intensive

and environmental safety regulation, NMP is normally being recycled in the solvent recovery process where the recovered material are being reused back in the process results in minimal loss in terms of energy or material. In accordance with the energy intensive recovery process, Tesla has implemented their own patented heat pump system to reduce and minimize the total energy consumption.

This is a system where two fractional distillation process are in charged with 4 heat exchangers each at the bottom and top of the fractional distillation column. The distillation column is where the NMP is being recovered. The heat exchanger whereby is to provide thermal conditioning from the bottom inlet and heat being released on the top of the distillation column. There are two electric heaters as well working before the heat exchanger at the bottom of the fractional distillation column. In this case, this process could be energy intensive in the sense where the energy removal at the top is nearly about the same as what is being introduced at the bottom of column. The temperature is subject to the boiling point of the NMP (about 202 °C), thus it's relatively energy intensive process. Consequently, closed loop heat pump system has its advantages over here. Instead of the heat being released and rejected into the air and wasted, in close loop system, the air will be reused at the bottom of the fractional distillation column via compressor. This can significantly reduce the net heating load (Tesla, 2017).

2.7.3 Argon purging for vacuum drying

Vacuum drying has proven to be one of the major energy consumers. Vacuum drying also known as post drying process. This process is to remove the residual moisture to achieve better electrochemical properties as moisture will affect the performance of cell. Based on (Huttner, Haselrieder and Kwade, 2020), the cell with least moisture content doesn't necessarily mean that it has the better electrochemical performance. Authors compare among 3 other drying method (non- post dried, medium vacuum post-dried, and long vacuum post dried), the results were surprised. Even long vacuum has the lowest moisture content, but it has the worst electrochemistry performance. On the other hand, cell undergo

argon purging for 20 minutes at 20 °C shows the highest energy capacity for cycling and rate tests.

The authors stated that binder PVDF could be the possible influences. A thermally activated diffusion creep of PVDF binder could cause the carbon black particles rearrangement and led to carbon black binder network integrity damaged together with the electric percolation pathways. Argon purging method has great potential to substitutes the current vacuum drying technology by better throughput and lower energy consumption.

2.7.4 Laser drying for wet cathode

As described above, wet cathode slurry consists of active material powder, binders, solvents and conductive agents will need to undergo a long drying chamber oven for removal of moisture and residual to achieve a great electrochemical property. In fact, for a 52 Ah of cell needed about 32.5 kWh of energy to remove 709.8 g of NMP solvent through the chamber oven (Pflieger, 2017)

The laser drying works by emitting laser radiation onto the surface of current collector. The radiation emitted will be absorbed directly by the wet slurry coating on the current collector. This can greatly reduce the amount of radiation wasted in the conventional drying oven which means the heat losses is very small. The laser process can reduce the energy consumption by halved. In spite of the benefits, as the process being scaled up with higher output power lasers for industrial processes, further optimization will be required (Dominik Hawelka, no date; Vedder et al., 2019) . As mentioned above, drying of wet slurry could influence the film adhesion of the current collector. However, after a series of experiment and testing, Dominik (2015) have proven that comparing with the conventional chamber oven process, the film adhesion strength does not show significant difference.

2.7.5 Cotes' dry room technology.

Dry room is one of the major contributors to high energy consumption due to the electricity needed to maintain the humidity level of the room. With the conventional desiccant dry room, it consumed up to 34.64 % of the total energy

consumption to keep the dry room humidity under 1% and few points of -40 °C to -120 °C. Cotes has their patented Exergic technology which enable massive energy reductions up to 50 % and reduction of CO₂ emissions up to 95 %.

By using the Cotes Exergic Technology, it can utilize the sustainable energy sources with combination of different source like waste heat, biomass, solar thermal panels, CO₂ heat pump and so on. Cotes Exergic technology only require hot water at a temperature of about 80 °C to 90 °C. Because the energy used to heat the water can come from a variety of sustainable energy sources and can be changed in the future if energy prices change, the Cotes Exergic Technology is more sustainable and future-proof. This flexibility is not possible if the dehumidifier is specifically designed for gas regeneration. In fact, running optimal conditions at low temperatures (80 °C to 90 °C) allows the dehumidifier's electric booster to increase drying capacity as needed without jeopardising the system's effectiveness or safety. (Cotes, 2021)

2.8 Summary

In the detail review of studies, it was found that for the cell electrode material manufacturing, co-precipitation demands higher energy compared to the calcination process. Furthermore, in the cell production, dry room, drying of cathode and vacuum drying are found to be the most energy intensive process. Averagely, drying accounts for 32.11 % of energy demand, 15.36 % for vacuum drying and 34.64 % for dry room operation. On the other hand, among the majority of the papers reviewed, cell material production and battery component are the key element that generates the most GHG emission to the environment. However, 116.50 kg CO₂-eq/kWh is the average amount of GHG emission for the reviewed papers with the range from 46 kg CO₂-eq/kWh to 197 kg CO₂-eq/kWh. Alternative solution like heat pump system, dry cathode, argon purging, and laser drying can greatly reduce the energy consumption and emission of GHG in the manufacturing of LIB.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This section presents on the methodology used and steps taken to obtain the desired results to achieve the aim and objective of this research study. Compilation of data from literature review by other authors will be needed to be used as an input into the simulation software to obtain the results. In this research study, OpenLCA (Life Cycle Assessment) software will be used as the simulation software to simulate the actual world emission data with the given input data from the compiled data. The results obtained from the simulation software include Primary Energy Demand (PED), Global Warming Potential (GWP), Acidification potential (AP), Photochemical Ozone Creation Potential (POCP), Eutrophication (EP), and etc. But however, the model runs on data such as PED and other information such as water and chemical consumption. These data tied in with a material we put as input into the model, such as nickel input into the process. Once the results are obtained, substitution of data will be made on specific stages as an alternative solution and process to further optimize the LIB manufacturing stages to reduce the PED and GWP, but still able to maintain or achieve higher throughput of the entire manufacturing stage.

3.2 Project flow chart

A project flow chart and schedule plan were built to understand the big picture of the flow of progress and method. Initially, research topics are studied to understand and then literature review are written accordingly. After that, the energy consumption of each process and amount of material provided by the other author will be compiled with filter over the outlier and incompatible data. With the compiled data and Ecoinvent 3.8 inventory database, they will be inserted as the input values into OpenLCA software. After all the input values are completed, LCA studies will be carried out. Once the results are out, if the results were found to be non-logical and irrelevant compared with the collected literature review data, data optimization and substitution of data will be needed

and the steps of inputting values into LCA software will be repeated until a desire output is obtained. Last, the desire results will be analysed and discuss and will be written in the report.

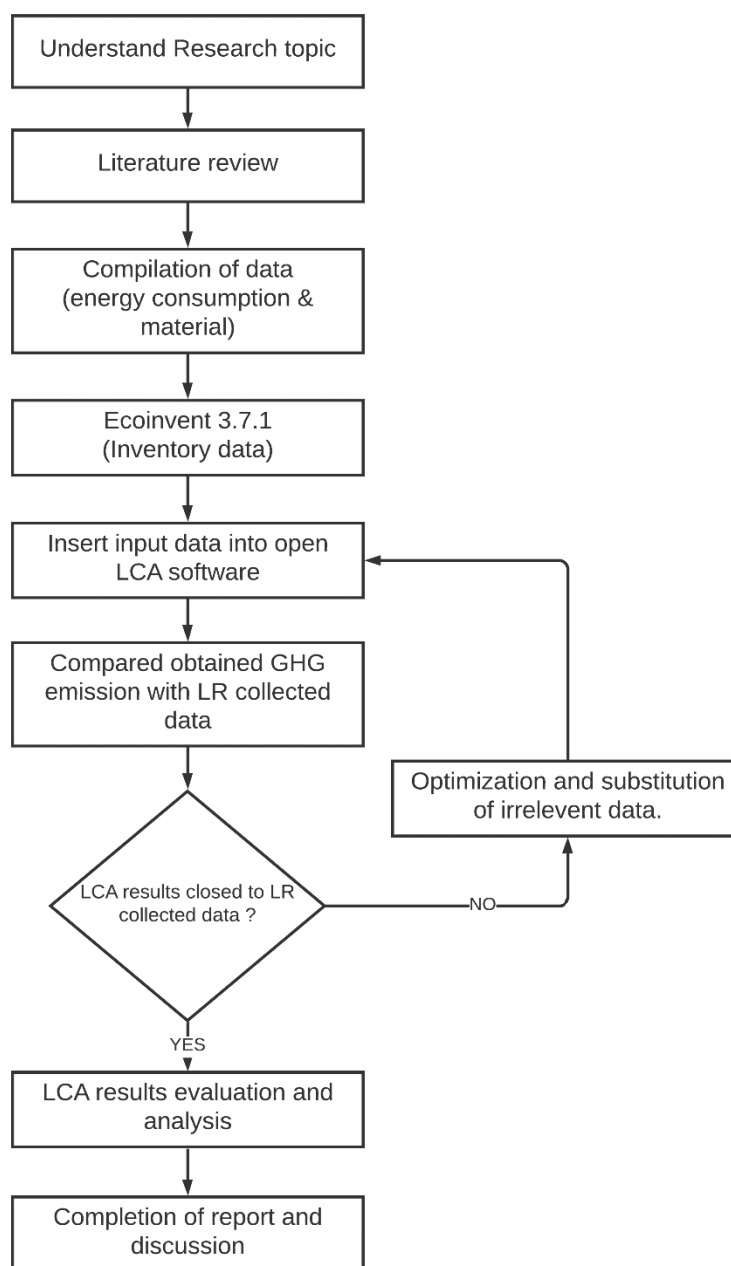


Figure 3.1: Project workflow and schedule.

