SUMMARY REPORT OF PROSPECTIVE LIFE CYCLE ASSESSMENT STUDY OF NCM811 P-CAM PRODUCTION AT THE TA KHOA REFINERY PROJECT

Prepared for
Blackstone Minerals Limited

September 2022

Authors: Laurens Tijsseling, Phoebe Whattoff

External Panel Review: Lyle Trytten, Viktor Kouloumpis, Mark Mistry

MINVIRO

Our Statement

Information contained in this report has been compiled and computed from sources believed to be credible. Application of the data is strictly at the discretion and the responsibility of the reader. Minviro is not liable for any loss or damage arising from the use of the information in this document.

Life cycle assessment is an environmental accounting method with an inherent level of uncertainty, and it should not be seen as having the same level of precision as financial accounting. Life cycle assessment requires a very large amount of data, particularly to calculate all the inputs and outputs for every step. Databases are often used for secondary data since it is impractical to collect all the necessary data from the original sources.

The report does not claim to be exhaustive, nor does it claim to cover all relevant products. While steps have been taken to ensure accuracy, the listing or featuring of a particular product or company does not constitute an endorsement by Minviro.

This material is copyrighted. It may be reproduced free of charge, subject to the material being accurate and not used in a misleading context. The source of the material must be identified, and the copyright status acknowledged.

Executive Summary

Minviro was appointed by Blackstone Minerals (BSX) to conduct a cradle-to-gate life cycle assessment (LCA) on the production of the nickel-cobalt-manganese (NCM) precursor cathode active material (pCAM) at the Ta Khoa Refinery in Vietnam. The study uses data from the October 2020 scoping study as well as pre-feasibility (PFS) studies published to the market in August 2021 (refinery) and January 2022 (mine and concentrator). This report is a summary of the LCA methodology and results. The full report contains confidential information which is not in the public domain at this time.

The project consists of five distinct stages of operation: open pit mining, underground mining, concentrating, concentrate transport, and refining. For each of these stages, technological and economic data was developed as part of the aforementioned PFS studies. The studies were based on the production of NCM811, a specification of pCAM consisting of nickel hydroxide, cobalt hydroxide and manganese hydroxide in an 8:1:1 ratio. The project will produce copper cathode and kieserite by-products.

This summary report focuses on the global warming potential (GWP) impact category, which refers to the relative amount of heat absorbed in the atmosphere by greenhouse gases as a multiple of the same heat that would be absorbed by carbon dioxide. The GWP was calculated to be 9.8 kg CO_2 eq. per kg NCM811. Results for all other impact categories can be found in Appendix A.

It was found that nickel concentrate from third parties, electricity from the Vietnamese grid, cobalt sulphate heptahydrate, and manganese sulphate monohydrate were the factors contributing most highly to the GWP impact category. Use of diesel in the open pit mine was the fuel source that contributed significantly to the GWP impact.

Scenario analysis was carried out to understand the reduction in GWP possible when pursuing an alternative project set up. This showed that a GWP of 6.3 kg CO_2 eq. per kg NCM811 can be obtained using scenario iterations that BSX is considering. In a scenario considering hydropower electricity, the contribution of electricity is negligible. Alternatively, it was shown that when using a diesel fuelled haulage fleet and when being connected to coal based electricity the GWP of the product would increase by 59% to 15.6 kg CO_2 eq. per kg NCM811.

The GWP of BSX's NCM811 pCAM material was also compared against NCM811 pCAM produced via a conventional route in China, evaluating the change in GWP for nickel sulfate hexahydrate from different natural resources, different processing routes and from different regions. These routes included nickel sulfate from Australian sulfide ore, New Caledonian laterite ore processed via a hydrometallurgical route, and Indonesian laterite ore processed via a pyrometallurgical route. This showed that compared to the alternative NCM811 pCAM production routes, the product originating from the Ta Khoa project has the lowest GWP.

Contents

List of Tables

List of Figures

List of Acronyms

Acronym	Meaning
ANFO	Ammonium Nitrate Fuel Oil
AWARE	Available Water Remaining
BPED	Bipolar Electrodialysis
BPNM	Ban Phuc Nickel Mines
BSX	Blackstone Minerals Limited
Co	Cobalt
CO_2	Carbon dioxide
DFS	Definitive feasibility study
DQR	Data quality rating
eq.	Equivalent
GWP	Global warming potential
HPAL	High Pressure Acid Leach
H_2SO_4	Sulphuric acid
IPCC	Intergovernmental Panel on Climate Change
kg	Kilograms
l	Litres
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MHP	Mixed Hydroxide Precipitate
MIBC	Methyl IsoButyl Carbinol
Mn	Manganese
mpta	Million tonnes per annum
MSV	Massive Sulphide Deposit
Ni	Nickel
NCM811	Nickel cobalt manganese, with a ratio of 8:1:1
NPI	Nickel Pig Iron
pCAM	Precursor Cathode Active Material
PFS	Pre-feasibility study
POX	Pressure oxidation
RKEF	Rotary Kiln Electric Furnace
SEX	Sodium Ethyl Xanthate
TKN	Ta Khoa Nickel Mine
TKP	Ta Khao Nickel Project
TKR	Ta Khoa Refinery
t	Metric tonne(s)
tpa	Tonnes per annum

1. Introduction

Blackstone Minerals Limited (BSX) commissioned Minviro Ltd. as life cycle assessment (LCA) practitioner in August 2021 to conduct a life cycle assessment for the production of precursor cathode active material (pCAM) at the Ta Khoa Project (TKP), Vietnam.

The LCA was conducted using the best available data taken from BSX's published scoping study in October 2020 and pre-feasibility studies, published in August 2021 and January 2022. The intended application of this LCA is to assist in project development and improvement. The results will be used for long term strategic planning and to communicate these results and comparative assertions to the public.

1.1. Project Description

BSX is developing the TKP in Northern Vietnam. The project is categorised into two sub-projects: (1) Ta Khoa Nickel (TKN) Project, and (2) Ta Khao Refinery (TKR) Project. For this LCA, the primary data used is from the January 2022 TKN Project PFS study on the Ban Phuc Nickel Concentrator and the August 2021 TKR PFS.

Nickel ore will be sourced from the Ban Phuc Nickel Mine (BPNM), a 90% owned subsidiary of BSX located 160 km west of Hanoi, near Ban Phuc village in Son La Province. The Ban Phuc Nickel Mine operated a high grade massive sulphide deposit (MSV) underground nickel mine for three years from 2014-2016.

The TKN Project intends to construct a new 8 Mtpa nickel concentrator to produce nickel concentrate from a blend of disseminated and MSV ore mined from the Ta Khoa region. The TKN will be fed disseminated nickel ore from a new open pit utilising an electrified mining fleet. Minor amounts of high grade MSV ore are produced from satellite underground mines, which would be used to blend with the disseminated Ban Phuc ore. The nickel ores will be transported to the 8 Mtpa concentrator, where it will be processed to produce nickel-copper-cobalt concentrate, before subsequent delivery to the TKR.

The TKR will receive nickel and cobalt concentrate from the Ta Khoa regional orebodies, as well as third party concentrates from around the globe. TKR will refine 800 ktpa of Nickel concentrate, averaging 10-12% Nickel. The end product produced at the refinery will be

NCM811, a specification of NCM pCAM consisting of nickel hydroxide, cobalt hydroxide and manganese hydroxide in an 8:1:1 ratio.