3.3 Literature review and data collected from LR

Several literature review and collection of data was done earlier to be used as the input values for the simulation software. Despite that, the range of collected data are very huge. For energy consumption data, the lowest obtained data was

28.4 Wh/Wh of cell produced by Sun et al. (2020) while the largest data was from Thomitzek et al. (2019) with 744.6 Wh/Wh of cell produced. These collected energy consumption data will be used as the input into the LCA software together with the ECOINVENT 3.8 inventory data. Besides, the GHG emission data range was relatively small. Lowest emission data from Shu et al. (2021) with 46.43 kg CO₂-eq/kWh and largest emission of GHG was Majeau-Bettez et al. (2011) research paper. These collected GHG emission data will be later compare with the obtained LCA results. The huge variation in data led by various factor. (E.g., cell chemistry material used in the study, technology used, types of approach, source of data and even the year of approach). Hence, in this research study, we going to filter out the outlier and incompatible data that are no longer on par with the current state of LIB manufacturing facilities and technologies.

3.4 System boundaries and life cycle inventory input.

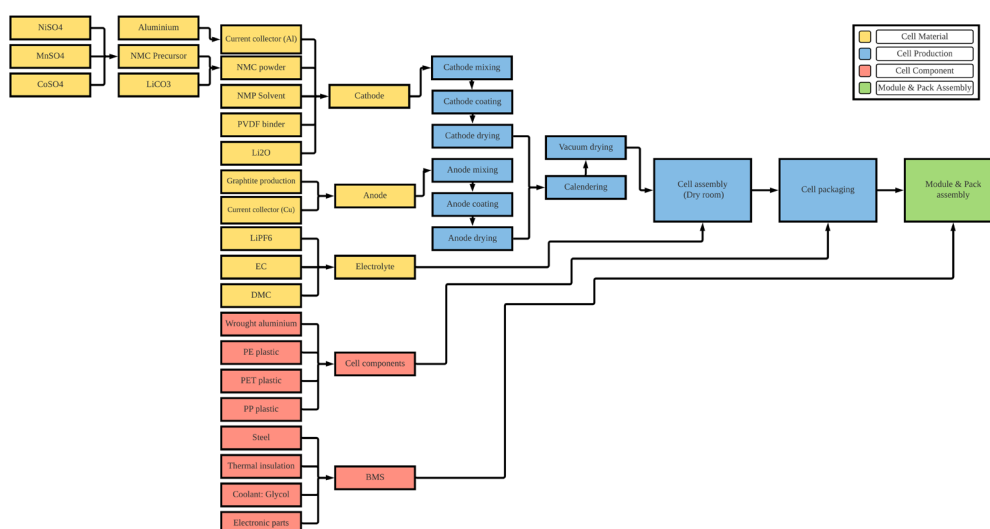


Figure 3.2: System boundaries

In these studies, data collected from the studied literature review will be used from cradle to gate. This system boundaries can be separated into 4 main sections of cell material, cell production, cell components and module and pack assembly. Cell material starts from upstream data from production of NMC precursor to the production of cathode and anode slurry. Besides, cell

production starts from coating of the cathode and anode to the extent of cell packaging which includes formation and end of life testing. However, the steps of cell assembly and cell packaging are not listed out in details as they are not significant contributor to the energy demand and emission data. Even though the steps are not listed in the figure, but the consumption data will be extracted and input into the LCA software.

Furthermore, cell components including the components used for manufacturing of cell casing components and battery management system. Cell components will be connected to cell assembly while battery management system will be connected to module and pack assembly in the system boundaries. Forth, module and pack assembly. This is the process where produced cell is being align and connected into a module and finally the module will be assembled into battery pack. This final stage will include the assembly of battery management system. This pack and module assembly steps are assumed to be manual process where are not associated with any energy demand or emission of GHG (Dai et al., 2019). On the other side, Ellingsen et al. (2019) and Kim et al. (2016) disclosed that this process's energy demand and emission of GHG to be minimal.

By building several models of LCA, we can analyse that which model or which factors contribute highest to the environmental impact. With this, we can clearly make some optimization on the major contributor to energy demand and environmental impact. For example, different country's electricity grid will be used in different model as every country has different electricity mix. In fact, China electricity grid will be examining first as most of the literature review data are taken from China electricity grid, hence the results of our LCA studies will be much accurate to the actual case. Besides, NMC battery chemistries will be used as the first base model among NCA, LFP and LMP battery chemistries as most of the data retrieved from the literature review studies are using NMC battery chemistries and NMC is the most widely adopted battery chemistries in the industries. NCA, LFP and LMP battery chemistries with different chemical composition will be examine as well to be compare with LCA results of NMC battery chemistries. Furthermore, Class I and Class II nickel will be examined and compare among the end results. Class I nickel believed to be less energy

intensive and less environmental impact especially in its upstream process due to its cleanliness and composition of compound. Finally, Alternative solution will be inserted into the LCA model to examine the impact or improvement brought up by the alternative method of equipment. The alternative solution is expected to be less energy demand from the manufacturing process and producing less environmental issues. Below Table 3.1 are the list of different models of LCA to be prepared for LCA simulation.

Table 3.1: Different model of LCA to be conducted

Electricity grid	Battery chemistries	Class of Nickel	Alternative Solution
China	NCA	Class I nickel	Tesla heat pump
US	NMC	Class II nickel	Dry Cathode
Europe			Cotes dry room technology

After obtaining the LCA results, LCA results will be analysed such as Primary Energy Demand (PED), Global Warming Potential (GWP), Acidification potential (AP), Ozone Formation (NO_x), Primary Energy Demand refers to the measures of total energy required by the lithium-ion battery manufacturing process. It covers the energy consumption, energy losses and distribution of energy in the process. Global Warming potential rely on one two factors: how effective is the gases in atmosphere at trapping heat, and the duration of gases staying in the atmosphere before it breaks down. The higher the GWP values, it equals to higher amount of carbon dioxide equivalent in the atmosphere. Acidification potential refers to the specific chemical compound that has the elements to produce acid rain. For example, sulphur dioxide, nitrogen oxide, nitrogen monoxide and other compounds. All these indicators will be analysed with proper consideration that are influencing to reduce the impact to the environment.

3.5 Construction of model in OpenLCA

In the entire life cycle analysis, ReCiPe Midpoint (H) is chosen as the impact methodology to generate the results for Global Warming Potential, Acidification and Ozone Formation and so on. While Cumulative Energy Demand is chosen for generating Primary Energy Demand which consists of both renewable and non-renewable category. Renewable energy is breakdown into wind, solar, geothermal, biomass and water, while non-renewable are break down into fossil, nuclear and biomass. However, to generate the results of LCA, functional units is important to ensure the comparative analysis is fair and comparable. With that, Dai et al. (2019) was taken as the reference functional unit to compare with. According to Dai et al. (2019) report, their EV Lithium-ion battery has gross pack energy of 23.5 kWh, weighs 165 kg which equivalent to 0.143 kWh/kg of battery pack. In order to standardize over all the LCA results. 7 kg of functional units is used which equals to 1 kWh of battery pack for easier comparison. In addition, to standardize across all the results simulate using OpenLCA, ECOINVENT 3.8 cut off database is used.

First of all, database will be key in the inputs and outputs tab shown in the following Figure 3.3. Then, provider will have to choose based on their respectively upstream. For example, for “electricity, high voltage”, its provider can be chosen from different source of electricity production such as coal, natural gas, hydroelectric, wind and etc. To standardize among all the scenarios, “electricity, high voltage” is chosen since lithium-ion battery factory typically consumes the high voltages, hence low voltage electricity source is not suitable in this scenario. Besides, the amount for each of the flow is set per kg of battery cell. For example, 0.2 kg of anode graphite material per 1 kg of battery cell means that to produce 1 kg of battery cell, 0.2 kg of anode graphite material is needed to complete the production. In this LCA, the transportation of the material is included in the simulation. Transportation is considered as one of the minor contributor to the high emission as vehicle and lorry used emits carbon monoxide to the surrounding too. In the provider tab in the software, “Market for anode graphite...” is chosen in the provider when transportation is included

in the model calculation, whereas “Production of anode graphite...” is chosen when the transportation process is excluded.

Inputs/Outputs: 1. battery cell production, Li-ion, NMC111 | battery cell, Li-ion, NMC111 | Cutoff, U (Renewable)

Inputs						
Flow	Category	Amount	Unit	Provider	Data	
Fe aluminium collector foil, for Li...	279:Manufacture of oth...	0.03000	kg	P market for aluminium collector foil, for Li-ion battery aluminium colle...	(3; 4;	
Fe aluminium, wrought alloy	242:Manufacture of bas...	0.02830	kg	P market for aluminium, wrought alloy aluminium, wrought alloy Cutoff...	(3; 4;	
Fe anode, graphite, for Li-ion bat...	272:Manufacture of bat...	0.20000	kg	P market for anode, graphite, for Li-ion battery anode, graphite, for Li-io...	(2; 4;	
Fe battery separator	272:Manufacture of bat...	0.02000	kg	P market for battery separator battery separator Cutoff, U - GLO	(2; 4;	
Fe cathode, NMC111, for Li-ion b...	272:Manufacture of bat...	0.41000	kg	P market for cathode, NMC111, for Li-ion battery cathode, NMC111, for ...	(3; 4;	
Fe chemical factory, organics	429:Construction of ot...	4.00000E-10	Item(s)	P market for chemical factory, organics chemical factory, organics Cuto...	(4; 5;	
Fe copper collector foil, for Li-ion...	279:Manufacture of oth...	0.12000	kg	P market for copper collector foil, for Li-ion battery copper collector foil, ...	(2; 4;	
Fe copper, anode	242:Manufacture of bas...	0.03350	kg	P market for copper, anode copper, anode Cutoff, U - GLO	(3; 4;	
Fe electricity, high voltage	351:Electric power gene...	0.09800	kWh	P electricity production, wind, >3MW turbine, onshore electricity, high v...		
Fe electricity, high voltage	351:Electric power gene...	0.00000	kWh	P electricity production, natural gas, conventional power plant electricity...		
Fe electricity, high voltage	351:Electric power gene...	0.08200	kWh	P electricity production, hydro, run-of-river electricity, high voltage Cut...		
Fe electricity, high voltage	351:Electric power gene...	0.00700	kWh	P electricity production, deep geothermal electricity, high voltage Cutoff...		
Fe electricity, high voltage	351:Electric power gene...	0.00000	kWh	P electricity production, hard coal electricity, high voltage Cutoff, U - C...		
Fe electricity, high voltage	351:Electric power gene...	1.00100	kWh	P electricity production, solar thermal parabolic trough, 50 MW electricit...		