The location of the TKR will be at the Gia Phu Industrial Cluster in the Son La Provence in Northwest Vietnam, approximately 30 km east of the TKN Project. The nickel concentrate feed material undergoes a pressurised oxidative leach, solvent extraction, neutralisation and precipitation process to produce the intermediate mixed hydroxide precipitate (MHP) product. Within the precipitation stage, magnesium sulphate is the primary salt left in solution. The solution is evaporated leaving a magnesium sulphate monohydrate (kieserite) co-product. This is a low-value product sold to the market. Additionally, copper cathode is produced as a co-product, which is leached out in the pressure acid leaching process, separated using solvent extraction and converted into copper cathode using electrowinning. Following that, MHP is then re-leached and further refined via solvent extraction, before precipitation of the final NCM811 product.

The TKR plant design is based on the base case installation of 800,000 tpa concentrate throughput, to produce around 194,568 tpa NCM811 pCAM. Other relevant project production estimates from the scoping study are given in Table 1.

Table 1. Blackstone Minerals Precursor Cathode Active Material Project Production Overview

Production Parameter	Value	Units
Deposit Type	Massive Sulphide Deposit	-
Nickel ore grade	0.41	% Ni
Location of Mine	Ban Phuc Mine, Vietnam	-
Location of Refinery	Phu Tho Province, Vietnam	
Life of Project	9.2	years
Ta Khoa Nickel Concentrate Production	225,000	t/year
Third Party Concentrate Import	575,000	t/year
NCM811 Production	194,568	t/year
LME Grade A Copper Cathode	2,841	t/year
Kieserite Co-Product	215,272	t/year

1.2. Scope of Assessment

The goal of this LCA is to determine the major project and process parameters contributing to the environmental life cycle impact of the production of NCM811 pCAM at the TKP. Another goal is to explore impact mitigation opportunities using scenario analysis. A comparison exercise was completed to compare the GWP of NCM811 pCAM produced from nickel (Ni) from different sources, to understand how the efforts by BSX to minimise environmental impacts compare against traditional and emerging production routes. These include:

1) A comparison against a NCM811 product using nickel from an Australian nickel sulphide deposit, produced via electric arc furnace smelting and ammonia refining steps.
2) A comparison against a NCM811 product using nickel from a high-pressure acid leach (HPAL) production process, located in New Caledonia.
3) A comparison against a NCM811 product using nickel matte produced from sulfidisation of Nickel Pig Iron (NPI), produced via rotary kiln-electric furnace (RKEF) process, in Indonesia.

These routes were chosen at the interest of the client to understand the environmental impact of traditional and emerging production routes that could supply nickel to the same market as BSX. The system boundaries of the processes benchmarked are comparable to those at TKR. Examples of this are using resource extraction as the start of the process for all routes, including transport of intermediate products and ensuring the processes produce the same functional end product.

2. Life Cycle Assessment Methodology

This LCA study was conducted according to the requirements of the ISO-14040:2006 and ISO-14044:2006 standards.[1] This chapter is a summary of the methodology used during the LCA study.

2.1. Goal and Scope

This study assesses the life cycle impact of the production of 1 kg of NCM811 pCAM from a nickel sulphide deposit extracted at the Ban Phuc Mine in Vietnam. The total production chain includes:

- **Mining and concentrating** - conventional drill and blast open pit and underground mining is used to extract the nickel bearing ore. The ore undergoes a series of crushing and grinding processes producing a slurry. This system is capable of processing 8Mtpa of ore. The slurry produced goes through a flotation circuit and filtration circuit to produce the nickel-copper-cobalt concentrate. Road transport of the concentrate to the refining facility (30 km) assumes a >32 metric tonne diesel lorry.
- **Refining to MHP** - nickel concentrate is transferred to the TKR facility where it undergoes pressure oxidation leach (POX). POX is followed by neutralisation, after which nickel and cobalt are recovered into mixed hydroxide precipitate (MHP). Copper is recovered in copper cathode and magnesium recovered in kieserite after MHP recovery. Following leaching of the metals, combined leach and wash liquor is fed into solvent extraction and electrowinning circuit. The copper is recovered as LME grade A copper cathode at this stage using electrowinning. Following removal of copper solution, nickel and copper are precipitated into a mixed MHP.
- **Refining of MHP to NCM811** - The bulk MHP is re-leached using sulfuric acid and fed into a solvent extraction refining circuit to produce an aqueous raffinate containing nickel. This is combined with cobalt and manganese sulphates in a molar ratio of 8:1:1 (Ni:Co:Mn). Third party cobalt sulfate heptahydrate is added to supplement cobalt extracted in the MHP refining stage. NCM pCAM is precipitated,

using aqueous ammonia and sodium hydroxide, and dried to produce the final NCM811 pCAM product.

The first objective is to understand the life cycle impact of producing NCM811 at TKP. A secondary objective is to support strategic planning and decision-making using scenario analysis. A tertiary objective is to communicate the results to stakeholders with interest in the nickel and battery pCAM space.

This LCA is a cradle-to-gate study, meaning the product life cycle impact is being assessed from the point of resource extraction to the end-gate. The end-gate has been set to the NCM811 product produced at the end facility. Upstream transport of reagents to the Ban Phuc Mine and Ta Khoa refining facility have been excluded due to the lack of data as the project is at PFS stage. Use of the product in cathode manufacturing and end-of-life is outside the scope of this LCA study. To understand the full life cycle impact of NCM811 pCAM from cradle-to-grave or cradle-to-cradle requires the extension of the system boundary into the use-phase and the end-of-life phases.

To evaluate the potential viability of the TKP and to decide whether to proceed with more definitive studies, pre-feasibility studies were completed for the TKR and TKN Projects in August 2021 and February 2022 respectively (henceforth referred to as “the Studies”). The Studies engaged various third party consultants including Simulus Engineers (TKR) and CPC, Golder and Optimize Group (TKN), and developed capital and operating cost to an accuracy of ±20-25%. The data generated for the delivery of the Studies provides estimates on the primary extraction of the open pit mine, the concentration and refining processes, and the project consumables associated with the production of the NCM811 pCAM and its associated co-products.

The final objective is to understand the environmental value proposition of producing NCM811 at the TKP against other production routes. The GWP impact of producing NCM811 pCAM at TKP is compared to other nickel-bearing products produced from:

- Nickel sulphide ore in Australia using smelting and refining;
- HPAL processing of laterite ores in New Caledonia;
- RKEF production processes produced from laterite resources in Indonesia.

For all comparison scenarios, the use and end-of-life management of the products derived from the products are not included within the LCA. These are cradle-to-gate studies. The cradle is defined as the extraction of raw materials and the end-gate for each route is set at the point of NCM811 pCAM production. Data generated for these alternative routes are obtained from Minviro's internal database. The primary objective for carrying out this comparison scenario analysis is to quantify the GWP of the alternative production route, compared to the GWP of NCM811 pCAM from the TKP.

This study has been conducted according to the requirements of the ISO-14040:2006 and ISO-14044:2006, including a third-party review by an external panel consisting of three independent experts.

The intended audience for this study includes parties that are interested in the NCM811 value chain, ranging from investors to customers and end-users. This study intends to communicate comparative assertions to the general public.

2.2. Functional Unit

LCA uses a functional unit as a reference to evaluate the components within a single system or among multiple systems on a common basis. The **functional unit** is the quantitative flow used for all inventory calculations and impact evaluations**. The functional unit for this study is defined as: one kilogram of NCM811 pCAM, produced from sulphide at the Ta Khoa Nickel Project mine and Ta Khoa Refinery, in Vietnam.**

The functional unit for the comparison scenarios is **one kilogram of NCM811 pCAM, produced from their respective nickel sources, in their respective locations.**

2.3. System Boundary

2.3.1. Ta Khoa NCM811 Precursor Cathode Active Material Production Route

This LCA models production of NCM811 pCAM from a sulphide deposit originating from the Ta Khoa Nickel Project and refined at the Ta Khoa Refinery facility at TKP. By weight the NCM811 pCAM product consists of 50.7% nickel, 6.5% cobalt and 6.0% manganese. For simplicity, this will be referred to as NCM811 assuming a ratio of 8:1:1. The life cycle impact of four distinct stages of the process are modelled: mining, concentrating, primary extraction and refining. The system boundary for the LCA study covering these stages is presented in Figure 1.

At the Ta Khoa Nickel Project, nickel-copper-cobalt bearing ore is extracted via open pit and underground mining techniques. ANFO is used to liberate ore and waste rock, electricity is used by the haulage fleet and diesel is used by all other vehicles on site. The February 2022 PFS study assumes electric fleet contract mining. The February 2022 PFS for the concentrator is based on 8 Mtpa throughput of nickel ore. Ore undergoes primary crushing, followed by SAG and Ball milling producing a flotation feed product with 80% passing 75 microns. The slurry is fed into a flotation circuit where the ore is concentrated to produce a nickel-copper-cobalt concentrate. Reagents used in the flotation circuit are soda ash (pH modifier), sodium ethyl xanthate (SEX) and potassium amyl xanthate (PAX) as collectors, methyl isobutyl carbinol (MIBC) as a frother, sodium silicate (dispersant) and a flocculant. The electricity for the mine and concentrator is sourced from high voltage of the Vietnamese grid.

Concentrate from BSX's nickel mine and concentrator is transported 30 km by truck to the Ta Khoa Refinery, which accounts for around 30% of the annual feedstock. The remaining concentrate is sourced from different locations from third parties. The environmental impact of the third party nickel concentrate is modelled by using public data available for the operations and projects from which the samples used in the PFS were sourced.

At the refinery, concentrate is conveyed into a repulp tank and combined with water then pumped in a pre-leach circuit, where acid from Bipolar Electrodialysis (BPED) membrane units and fresh acid is added. This initiates the leaching of the solids and magnesium from the concentrate. Recycled heat is used to maintain the temperature of 60-70 °C. The pre-leach discharge is then pumped into the autoclave feed tank. The following step is the pressure oxidation stage (POX) and solid-liquid separation stage to recover cobalt, copper and nickel. Following this, the combined leach and wash liquor is fed into a solvent extraction and electrowinning circuit (CuSX/EW) where copper is recovered as LME grade A copper cathode.

The purified liquid from the CuSX stage is neutralised with limestone, forming a precipitate containing impurities that are recycled back into the process. Magnesia is added to the neutralised liquor to precipitate the bulk of nickel and other base metals as MHP1. The precipitate is then thickened, filtered and washed. The barren liquor from MHP1 still contains nickel, which is recovered by adding hydrated lime. This produced MHP2, which is recycled. The barren liquor from MHP2 contains large concentrations of magnesium. This is fed through a crystallisation circuit, producing kieserite co-product, sold as a marketable fertiliser.

MHP1 solids are releached with sulphuric acid, producing a nickel sulphate liquid. Remaining impurities within this liquid are removed through solvent extraction (CoMgSX) that produces an aqueous purified solution containing nickel and sodium. CoMgSX liquid containing nickel in solution combined with cobalt sulphate and manganese sulphate is fed into a NCM precipitation circuit, using ammonia and sodium hydroxide to increase the pH. The precipitate is then dried as an NCM811 pCAM product. Ammonia, sodium hydroxide and sulfuric acid are recovered from the barren liquid via BPED and recycled back into the process. Electricity for the refinery is assumed to be sourced from the Vietnamese grid.