Outputs									
Flow	Category	Amount	Unit	Costs/Rev...	Uncertainty	Avoided p...	Provider	Data qual...	Descripti...
Fe battery cell, Li-ion, NMC111	272:Manufacture of b...	1.00000	kg	14.55239 ...	none				

General information | Inputs/Outputs | Administrative information | Modeling and validation | Parameters | Allocation | Social aspects | Impact analysis

Figure 3.3: Input and output editing page on OpenLCA

After inserting all the necessity input, then key in the correct functional unit in the target amount section which is 7 kg for 1 kWh of cell. Next, ReCiPe 2016 Midpoint (H) and Cumulative Energy Demand is chosen as the impact assessment method. ReCiPe (as chosen as well by Dai et al., 2019) is used as the reference value, since it is preferred to use back the same impact assessment method to standardise the comparison. In short, the calculation type will choose quick results for fast analysis and results while Analysis calculation type will show the detailed breakdown of the process, but it takes longer time for calculation.

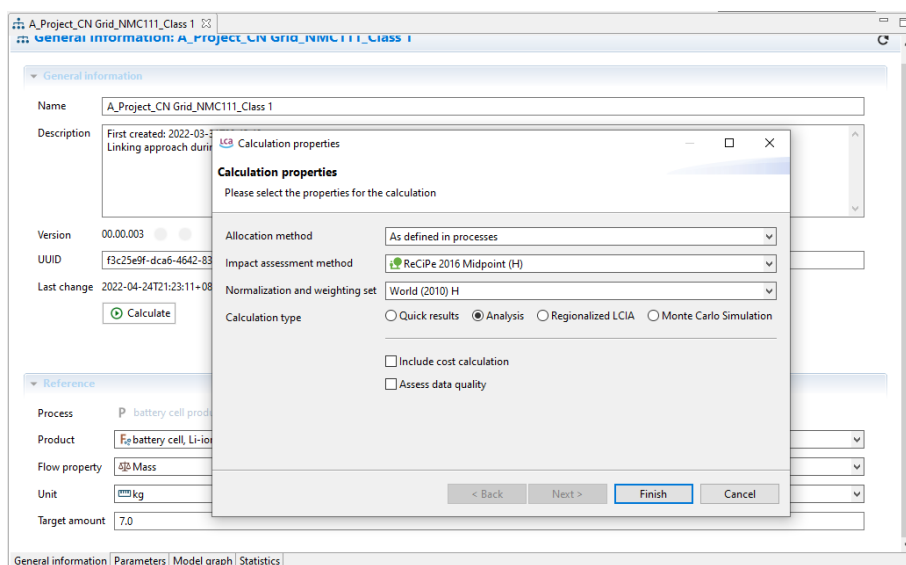


Figure 3.4: Choosing Impact assessment method after complete input database

Below Figure 3.5 is the model graph of partial of the cell production. In this tab, the graph can be expanded or collapsed to see the overall view of cell production input and output. In this tab, what we chose in the provider tab in the first step (Figure 3.3) will be shown here as the upstream linkage tree. For example, the upstream process of cathode production is market for NMC111 oxide production. Initially when we chose the provider, we will have to choose “market for NMC111 oxide” so that it will reflect the option we chose in the model graph below. In this section, if the graph was completely expanded, we can see the entire cell production line with bird’s eye view from the mining of material to the transportation, and finally production of lithium-ion battery using the material. Hence, an accurate selection of provider is important as provider could affect every single process before the selected process.

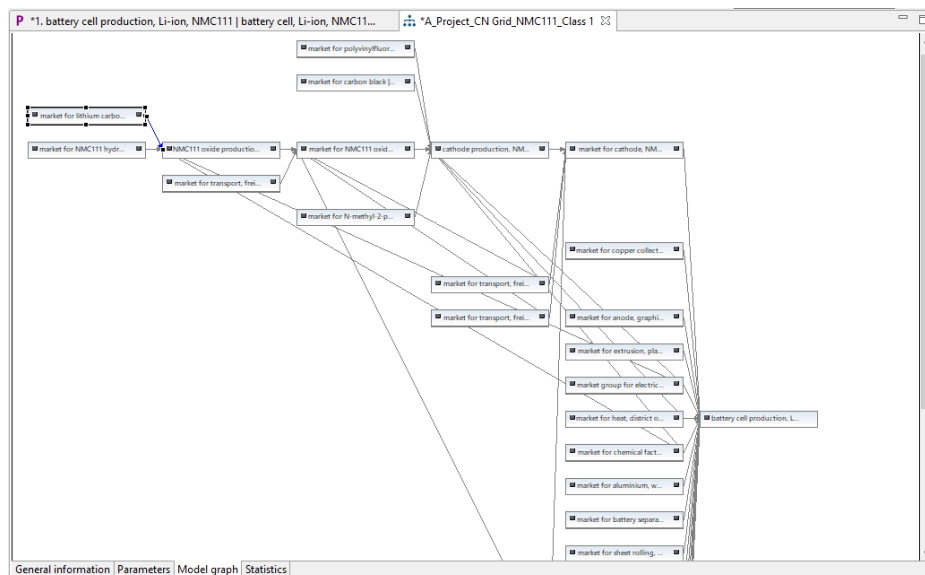


Figure 3.5: Model graph breakdown of the entire cell production

Finally, after calculating the LCA model, the results will be shown in the impact analysis tab with full list of impact category. In fact, the results can be broken down even further by choosing analysis option as shown in Figure 3.3 (the results will be shown as in Figure 4.1 where it shows every single process impact to the environment). With that, we can determine and analyse from that to understand which process has the higher impact and which process is insignificant here. In here, all the important impact category are given for example Global Warming Potential, Ozone Formation and Acidification. While for energy consumption, a different impact assessment is needed to evaluate which is Cumulative Energy Demand which is to switch the impact assessment method as shown in Figure 3.4.

Impact analysis: ReCiPe 2016 Midpoint (H)

Subgroup by processes Don't show < 1 %

Name	Category	Inventory result	Impact factor	Impact result	Unit
> Fossil resource scarcity				34.57589	kg oil...
> Stratospheric ozone depletion				7.28195E-5	kg CF...
> Global warming				123.09675	kg C...
> Fine particulate matter formation				0.45391	kg P...
> Human carcinogenic toxicity				13.13995	kg 1,...
> Freshwater ecotoxicity				51.28584	kg 1,...
> Water consumption				9.94857	m ³
> Ozone formation, Human health				0.37196	kg N...
> Ozone formation, Terrestrial ecosystems				0.37784	kg N...
> Mineral resource scarcity				18.28417	kg C...
> Marine ecotoxicity				66.57292	kg 1,...
> Human non-carcinogenic toxicity				928.74619	kg 1,...
> Freshwater eutrophication				0.08352	kg P eq
> Ionizing radiation				15.65331	kBq ...
> Marine eutrophication				0.01881	kg N ...
> Land use				0.01967	m ² a ...
> Terrestrial acidification				1.30484	kg S...
> Terrestrial ecotoxicity				6404.25272	kg 1,...

General information | Inventory results | Impact analysis | Normalization and weighting | Locations | Grouping | LCIA Checks

Figure 3.6: Results tab showing different category of impact analysis

3.6 Summary

After compilation and filtration of the data collected from literature review, the compiled energy consumption data and uses of ECOINVENT 3.8 inventory database will be needed. In the building of model in the LCA software, the data will be inserted into the built model for simulation. The output emission data will be obtained after the LCA simulation process. The obtained data will then be analysed and optimization to further improve the entire battery manufacturing process.

CHAPTER 4

RESULTS & DISCUSSION

4.1 Breakdown analysis of cell production.

For the following model will be constructed based on battery type NMC111 as NMC111 is being widely by most of the car manufacturer as of global sales 2020 to 2021 May which the sales amount is shown in the Table 2.1 above. After conducting LCA of class 1 nickel NMC111 battery type with China electricity grid, the breakdown analysis of every upstream process is generated as shown in the Figure 4.1 below.