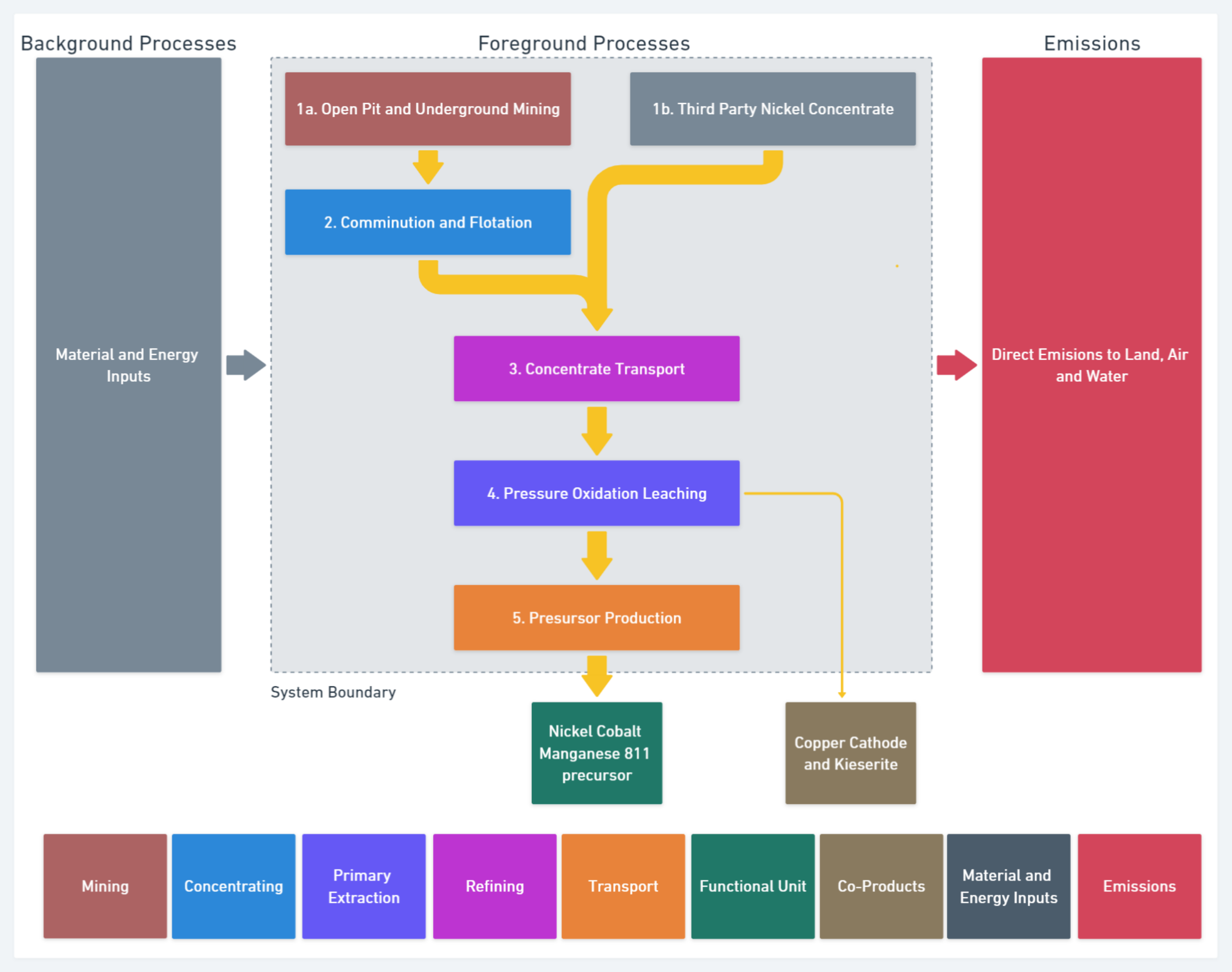

Figure 1. System Boundary Applied to the Life Cycle Assessment Study

2.3.2. Comparison Scenarios

A second system that is investigated is the production of NCM811 pCAM using data from an operational pCAM facility in Shanghai. Cobalt sulfate heptahydrate, manganese sulfate monohydrate, sodium hydroxide, ammonia and nickel sulfate are mixed and treated with thermal energy by combusting natural gas.

Cobalt sulfate heptahydrate and manganese sulfate monohydrate are assumed to come from the same source as assumed for the system discussed in section 2.3.1. Besides the difference in process set up, the influence of different nickel sources will also be investigated. This consists of the following nickel sulfate hexahydrate production routes:

- Nickel sulfate hexahydrate produced from Australian nickel sulfide ore. Ore is extracted using conventional open pit and underground mining methods, after which the ore undergoes a number of comminution and flotation steps to produce a nickel sulfide concentrate. This concentrate is transported to a smelter, where nickel matte is produced via flash smelting. The nickel matte is refined into nickel powder using an ammonia leaching and hydrogen reduction process. Nickel powder is releached using sulfuric acid, which is crystallised into nickel sulfate hexahydrate using thermal energy from natural gas. Electricity is assumed to be sourced from a natural gas source for all distinct stages.[6]
- The industrial average LCA datapoint developed by the Nickel Institute in 2021.[7] This number is based on a combination of data from Nickel Institute members and other datasets which are not fully disclosed.
- Nickel sulfate hexahydrate produced from New Caledonian laterite ore using high pressure acid leaching (HPAL). Ore is extracted using conventional open pit mining methods. Coarse ore is removed using a screening process, after which the undersize ore is chemically treated using sulfuric acid, under high temperature and high pressure. The slurry is neutralised using limestone, after which nickel and cobalt in solution are precipitated into a mixed hydroxide precipitate (MHP) using limestone. This MHP is to be releached using sulfuric acid, which is crystallised to produce nickel sulfate hexahydrate using thermal energy from coal. Electricity is assumed to be produced by combusting coal.[8]
- Nickel sulfate hexahydrate produced from Indonesian laterite ore using a rotary kiln electric furnace (RKEF), where initially nickel pig iron (NPI) is produced by pyrometallurgically treating the laterite ore. NPI is converted into nickel matte by adding sulfur, air and a flux. The majority of the iron in the NPI feedstock is moved to a slag. The nickel matte intermediate product is shipped to China, where it is leached using sulfuric acid. Oxygen is added for oxidation, after which nickel sulfate is produced using thermal energy from coal. Electricity for the process in Indonesia is assumed to be sourced from combusting coal. Electricity used for the process in China is assumed to be sourced from the regional grid.

2.4. Multi-Output Allocation

For the stages where copper, nickel and cobalt are together in the ore and processed mass-based allocation is used. This approach is recommended for base metals.[4,5] System expansion is not deemed appropriate for metallic products, as due to variability in ore grades and processing routes there are currently no appropriate global averages for copper and cobalt products. Therefore, the impacts of mining, concentrating, transport and MHP stages are divided between the three metals on a mass basis.

For non-metallic co-products, system expansion is the preferred approach as alternative production routes are often available for non-metallic co products.[5] System expansion assumes that the co-product will replace an equivalent of that product on the market. For that replacement, a credit is given to the production processes of the primary product. In this case the environmental impact of the MHP stage is discounted by the co-production of kieserite.

2.5. Life Cycle Inventory

2.5.1. NCM811 Precursor Cathode Active Material Production Route

This study was desk-based, meaning that all data was either provided by BSX, collected from public sources, or assembled from public and private databases. Background data was used from Ecoinvent 3.7.1. Key assumptions were:

- Electricity is sourced from the Vietnamese grid.
- The distance between the concentrator and the refinery is 30 km, which is covered by diesel powered trucks.
- Water consumption per kg product assumes that 17% of the water entering the concentrator leaves the plant with the tailings. Remaining 83% is recycled into the concentrator. This is currently an assumption, as BSX is currently developing an updated water balance as the previous version did not account for dry stack tailings.
- Around 70% of the nickel feedstock of the refinery is sourced from third party nickel concentrate. The origin of these feedstocks is confidential information and cannot be shared in this report. The life cycle impact of the third party nickel concentrate has been modelled using publicly available data.

The following flows and processes were included in the study:

- All electricity and fuel flows.
- Mining of ore and waste rock (both ore and overburden).
- Concentration of the ore to a nickel concentrate.
- Transport of the concentrates to the refining site.
- Hydrometallurgical extraction and refining of nickel from the different concentrate sources into the NCM811 product.
- Direct CO_2 emissions on site.

The following flows and processes are not included in the study:

- Transport of consumables to site and of the final product to a customer is not included.
- Environmental impacts of tailings.
- Water treatment on site.
- Direct emissions to air, land and water that are not CO_2.
- Packaging of the final product.
- Materials required for construction of the mine, concentrator expansion and refinery.

2.5.2. Scenario Analysis

To understand the change in GWP for different project iterations, a number of scenarios were evaluated. This was done by switching a number of process inputs to lower or higher impact alternatives. The system boundary does not change in these scenarios. The following scenarios were modelled:

- A scenario in which it is assumed that the electricity is sourced from a coal powered electricity source rather than the Vietnamese average electrical grid.
- A scenario where it is assumed that the haulage fleet is diesel fuelled rather than electric.
- A scenario where all electricity is sourced from run-of-river hydro powered electricity.

- A scenario in which it is assumed that hydrogen is produced as a co-product of producing oxygen using an electrolyser rather than a cryogenic oxygen plant.
- A scenario in which the diesel fuelled excavators are replaced by electric excavators.
- A scenario in which cobalt hydroxide is used as a feedstock in the refinery rather than cobalt sulphate heptahydrate.

2.6. Life Cycle Impact Assessment

The LCIA category presented in the body of this report is Global Warming Potential. This impact category was chosen for this as it provides quantitative insights in the relevant impacts for batteries. All other LCIA results for the impact categories that are part of the Environmental Footprint 3.0 LCA methodology can be found in Appendix A. The LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks.

2.6.1. Global Warming Potential

Baseline model of 100 years based on IPCC 2013

Climate change can be defined as the change in global temperature caused by the greenhouse effect of “greenhouse gases” released by human activity. There is now scientific consensus that the increase in these emissions is having a noticeable effect on climate. Climate change is one of the major environmental effects of economic activity, and one of the most difficult to control because of its global scale.[9] The environmental profiles characterization model is based on factors developed by the UN’s Intergovernmental Panel on Climate Change. Factors are expressed as GWP over the time horizon of different years, the most common historically being 100 years, measured in the reference unit, **kg CO_2 eq.**

The Greenhouse Gas Protocol identifies three “scopes” of GHG emissions which have been included in this study, however it should be noted that scopes of emissions are not a framework inherent to LCA. The GHG Protocol defines scopes of emissions as:

Scope 1: Direct GHG emissions (e.g. furnace off-gas, combustion of fuels)
Scope 2: Indirect GHG emissions from consumption of purchased electricity, heat, or steam (e.g. emissions embodied in grid power or embodied in steam at an industrial park)

Scope 3: Other indirect emissions such as the extraction and production of purchased materials and fuels, transport-related activities in vehicles not owned or controlled by the reporting entity, electricity-related activities (e.g. transmission and distribution losses) not covered in scope 2, outsourced activities, and waste disposal. Scope 3 emissions can be either “upstream” or “downstream”. In a cradle-to-gate LCA, “upstream” scope 3 must be included.

2.7. Assumptions and Limitations

The primary limitation of this study is the uncertainty associated with the level of definition of this project, compared to an operational facility. As this project is currently at PFS stage, a 25% uncertainty has been assigned.

For the refinery, it is assumed that for the base case scenario, one third of the nickel concentrate feedstock is sourced from the Ban Phuc mine in Vietnam. The other two thirds of the nickel concentrate feedstock are from third parties, which has been accounted for by developing LCA models for those routes. It must be noted that the uncertainty of those LCA models is higher compared to the developed LCA model using BSX’s primary data.

The third party nickel concentrates could have a different nickel concentrate grade than what was found in the public documentation. The average concentrate nickel grades were based on values assumed by BSX in the PFS study. If the nickel concentrate is sourced from alternative sources, this will influence the environmental impacts of the NCM811 product and will influence the metallurgical and environmental performance of the refinery.

For both cobalt sulfate heptahydrate and nickel sulfate monohydrate used in the refinery, data points from Minviro’s internal database were used. It must be noted that different production routes of the cobalt and manganese sulfate feedstock could deliver different environmental impact assessments results.

The GWP of NCM811 produced from different nickel sulfate hexahydrate sources is evaluated and compared against the NCM811 product from TKP. The pCAM manufacturing process is different from the technology used at TKP. The conventional manufacturing process uses natural gas, ammonia and sodium hydroxide. The process developed by BSX is electrified and regenerates consumables.

Scenario analysis calculations should be considered optimistic and indicative of the reduction in environmental impact in the case that the particular scenario is pursued by BSX. It should be noted that the calculation methodology for scenario analyses does not hold the same data quality or certainty as a scoping study.

Diesel produced in different countries is likely to have varying impacts. The characterisation factor used in this study is not regional, it is based on a global characterisation factor.

For other assumptions, see section 2.5.

2.8. Interpretation

The results were interpreted with reference to the goal and scope, comparing the impacts associated with the identified process routes, geographic regions, and technology implemented. Contribution analysis, sensitivity analysis, and uncertainty analysis were carried out to support the interpretation of the LCA.

2.9. Data Quality Review

Review of the data quality was carried out as part of this LCA study, which can be found in the full LCA report.

2.10. Critical Review

A critical panel review has been carried out by independent experts, and together they cover the required competencies relevant to the panel review. Their findings and suggestions to improve the study can be found in the appendices of the full LCA report.

3. Global Warming Potential Results

3.1. Project Total

The total GWP for Ta Khoa NCM811 pCAM product is 9.8 kg CO_2 eq. per kg NCM811 according to the LCA model produced by Minviro. The total GWP is broken down by stage of the LCA (Figure 2):

- Open pit and underground mining contribute 0.2 kg CO_2 eq. per kg NCM811
- Concentrating of the ore contributes 0.7 kg CO_2 eq. per kg NCM811
- Transport of the concentrate contributes < 0.1 kg CO_2 eq. per kg NCM811
- Importing third party concentrates contributes 4.4 kg CO_2 eq. per kg NCM811
- Extraction of nickel and cobalt to produce MHP contributes 1.8 kg CO_2 eq. per kg NCM811
- Refining of MHP into NCM811 contributes 2.8 kg CO_2 eq. per kg NCM811

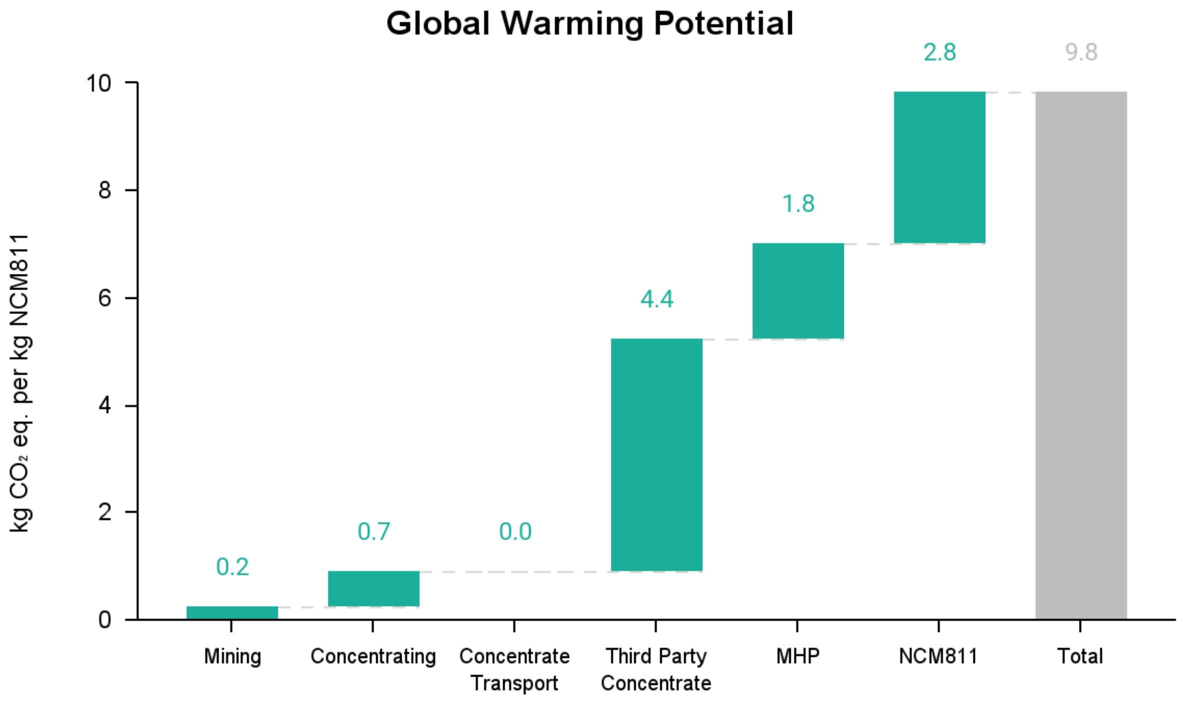

Figure 2. Total Global Warming Potential by Stage

3.2. Contribution Analysis

Contribution analysis of the global warming potential is presented in Figure 3. The top three contributors to GWP in the production of the Ta Khoa NCM811 product are:

- 4.4 kg CO_2 eq. per kg NCM811 associated with embodied impact of the third party nickel concentrates that are sourced for the refinery.
- 2.4 kg CO_2 eq. per kg NCM811 associated with the impact of electricity consumption in the mining, concentrating and refining of the ore.
- 1.0 kg CO_2 eq. per kg NCM811 each for the direct CO_2 emissions released from the breakdown of limestone within the production of mixed hydroxide precipitate, and from the embodied impact of using cobalt sulfate heptahydrate within the refining NCM811.