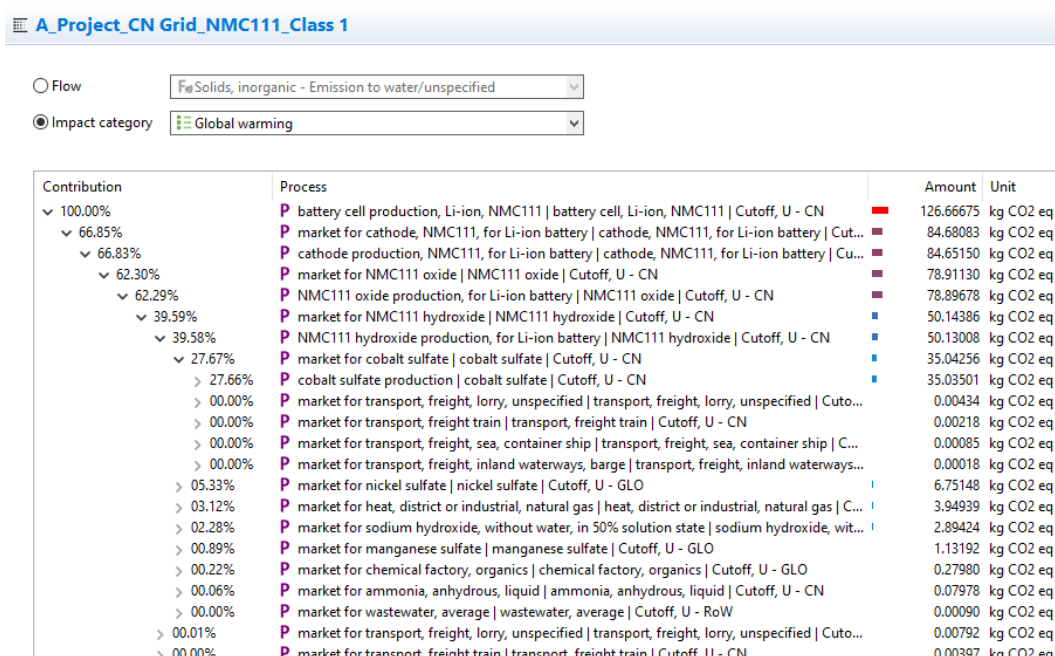


Figure 4.1: Breakdown analysis of NMC111 cell production.

Table 4.1: Breakdown analysis of the NMC111 battery cell production based on greenhouse gas emissions

	Process	Percentage	GWP (kg CO₂-eq)
1	NMC111 battery cell production	100%	126.67
2	Cathode production	66.85%	84.68
3	NMC111 oxide production	62.30%	78.91
4	NMC111 hydroxide production	39.59%	50.14
5	Cobalt Sulphate production	27.66%	35.04
6	Anode production (Graphite)	6.94%	8.79
7	Nickel Sulphate production	5.33%	6.75

In fact, for the production of battery cell, it starts from upstream mining of nickel ore and ends with the production of Li-ion battery cells. This includes all the battery cell components and the materials for additional components like (external case, tabs, etc.). The chosen impact category is global warming potential with the unit of kg CO₂-eq. For every amount emitted as shown is per 7kg of battery cell which equivalent to 1kWh of battery cell as well. According to the generated results, the total amount of global warming potential emission is 126.67 kg CO₂ equivalent. For every emission of the particular process included each indirect downstream process from the ore. Hence, the amount shown is the accumulation since the upstream process. Cathode production is 66.85% with cumulative amount of 84.68 kg CO₂-eq. In this process, Li-NMC oxide is mixed with carbon black, PVDF in ratio while NMP is used to prepare cathode slurry. The input materials are mixed to form a slurry, then the mixture is dried with the solvent evaporating away, cut and calendared to form the cathode of a Li-ion battery. The energy required to coat the aluminium conductor foil with the cathode slurry is included in this dataset, because it was not possible to separate it from the energy required for the drying step. Next is the NMC111 oxide production has 62.30% with GWP of 78.91 kg CO₂-eq. This process also known as NMC111 powder production where NMC111 precursor (NMC111 hydroxide) and lithium carbonate are mixed and heated in the

calcination kiln for two rounds. The production process is completely automated and almost all electricity consumption is attributed to calcination kiln (Dai., 2019).

The upstream process for NMC111 oxide production is NMC111 hydroxide production which attributed 39.59% which equivalent to 50.14 kg CO₂-eq. This process starts with mixing of NiSO₄, MnSO₄ and CoSO₄ with addition of sodium hydroxide (NaOH) and ammonium hydroxide (NH₄OH) and finally produced NMC111 hydroxide (NMC(OH)₂) through co-precipitation of nickel sulphate (NiSO₄) (Dai., 2019). In order to produce NMC111 hydroxide, nickel sulphate and cobalt sulphate both are important elements. However, based on the obtained results, cobalt sulphate has much higher emission portion compared to nickel sulphate which is 35.04 kg CO₂-eq and 6.75 kg CO₂-eq respectively. This is compatible with the results generate by Dai. et al. (2019). In the supplementary data, it shows that with cobalt sulphate release about two times more than nickel sulphate per 1 kg of NMC 111 powder. With these results are generated by NMC111 cell production with 1:1:1 ratio of nickel sulphate, cobalt sulphate and manganese sulphate. However, there are still a lot more production of NMC 811 with ratio of 8:1:1 of nickel sulphate to the other two sulphate compound or NMC 622. In a whole, emission of nickel is still an worrying issue to the environment regardless of high emission of cobalt as well.

4.1.1 Cobalt sulphate and its impact to the environment

According to Adamas Intelligence (2021), total battery capacity deployed on roads has total combined amount of 108GWh which is 157% more than previous year 2020. Furthermore, one of the major cell suppliers CATL has deployed 253% of more watt-hours of battery capacity on roads with 238% increase in use of lithium, 185% increase in nickel and 170% increase in cobalt deployed onto roads over the same period. In overall, 58,900 tonnes of nickel were deployed onto roads in 2021 H1 followed by 12,600 tonnes of cobalt were deployed on roads. Leaving aside of the impact of nickel application in battery cell, cobalt also considered to become one of the major issues to the environment and even to the extent of human rights.

Cobalt is considered as one of the highest material supply chain risks to the electric vehicle industries in short and medium term. One EV lithium-ion battery could have up to 40 kg of cobalt in each 100 kWh of battery pack. Also, 50% of the world's cobalt reserve are in Democratic Republic of Congo where potential for political instability and high disruption. Currently, Congo has produced more than 70% of the world's cobalt itself, but however there are some artisanal some cobalt production poses major reputational risk due to exploitation of human rights, and use of child labour (Desai P., 2022)

In short, the relationship between the miners and the mine is like slave and masters (Pattison P., 2021) The miners receive extremely low basic wage with possibilities of wages deduction, they have no ways to voice out or argue, else will be fired with leave them with no better choice but to continue to sacrifice their life for these. The environment is so harsh and dangerous in those DRC's informal, or artisanal cobalt mines. To the extent, some child labour and miners are being buried alive as tunnels cave in. This has finally provoked an international outcry in the recent years. Some corporations in the cobalt supply chain have pledged to discontinue sourcing the mineral from artisanal mines but instead get them from large-scale industrial mines, which are considered as a safer alternative for both workers and corporate reputations. Even though some battery and car manufacturers have reduced the amount of cobalt in their batteries, BMI predicts that cobalt sales into the sector will increase 4 to 5 times over the next decade. According to the World Bank, demand for cobalt production will increase 585% by 2050. Pattison P. (2021).

4.2 Comparison of electricity grid from different country.

By comparing among the countries with one of the largest production volumes of lithium-ion battery. These are the breakdown of electricity production by source by China, Europe, and United States as of 2020 shown in the Figure 4.2.

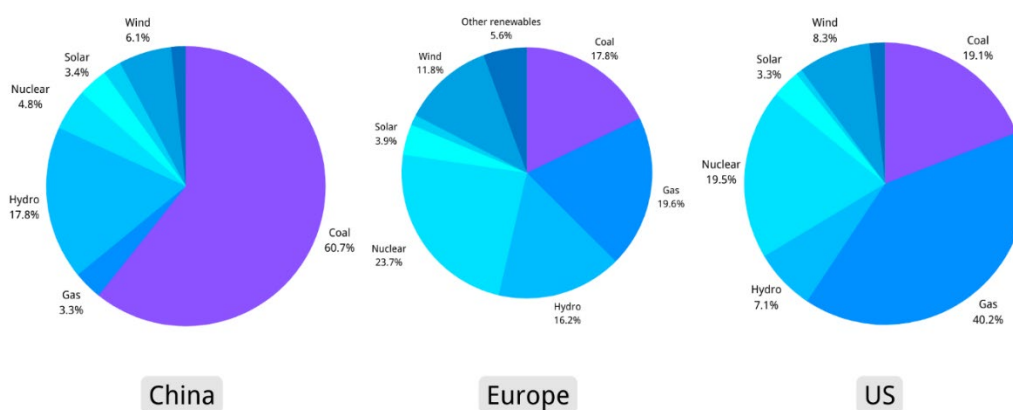


Figure 4.2: Electricity grid breakdown by countries.

Specifically for China, Most of their electricity generation are from coal with attributed to be the highest among all categories as well as the highest among both the other two countries. It's about 60.7 % which equivalent to 4631.22 terrawatt-hour of electricity production using coal followed by hydropower of 17.78 % and the other remaining source like nuclear, windpower, solar and so on. The total amount of China electricity production by the year of 2020 has reach 7623.7 TWh. Moving on next, Europe electricity grid mix has much evenly distributed source from all aspect. For Europe, the highest percentage of source is from nuclear energy which covered up 23.71 % of entire europe electricity production followed by gas with 19.61 %, coal 17.84 %, hydropower of 16.15 % and so on. Generation of electricity by using oil is shown to be the least for all three countries. On the other side, United State uses gas power to generate their electricity with up to 40.23 % of the entire production. This has followed by nuclear and coal with similar percentage of 19 %. However, the dominant source of production was the same until 2016. Since 1985 years, the dominant was coal that generate the most electricity for the countries, but until 2010 onwards the amount of electricity generated by coal has been dropping and finally in 2016, the amount of electricity generated by gas has exceed the amount of electricity generated by coal and gas became the dominant source of production for united state possibly due to policy changed to protect against the deteriorating mother earth as coal is one of the major pollution factors to the enviroment.