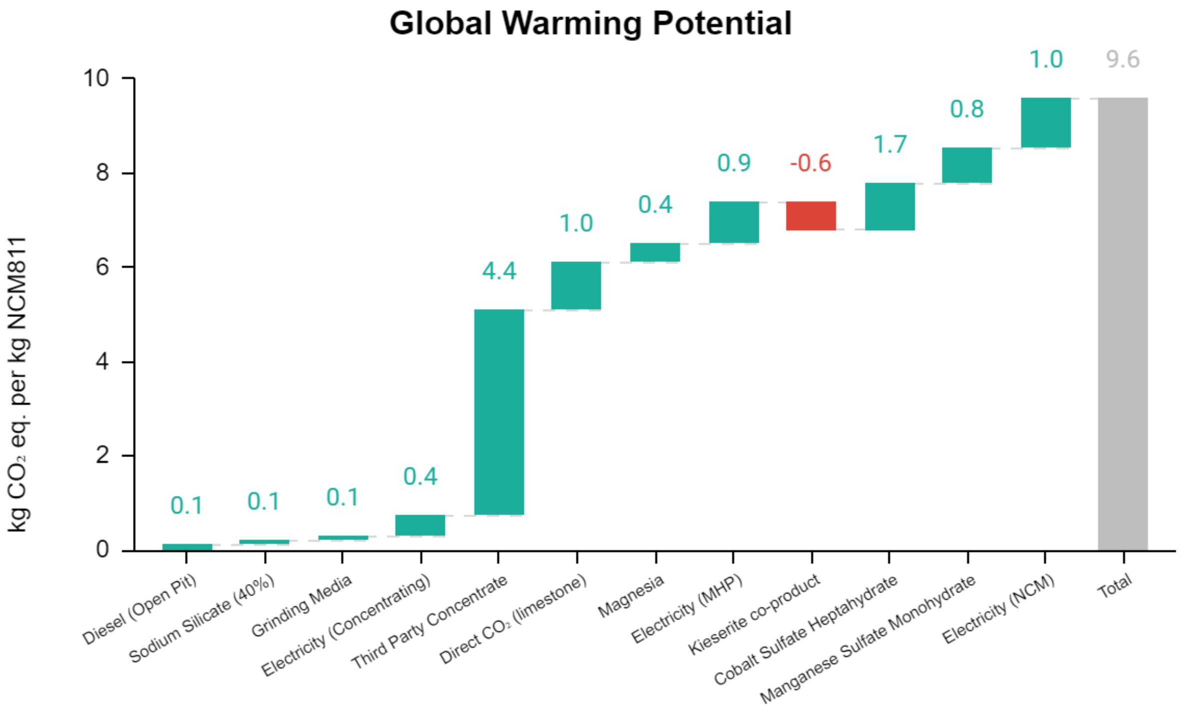

Figure 3. Global Warming Potential Contribution Analysis

The above figure does not include contributors to GWP worth less than 0.05 kg CO_2 eq. per kg NCM811 for visualisation clarity, however these small contributions are included in the overall result.

3.3. Breakdown by Scope

The global warming potential broken down by scopes (1, 2 and 3) is presented in Figure 4.

- The top contributors of scope 1 emissions are the combustion of diesel in the mining stage and from the utilisation of limestone in the MHP production stage.
- The scope 2 emissions are as a result of the electricity being sourced from the Vietnamese grid, which partially relies on coal. The overall scope 2 emissions are larger than the scope 1 emissions.
- The top contributor of scope 3 emissions is the third party nickel concentrate used in the refinery. The top contributor to the scope 3 emissions within the NCM811 refining stage comes from the embodied impact of cobalt sulfate heptahydrate and manganese sulfate monohydrate used to produce the NCM811 product.

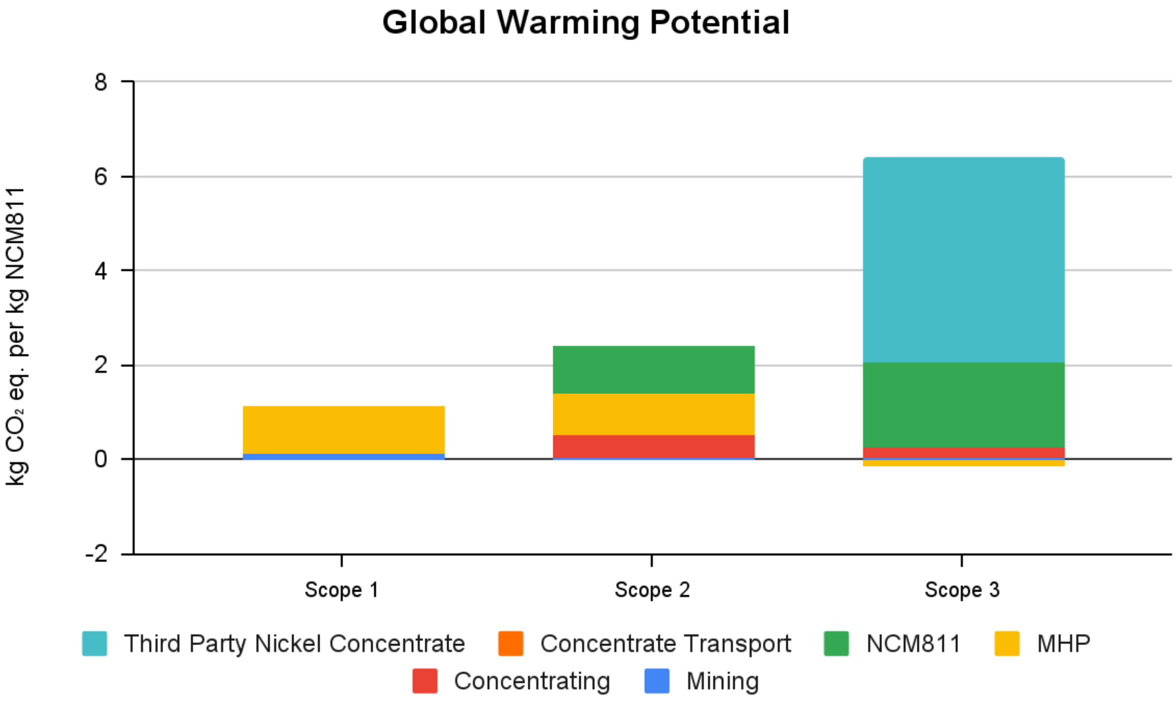

Figure 4. Global Warming Potential Contribution Analysis by Scope of Emissions

4. Scenario Analysis

In this section the change in GWP for the scenarios identified in section 2.5.2 will be described. First, the results of the scenarios that are being considered for GWP reduction by BSX will be described. These are presented in Figure 5, with the following results:

- Using a 100% run of river hydro powered electricity rather than electricity from the Vietnamese grid leads to a decrease in GWP of 2.4 kg CO_2 eq. per kg NCM811.
- Electrifying the excavators in the open pit mine could lead to a decrease in GWP of 0.1 kg CO_2 eq. per kg NCM811.
- Utilising cobalt hydroxide as a feedstock rather than cobalt sulfate heptahydrate could decrease the pCAM GWP by 1.0 kg CO_2 eq. per kg NCM811. It must be noted that cobalt hydroxide contains more impurities compared to cobalt sulfate heptahydrate and may require pre-processing at the refinery, meaning this result is likely very optimistic.
- Under the assumption that the project has access to 100% run of river hydro powered electricity (first bullet point), producing hydrogen as a co-product could decrease the GWP of the NCM811 product by 0.4 kg CO_2 eq. per kg NCM811. This calculation uses a system expansion approach, assuming that the hydrogen co-product replaces one kilogram of hydrogen on the market.