There are several assumption are to be made due to limitation of studies as well as insufficient data. For the input of the process, the origin of nickel ore are assumed to transported from Indonesia to respective countries. But however, production of nickel class 1 are made by different country, hence, the electricity input provider is chosen based on the country grid. After conducting the LCA, several important impact categories are retrieved from the results like Global Warming Potential (GWP) and Primary Energy Demand (PED) together with the Acidification and Ozone Formation.

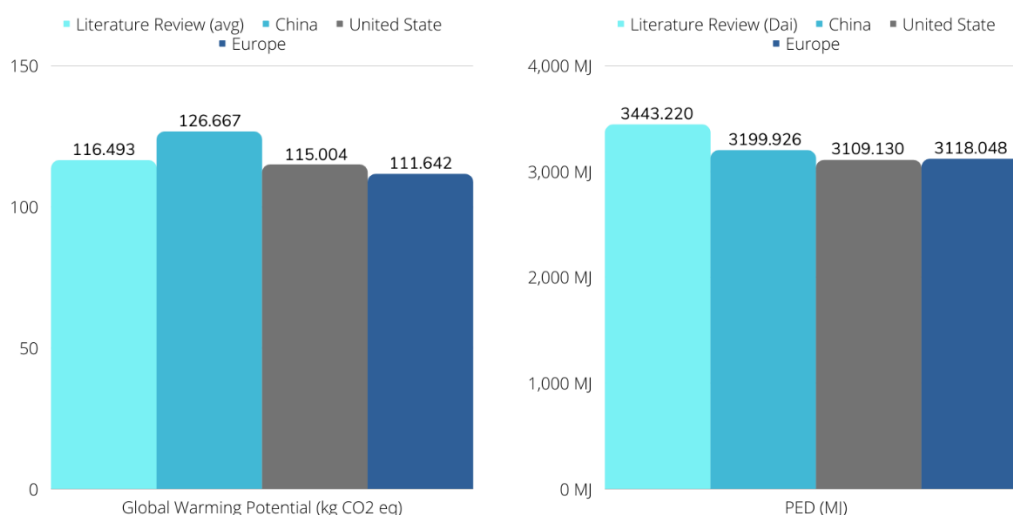


Figure 4.3: Comparison of LCA results by country based on LCA conducted on NMC111 battery production

Based on the given results, it can be observed obviously that China has the highest global warming potential indicator which is 126.67 kg CO₂-eq compared to United State and Europe production of lithium-ion battery cell with 115 kg CO₂-eq and 111.64 kg CO₂-eq. This can be explained by their electricity grid mix as shown above in the comparison Figure 4.3. China major source of electricity is from burning of coal. Practically, coal power plant generate steam by burning coal mined from the earth. The steam is forced through a turbine at an extreme high pressure where the turbines are linked to generator to generate electricity at high speed. A single coal power plant can generate enough electricity to power up 70,000 homes. Coal fired power plants and coal mines pollutes the air mainly due to emissions of methane (CH₄), Sulphur dioxide (SO₂), nitrogen oxides (NO_x), as well as the carbon monoxide (CO).

According to "Coal and Air Pollution" (2017), averagely a typical coal plant of about 500 MW generates 3.7 million tons of carbon dioxide. This amount equivalent to chopping down 161 million of trees. In short, carbon dioxide pollution is the principal human cause of climate change and global warming. Thus, since China has more than 60% of their electricity generated by coal plant, naturally it will have the highest emission of carbon dioxide equivalent gas. However, United State has slightly higher emission than Europe possibly due to their high proportion of electricity production by natural gas and coal. Based on the article "Natural Gas vs Coal – Environmental Impacts" (2020) U.S Energy Information Administration mentioned that natural gas emits almost 50 % less carbon dioxide than coal production. Even though natural gas emits less than burning coal, but it has a bigger methane emission where it leaks to the atmosphere during extraction of natural gas. On the other side, Europe has lesser portion of fossil fuel but instead has more proportion for renewable energy like nuclear, hydropower and wind.

Moving on to Primary Energy Demand, the simulated results by OpenLCA has shown a very similar results for different country grid. The different country grid has different PED possibly due to the use of machinery, production planning, processes, technologies used, energy saving method and etc. By taking Dai et al. (2019) results as the reference PED value since their functional units and assumption are the nearest to our model. For entire cell production, Dai et al. (2019) reported that 40.7 kWh of PED is consumed per kWh of cell produced. By using the same functional unit of 23.5 Wh per pack, the PED is converted in units of megajoule which equals to 3443.22 MJ. The value is very similar to the results generated in OpenLCA which is 3199.93 MJ. The difference in value could because of different assumption made, slightly different in functional unit as well as the input into LCA software.

4.3 Comparison of type of battery chemistry.

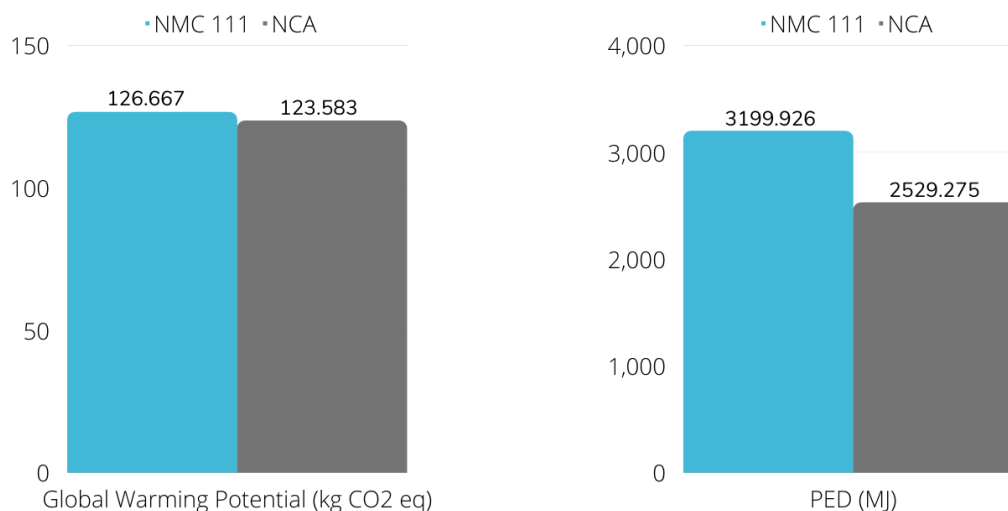


Figure 4.4: Comparison of LCA results by type of battery chemistry

Regarding the comparison between different type of battery chemistry, electricity grid has standardized by using China electricity grid since China is one of the major suppliers of NMC111. First, from the result shows that the production of NMC111 cell type generates more carbon dioxide equivalent than the production of NCA cell type. The extra 3 kg of carbon dioxide equivalent can be explained by the chemistry composition of NMC 111 and NCA. For the same weight of a cell, has lesser portion of nickel compared to NCA due to their ratio for nickel NMC111 is made up of only about 30 % of nickel in their composition where (Porzio et al., 2021) stated there is only 0.197 % mass of cathode active material are contributed by nickel while for NCA, nickel has account for 0.489% mass of cathode active material due to its large proportion of nickel content which has 80% of nickel. In fact, nickel is the major contributor to carbon dioxide emission and air pollution. Looking into acidification impact, NCA release more than doubled of the acidification amount.

Tracking back to the cause of acidification, burning of fossil fuel that cause emission of carbon dioxide is one of the main sources of acidification. With higher ratio of nickel content in NCA cell compared to NMC111, the production of NCA cell and every involved upstream process will generate

much more carbon dioxide to the environment as more nickel is needed to produce same amount of battery capacity. Next, Primary Energy Demand. There is almost 600 MJ in difference for NCA and NMC111 cell produced. There are several reasons for the difference in value. First, the manufacturing process of battery cell including every upstream process. With nickel rich NCA, it might need higher energy demand to produce the same battery cell, but this is will still depends on which source of nickel is being used for the battery production line. Moreover, by focusing on only the battery chemistry itself, different chemical composition of battery cell will have different physical and chemical properties. The difference in physical and chemical properties will directly impact the process in terms of mixing and drying process and timing. With different processes, it will need different machinery to meet the requirement, hence there will be difference in energy demand regardless it's electricity energy, heat energy or others. Factory scale is one of the major reasons as well. Different scale of factory caters for different annual capacity of cell. Hence, with different scale of factory, machinery choice is different as well. With higher production capacity factory normally are equipped with higher efficiency machine with lesser wastage of energy and material. Hence, larger scale factory generally has lesser energy demand with initial condition of same measures of functional units.

4.4 Comparison of Class 1 nickel and Nickel Pig Iron.

The following LCA model is built using the production of class 1 and class 2 nickel input from Indonesia. Difference of production of class 1 and class 2 nickel is in their processing of nickel from nickel ore. However, the process that differentiate between these two classes of nickel is the energy consumption by class 2 nickel. In fact, to produce the same amount of nickel, class 2 nickel needed higher portion of nickel laterite than nickel sulphide which contain about 99.8% of nickel.