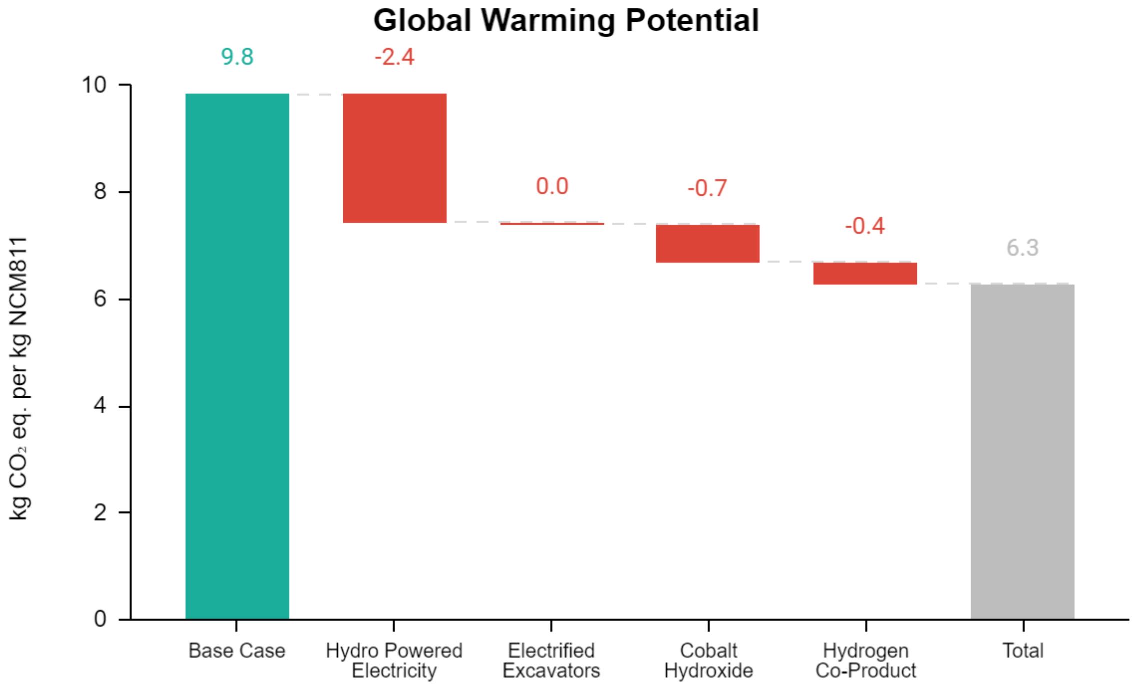

Figure 5. Global Warming Potential Reduction Opportunities via Scenario Analysis

Figure 6 presents the results where the GWP value proposition of using renewable electricity and an electric haulage fleet at the Ta Khoa project is quantified.

- Utilising coal based electricity to power the electric haulage fleet increases the GWP by 0.1 kg CO_2 eq. per kg NCM811
- Using coal based electricity to power all other electricity consuming components on site leads to a further increase in GWP of 5.6 kg CO_2 eq. per kg NCM811.
- Using a diesel fuelled haulage fleet rather than an electric haulage fleet (powered by coal based electricity) changes the GWP by < 0.1 kg CO_2 eq. per kg NCM811. This value is low as the majority of the nickel used in the refinery is sourced from third parties rather than BSX's nickel mine and concentrator. Additionally, it shows that the difference between a diesel fuelled fleet and an electric fleet powered by coal based electricity is marginal.

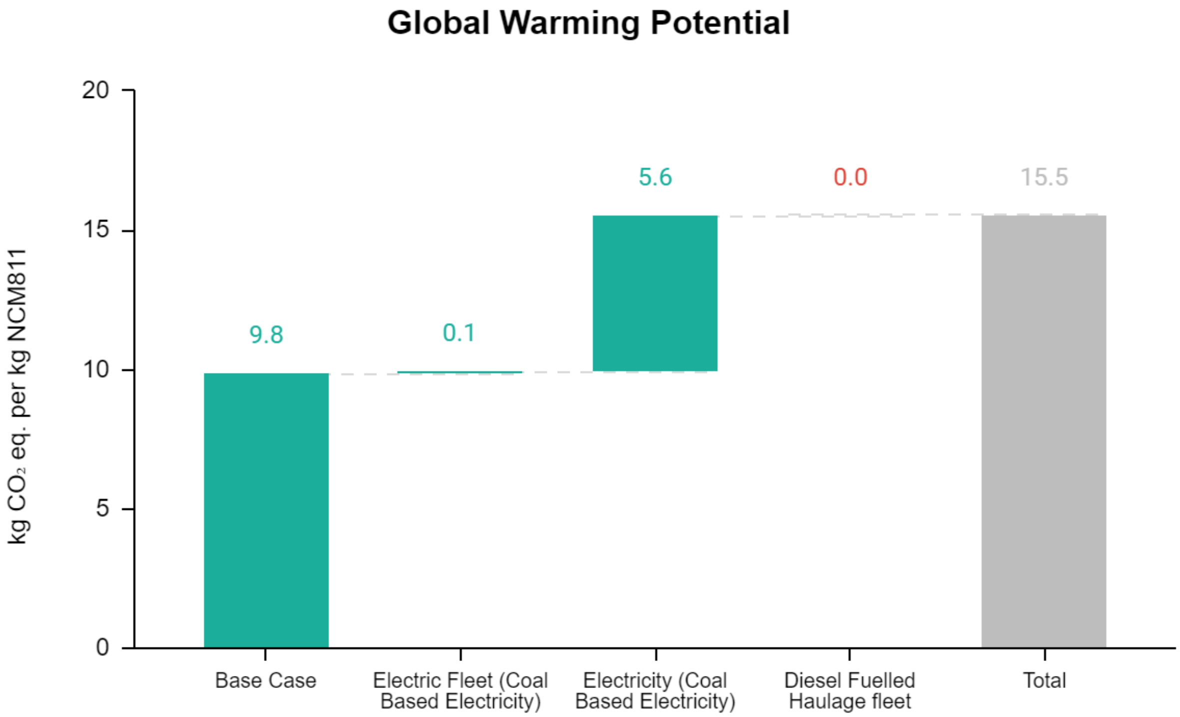

Figure 6. Global Warming Potential Scenario Analysis for Alternative Energy Sources