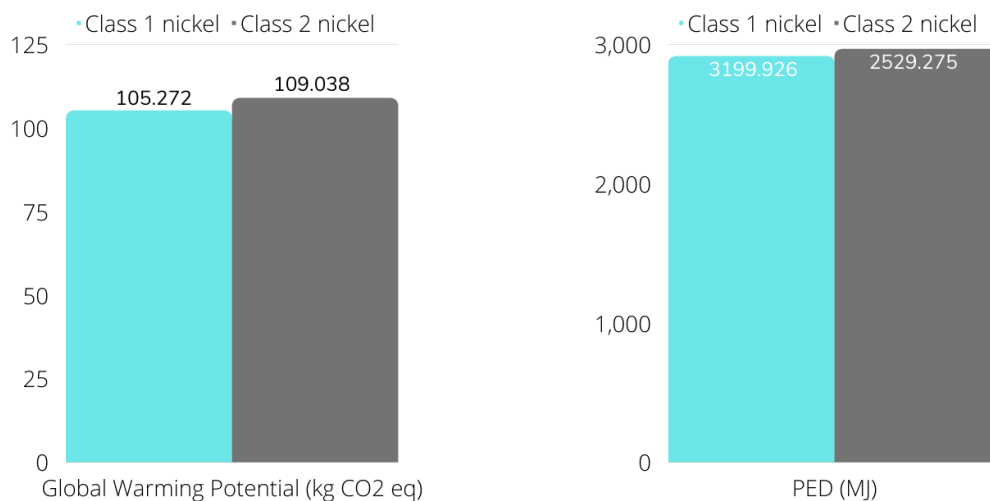


Figure 4.5: Class 1 nickel and Class 2 nickel form Indonesia.

Next, by observing the difference in percentage, GWP of class 2 nickel was found to be 3.45 % higher than class 1 nickel. This is compatible with the theory mentioned above. Class 1 nickel generate 105.272 kg CO₂-eq while class 2 nickel generate 109.038 kg CO₂-eq. Despite of the minor difference between the two classes of nickel, the electricity needed by class 2 nickel is double the electricity needed by class 1 nickel which is 11.53 kWh/kg of nickel and 5.25 kWh/kg respectively. This has shown the energy intensive of class 2 nickel. The difference of 3.45 % could make a significant impact to the environment when calculate the emission of GHG in terms of annual production. On the other hand, Class 2 nickel required 2969.686 MJ of energy compared to 2918.122 MJ of energy for class 1 nickel. The increment of GWP and PED by class 2 nickel could be caused by high-pressure acid leaching (HPAL) process and smelting process. Both processes consumed high amount of energy and generate high GHG as the energy is almost exclusively provided by burning coal. Typically, it releases 90 tons of CO₂ for every ton of nickel produced if smelting, refining and emission of CO₂ are counted. (Rice C., 2020)

4.5 Recommended solution to optimize lithium-ion battery production.

As mentioned in the objective of this project. One of the main objectives of the project is to optimize the energy consumption and GHG emission in LIB manufacturing. After conducting LCA research and analysis, several major contributors are revealed which demand for energy and emits GHG to the

environment. There are several ways to further optimize the current LIB facilities in terms of GHG emission as well as energy demand for LIB cell production. Technology mentioned in subsequent subtopics will be either being used in the LIB cell production already just it is not being mass adopted or yet to be implemented in the LIB cell production.

4.5.1 Tesla closed loop heat pump system (energy reduction by 85%)

First, Tesla Motors has mentioned that they have implemented their patented heat pump system that can reduce and minimize the total energy needed by solvent refining system by up to 85%. (Tesla, 2017). According to Dai et al. (2019) supplementary data, NMP consumed about 100MJ of energy per 1 kg of material in NMC battery. With that, since functional units used is 7kg, thus we assumed 700 MJ of energy is consumed by NMP solvent per 1kWh of cell produced. Which is 21 % of the entire cell production energy consumption. By calculating in the 85 % of energy reduction by Tesla heat pump, here is the results as shown in Figure 4.6 below.

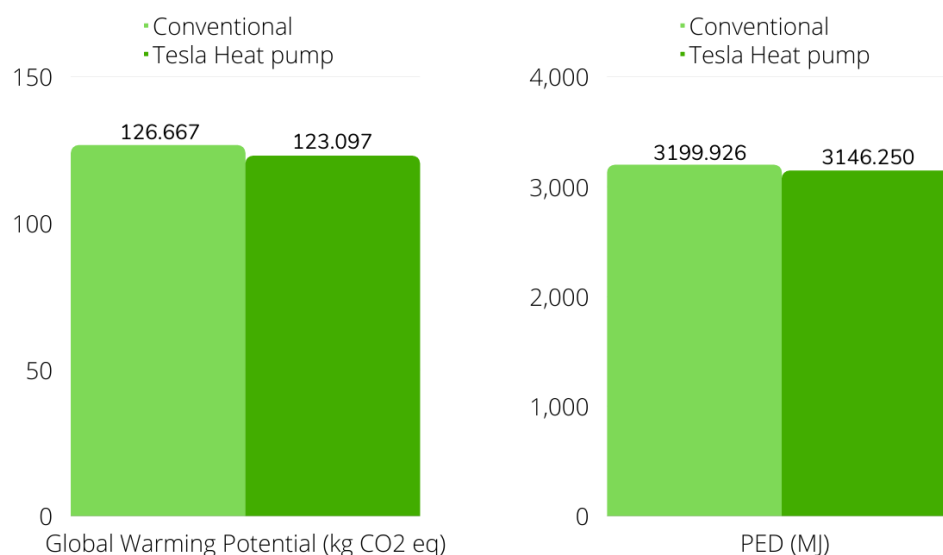


Figure 4.6: Percentage reduction of conventional manufacturing vs after installation of tesla heat pump technology.

With the comparison Figure 4.6 above, it can be clearly seen that after the installation of Tesla heat pump system at the LIB manufacturing particularly after the NMP solvent recovery system. It can reduce the total energy

consumption as well as the GHG emission by $1.68 \% + \alpha$ and $2.82 \% + \alpha$. However, alpha, α is added here after the percentage reduced can be explained by the following reason. First, the LCA model in OpenLCA is referring to Dai et al. (2019) model. Dai et al. (2019) mentioned that NMP is normally being recovered from electrode drying and recycled due to its high cost and safety and environmental concerns which results in minimal loss from process. Thus, NMP solvent is not a significant contributor to any of the impact or emission in the studies. With that said, the 85 % energy reduction by Tesla heat pump can assumed to be insignificant in the studied LCA model as well.

Tesla heat pump is currently being used in the current factory production line at the Gigafactory. However, the other lithium-ion battery manufacturer will be required to apply this technology to their production facilities to further reduce the energy consumption by processing NMP solvent. This technology is feasible to be applied on the production line, however the performance is a concern where it does not match the cost of investment. It could take an extended period of time to recuperate the cost of investment i.e. low ROI.

4.5.2 Dry cathode

At Tesla's 2020 Battery Day, they have presented a novel way to manufacture battery electrode by eliminating wet electrode and implement new dry electrode process. With the previous conventional wet electrode, it involves mixing of liquids with cathode or anode powders and using huge and gigantic machinery to coat and dry the wet electrode. With the high-power output of drying oven, this process consumes tonnes of energy. The new dry electrode technology allows the electrode powder (NMC111 oxide) convert directly into electrode film without the need of coating and drying. According to Tesla (2019), this can improve the cell manufacturing efficiency by reducing the energy consumption by 70%. With that, an LCA model was constructed with 70% of energy reduced than the conventional wet electrode model. Changes only made to the process with impact more than 1%. Process that has impact to results but less than 1% will be consider negligible.

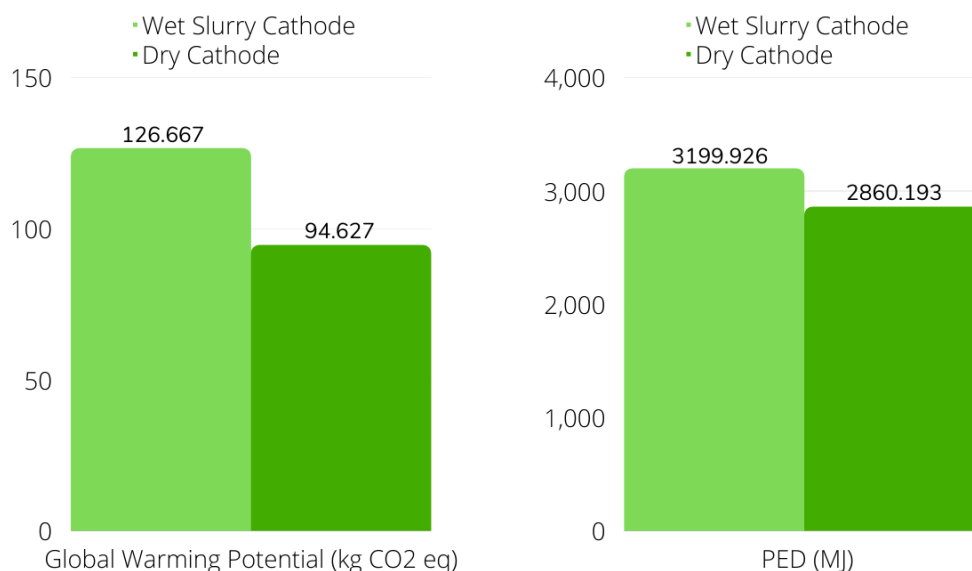


Figure 4.7: Percentage reduction of wet slurry cathode vs dry cathode production.

As can be seen on the comparison chart above, after applying the dry cathode technology which can greatly reduce the energy consumption by 70%, the LCA model has shown a positive result. By looking at GWP, dry cathode has greatly reduced the GHG emission by 25.29%. Having said that, it means the consumption of electricity and heat energy are reduced which consequently reduced the burning of coal which is source of electricity and heat energy. The source of electricity is also one of the major contributors to the GHG emission. Therefore, it can conclude that when consumption for electricity and heat energy is reduced, carbon dioxide emission will be reduced as well especially for this model that are construct using China electricity grid where most of their source of electricity is from coal combustion. Lesser emission of carbon dioxide reduces the NOx equivalent and Sox equivalent as well by 20.65 % and 6.94 %. On the other hand, primary energy demand has decreased as well from 3199.93 MJ into 2860.19 MJ.

The impressive performance of more than 25 % reduction in GWP translates to a massive impact towards the environment in the long run. Hence, applying dry cathode to the existing lithium-ion battery manufacturing process has become a trend. Besides, some of the manufacturers or organization has seen the huge potential of dry cathode technology and have been investing into the

research of this technology. For example, TDK ventures decided to focus particularly on the dry cathode technologies hoping to see the improvement of technologies and encourage for the transition to more sustainable energy. (Batterybits, 2021).

4.5.3 Optimization of energy source of Indonesia.

In this comparison, Indonesia electricity grid is taken as the reference baseline case to compare with the other 3 scenario. Originally, in 2018 Indonesia electricity source is made up of 55.5 % of coal, 19.87 % gas, 7.95 % of hydro, 6.38 % of oil, 10.18 % of other renewable including bioenergy and geothermal, solar and wind energy is insignificant here with 0.03 % and 0.04 % respectively. However, the following scenario 2 is made up of 15 % wind and 15 % solar that came from deduction of 30 % coal which become 25.5 % coal, and the remaining remain the same. Scenario 3 is made up of 30 % solar from the coal while scenario 4 is made up of 30 % wind energy from the coal percentage.

Table 4.2: Comparison of different scenario for different source of electricity.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	Baseline	15% wind 15% solar	30% Solar	30% Wind
Global Warming Potential (kg CO₂ eq)	327.96	237.87	238.43	237.30
Ozone Formation (kg NO_x eq)	1.78	1.27	1.27	1.27
Acidification (kg SO_x eq)	2.70	2.37	2.37	2.39
Primary Energy Demand (MJ)	4525.00	3903.15	3744.40	4061.93

After conducting the simulation, we observed that the deduction of 30 % coal into renewable energy of half solar and half wind has reduced the global warming potential impact by 27.47 % which equivalent to 90.09 kg CO₂-eq reduced. Looking at the PED, for the conversion of 30 % coal into 30 % renewable energy has also reduce the primary energy demand by roughly 621.85 MJ. In fact, this reduction of GWP and PED is not only shown in the second

scenario but also reflect in the other two scenario with 30 % solar and 30 % wind energy.

Furthermore, by comparing among the 3 renewable energy sources, it shows a clear result that the scenario with wind energy require higher amount of energy than the scenario with higher percentage that came from solar. Scenario 2 and scenario 4 both has higher PED than scenario 3 with 30% of solar. Scenario 3 with 30% of solar consumed only about 3744.44 MJ of energy than scenario 2 with 3903.15 MJ and scenario 4 with 4061.93 MJ. With that said, we assume that electricity generation by wind energy consumed slightly higher PED than solar energy. However, scenario 3 with 30% solar energy release slightly higher amount of greenhouse gas with about 238.43 kg CO₂-eq than the other two scenarios which only released about 237.87 kg CO₂-eq for scenario 2 and 237.30 kg CO₂-eq for scenario 4. We can conclude that solar energy release slightly higher amount of greenhouse gas than wind energy. In short, regardless of which type of renewable energy source used, all the renewable uses less energy demand and release lesser amount of greenhouse gas emissions to the environment compared to baseline (current electricity grid).

4.5.4 Optimization of dry room using Cotes dry room technology.

Cotes Exergic Technology provide an Ultradry-air solution for battery dry room that enable massive energy reduction, cost reduction as well as CO₂ emissions reductions (Cotes, 2022). In OpenLCA, the 50% energy reductions are applied only on the cell production phase where cell is going through formation stages which is the stages where dry room is operating. For instance, Cotes uses only hot water at about 80 °C to 90 °C power their dry room dehumidifier system to ensure dew point at -120 °C for unstaffed dry room and -70 °C for a manned room. In fact, Cotes, (2022) utilizes renewable energy sources to heat up the water as this can achieve energy cost savings and carbon footprint. After applying this technology onto the OpenLCA database by reducing up to 50 % as promised by them, the results before and after are shown in the Figure 4.8 below.

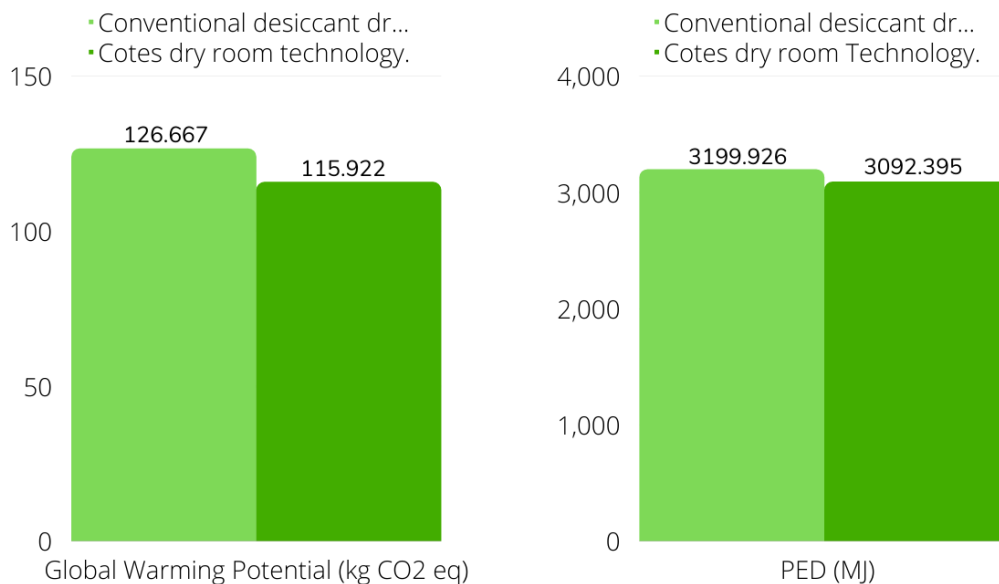


Figure 4.8: Comparison of conventional desiccant dry room and Cotes dry room technology.

In the Figure 4.8, Cotes dry room technology has optimised the cell production by reducing GWP by 9.27 %. From conventional desiccant dry room emission of 126.67 kg of carbon dioxide equivalent reduced to 115.92 kg of carbon dioxide equivalent. On the other hand, primary energy demand has reduced from 3199.93 MJ to 3092.30 MJ of total 3.48 %. The percentage of reduction is not as much as promised by Cotes of 50 % of energy reduction and 95% of carbon dioxide emissions reductions. This could possibly be due to the conventional base case emissions and energy consumption mainly is not from the operation of dry room. The percentage attributed by dry room in OpenLCA database is low, thus the change of reduction is not significant to the entire cell production. Regarding the feasibility of the installation of this Cotes dry room technology, it can be the replacement for the conventional desiccant dry room, however further investigation is needed on the actual performance in real life scenario. The ROI of this investment are to be determined as well.

4.5.5 Conversion to fully renewable source.

According to "Tesla Impact Report 2020", (2020), Gigafactory Nevada will be fully covered with solar panels by end of 2021. When complete installation of solar panels on top of the Gigafactory, it will have a total capacity of 24,000 kW.

With that said, a new model of LCA will be created by using fully renewable energy mainly with solar energy as the electricity production source to replace the coal and gas energy production. The complete breakdown of electricity grid of the original Nevada and fully renewable grid is shown in Appendix I. In short, 68.50 % of natural gas of the original grid of Nevada and 7.30 % of coal was swap by solar energy with total of 84.30 % together with 8.25 % of hydroelectric, 6.87 % of geothermal and 0.58 % of wind energy of original grid.

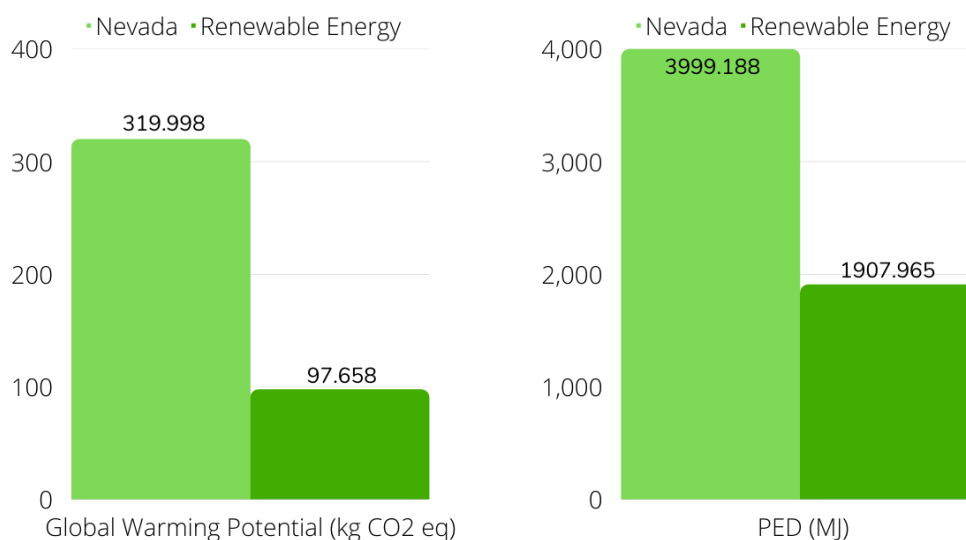


Figure 4.9: Comparison of Nevada electricity grid and fully renewable energy.

Comparing the conversion to fully renewable energy and Nevada original grid, renewable energy has reduced the GWP by 227.67 % and PED by 109.60 %. With high percentage of fossil fuel, it releases high amount of carbon dioxide equivalent, as burning of coal and natural gas, while renewable energy solar panel retrieve the sunlight UV and heat to convert into electricity, this does not burn any fossil fuel which is the major source of carbon dioxide emission.

With the high percentage of improvement, this optimisation method is worth the upgrade and investment. Feasibility-wise, Tesla almost completed their installation of full coverage of solar panels on their factory roof where more energy can be saved, and lesser emission are being released into the atmosphere. Besides, other manufacturers must adopt this technology into their manufacturing process to achieve the reduction and improvement brought by this technology. With that, the sustainability of manufacturing lithium-ion

battery can be secured for a longer period. However, a detailed return of investment (ROI) analysis should be conducted to assess the break-even period before investment into this technology.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

After conducting all the above model and a series of results has obtained. From that we can conclude that the best-case scenario which release the least amount of GWP, and PED is Europe electricity grid, NCA cell type by using Class 1 nickel source. The best case is highlighted in green in table 5.1. On the opposite, the worst-case scenario which emits the highest amount of GWP, and PED is highlighted in brown, which is China electricity grid, NMC cell type using Class 2 dirty nickel.

Table 5.1: Comparison of best case and worst case.

Electricity grid	Battery chemistries	Class of Nickel
China	NCA	Class I nickel
US	NMC	Class II nickel
Europe		

For the optimization method, several technologies that proposed has shown an impact to the conventional LCA model. Optimization using Tesla heat pump has shown a lower percentage reduction of 2.82 % for GWP and 1.68 % for PED. Then followed by Cotes' dry room technology has reduced GWP by 9.27 % and PED by 3.48 % compared to the conventional desiccant dry room system. Next, Dry cathode has improved the cell production by reducing the GWP by 25.29 % and PED by 10.62 %. The final one is the conversion of non-renewable energy natural gas to solar panel renewable energy. This conversion has reduced 227.67 % of GWP and 109.60 % of PED.

Table 5.2: Percentage reduction of GWP and PED for different optimization method.

Optimization method	% Reduction	
	GWP	PED
Tesla Heat pump	2.82 %	1.68 %
Dry Cathode	25.29 %	10.62 %
Cotes Dry Room Technology	9.27 %	3.48 %
Conversion to fully renewable energy	227.67 %	109.60 %

From the above, Tesla heat pump and Cotes' dry room technology are the existing technology that already being used in the industries while dry cathode is still in the testing phase where mass production using dry cathode is still pending for trials. Conversion to fully solar renewable energy by Tesla Gigafactory Nevada are yet to be complete.

To conclude all the results obtained above, the best-case scenario to manufacture a battery cell is by using fully renewable electricity grid to reduce the emission of carbon dioxide due to burning of fossil fuel, apply dry cathode technology into the production to avoid the drying phase, which is one of the most energy intensive one. In fact, for the chemical composition, NCA battery cell type is the most preferable one where the nickel must be obtained from class 1 clean nickel source to avoid the extensive process that require for high energy for class 2 nickel production. In a nutshell, the objective of this project to examine existing process, construct LCA model and recommend alternatives solution to optimize the manufacturing process has been achieved.

5.2 Recommendation for future work.

The Life Cycle Assessment of lithium-ion battery manufacturing was studied particularly due to the high emission of carbon dioxide equivalent and high energy demand. In order to determine the detail and accurate manufacturing process, an actual on-site case study is preferred where the actual energy consumption and energy demand by the actual battery production line is being monitored and studied. From the data collected from the actual site visit,

analysis can be made to understand the breakdown of each process so that it can reflect the actual emission and energy demand by the factory to the environment. By getting the actual and accurate database, the simulate results will be much closer to the actual emission value to further reduce the percentage error.

On the other hand, when simulating using OpenLCA, a complete database from the origin website is a compulsory to ensure there are full set database available for each case for more accurate results. Without complete set of database or free database will not be enough for modelling OpenLCA for various case and scenario which in turn leads to inaccurate results.

When selecting input stream from the database to key into the LCA model for optimization, a detailed research and background study of the particular method is needed to completely understand the accurate amount in and out and changes made. For example, “Tesla impact report 2020” (2020) stated that Tesla will complete the installation of solar panels on their roof to power their entire battery by using fully renewable. But however, how many percent of electricity are from their solar panels and how many percent are from other renewable energy are remains unknown. Hence, when too many assumptions are made, the accuracy of the results will definitely be reduced.

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APPENDIX

Appendix A: GHG emission data of cathode powder production.

Cathode powder production	GHG (kg CO₂-eq)
NiSO ₄	1.82
CoSO ₄	3.79
MnSO ₄	0.36
Li ₂ CO ₃	1.46
NaOH	1.82
NH ₄ OH	0.15
Co-precipitation	2.94
Calcination	3.76
Total	16.11

Appendix B: GHG emission data of cell material production.

Cell material production	Sun 2020	Dai 2019	Average
NMC111 Powder	48.51	28.49	50.67%
Graphite/Carbon	7.27	5.37	8.66%
Binder	0.52	0.36	0.60%
Copper	4.21	2.54	4.47%
Wrought Aluminium	36.91	12.39	29.54%
Electrolyte: LiPF ₆	3.16	1.37	2.83%
Electrolyte: EC	2.10	0.15	1.15%
Electrolyte: DMC	1.05	0.54	1.02%
Plastic: PP	0.52	0.20	0.44%
Plastic: PE	0.52	0.07	0.32%
Plastic: PET	0.52	0.05	0.30%
Steel	-	0.12	-
Thermal Insulation	-	0.06	-
Coolant: Glycol	-	0.53	-
Electronic Parts	-	6.79	-
TOTAL (kg CO₂ eq)	105.37	51.53	100.00%

Appendix C: Comparison of LCA results by country based on LCA conducted on NMC111 battery production

	China	United State	Europe
Global Warming Potential (kg CO₂ eq)	126.67	115.00	111.64
Ozone Formation (kg NO_x eq)	0.76	0.635	0.69
Acidification (kg SO_x eq)	1.31	1.98	1.99
Primary Energy Demand (MJ)	3199.93	3109.13	3118.05

Appendix D: Comparison of LCA results by type of battery chemistry

	NMC 111	NCA
Global Warming Potential (kg CO₂ eq)	126.67	123.58
Ozone Formation (kg NO_x eq)	0.76	0.86
Acidification (kg SO_x eq)	1.31	2.96
Primary Energy Demand (MJ)	3199.93	2529.28

Appendix E: Class 1 nickel and Class 2 nickel from Indonesia.

	Class 1 nickel	Class 2 nickel	% Difference
Global Warming Potential (kg CO₂ eq)	105.27	109.04	3.45%
Ozone Formation (kg NO_x eq)	0.62	0.64	3.19%
Acidification (kg SO_x eq)	1.15	1.16	1.11%
Primary Energy Demand (MJ)	2918.12	2969.69	1.74%

Appendix F: Percentage reduction of conventional manufacturing vs after installation of tesla heat pump technology.

	Conventional	Tesla Heat pump	% Reduction
Global Warming Potential (kg CO₂ eq)	126.66	123.10	2.82% + α
Ozone Formation (kg NO_x eq)	0.76	0.75	1.47% + α
Acidification (kg SO_x eq)	1.31	1.31	0.48% + α
Primary Energy Demand (MJ)	3199.93	3146.25	1.68% + α

Appendix G: Percentage reduction of wet slurry cathode vs dry cathode production.

	Wet Slurry Cathode	Dry Cathode	% Reduction
Global Warming Potential (kg CO₂ eq)	126.67	94.63	25.29%
Ozone Formation (kg NO_x eq)	0.76	0.60	20.65%
Acidification (kg SO_x eq)	1.31	1.22	6.94%
Primary Energy Demand (MJ)	3199.93	2860.19	10.62%

Appendix H: Comparison of conventional desiccant dry room and Cotes dry room technology.

	Conventional desiccant dry room	Cotes dry room Technology.	% Difference
Global Warming Potential (kg CO₂ eq)	126.67	115.92	9.27%
Ozone Formation (kg NO_x eq)	0.76	0.71	7.72%
Acidification (kg SO_x eq)	1.31	1.28	2.49%
Primary Energy Demand (MJ)	3199.93	3092.40	3.48%

Appendix I: Comparison of Nevada electricity grid and fully renewable energy

	Nevada	Renewable Energy	% Difference
Global Warming Potential (kg CO₂ eq)	319.99	97.66	227.67%
Ozone Formation (kg NO_x eq)	1.83	0.65	179.82%
Acidification (kg SO_x eq)	2.72	1.95	39.57%
Primary Energy Demand (MJ)	3999.18	1907.96	109.60%

Appendix J: Comparison of original Nevada grid and fully renewable energy

Nevada Grid	Original Grid	Conversion (Tesla)
Natural Gas	68.50%	0%
Coal	7.30%	0%
Geothermal	6.87%	6.87%
Solar	8.50%	84.30%
Hydro	8.25%	8.25%
Wind	0.58%	0.58%

Appendix K: Electricity breakdown for Indonesia scenario

Entity	Baseline	Scenario1	Scenario 2	Scenario 3
Coal (% electricity)	55.50	25.50	25.50	25.50
Gas (% electricity)	19.87	19.87	19.87	19.87
Hydro (% electricity)	7.95	7.95	7.95	7.95
Solar (% electricity)	0.03	15.03	30.03	0.03
Wind (% electricity)	0.04	15.04	0.07	30.07
Oil (% electricity)	6.38	6.38	6.38	6.38
Other renewables (% electricity)	10.18	10.18	10.18	10.18