5. Comparison Scenarios

Figure 7 shows the GWP of NCM811 pCAM produced from various nickel sources for both TKP and for a conventional NCM811 pCAM production process in China. Differences between the NCM811 production process used in China and the process developed by BSX are given in section 2.8. The results for the other four scenarios are as follows:

- NCM811 produced in China using nickel sulfate hexahydrate produced from Australian nickel sulfide ore has a GWP of 15.7 kg CO_2 eq. per kg NCM811. Over half of this impact comes from the nickel sulfate hexahydrate input, which contributes 9.2 kg CO_2 eq. per kg NCM811.
- NCM811 produced in China assuming the industry average datapoint made available by the Nickel Institute has a GWP of 16.1 kg CO_2 eq. per kg NCM811. The contribution of nickel sulfate hexahydrate is 9.7 kg CO_2 eq. per kg NCM811.
- NCM811 produced in China using nickel sulfate hexahydrate produced from New Caledonian nickel laterite ore via an HPAL process has a GWP of 22.2 kg CO_2 eq. per kg NCM811. Nickel sulfate hexahydrate contributes 15.7 kg CO_2 eq. per kg NCM811 to the total GWP.
- NCM811 produced in China using nickel sulfate hexahydrate produced from Indonesian nickel laterite ore via an RKEF smelting to produce nickel matte as an intermediate has a GWP of 58.4 kg CO_2 eq. per kg NCM811. Nickel sulfate hexahydrate contributes 52.0 kg CO_2 eq. per kg NCM811 to the total GWP.

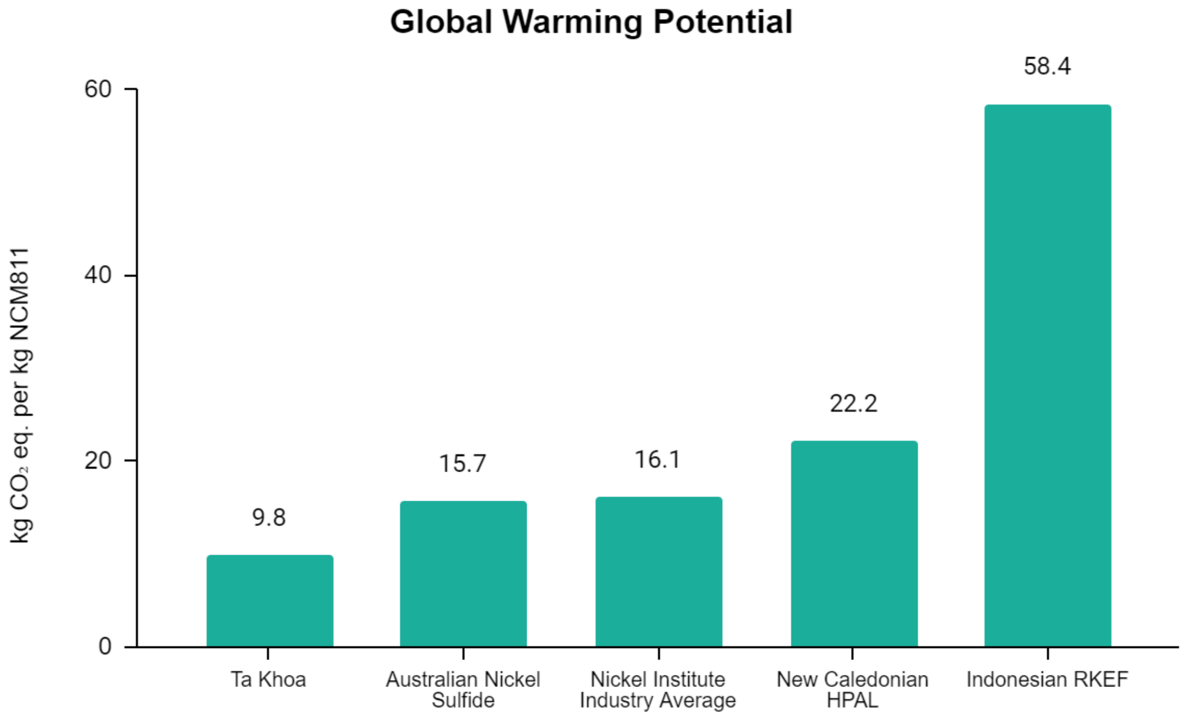

Figure 7. Global Warming Potential Comparison Scenarios for NCM811 from Alternative Nickel Sources

6. Conclusions and Recommendations

6.1. Conclusions

This report summarises the methodology and results of a larger LCA study where the environmental impact of producing pCAM NCM811 at TKP was quantified using LCA.

The total GWP was calculated to be 9.8 kg CO_2 eq. per kg NCM811. The embodied impact of third party nickel concentrate contributed to around 45% of the total GWP of the NCM811 product. Additionally, it was shown that the GWP of the NCM811 product has a significant contribution from electricity used in mining, concentration and refining of the ore, and the embodied impact of cobalt sulfate heptahydrate and manganese sulfate monohydrate.

Scenario analysis was carried out to understand the reduction in GWP possible when pursuing an alternative project set up. This showed that compared to the base case, the GWP can decrease by around 3.5 kg CO_2 eq. to 6.3 kg CO_2 eq. per kg NCM811. Depending on the source of nickel concentrate feedstock, the GWP can decrease even further.

Alternatively, it was shown that when using a diesel fuelled haulage fleet and when being connected to coal based electricity the GWP of the product would increase by almost 59% to 15.6 kg CO_2 eq. per kg NCM811. The majority of this increase in impact would come from the use of coal based electricity. The relative increase from moving to a diesel fuelled fleet is minor.

The GWP of BSX's NCM811 pCAM was compared against NCM811 pCAM produced via a conventional route in China. Additionally, the change in GWP of nickel sulfate hexahydrate sourced from Australia, New Caledonia, Indonesia and an industry average standard was evaluated. This showed that the GWP of pCAM produced at the TKP is the lowest of the routes studied in this LCA.

6.2. Recommendations

Minviro has several recommendations for BSX to improve the quality of this LCA and to improve the environmental performance of the NCM811 product.

- The main limitation of the study is the data quality, related to the project currently being at PFS stage. Minviro recommends updating the study when DFS and operational data is available.
- The use of third party nickel concentrate in the refinery showed to be the main contributor to the GWP and WSF results. Minviro recommends collecting LCA data from the suppliers to decrease the uncertainty around the life cycle impact of the third party nickel concentrates. Additionally, BSX has expressed an interest to understand what the difference in life cycle impact could be when using nickel concentrate from different feedstocks. As described in the study, that will also have consequences for the overall refinery process. To fully understand the consequence, Minviro recommends running a scenario analysis with an updated mass and energy balance developed for specific nickel concentrate feedstocks.
- At this stage the impact of building the mine, concentrator and refinery is not included. It is expected that this contribution will be small. However, for products with a low life cycle impact from its production process, the relative contribution of the construction consumables could be higher than expected.
- Electricity sourced from the Vietnamese grid was shown to be a major contributor to the environmental impact that BSX has direct control over. It is recommended to source renewable electricity for the project, either physically or by using power purchase agreements or similar.
- It is recommended to explore the CO_2 sequestration potential of the concentrator tailings. This could lead to a decrease in GWP of the NCM811 product, although it should be noted that CO_2 sequestration by tailings is not yet fully understood.

References

1. Klöpffer, W. The critical review of life cycle assessment studies according to ISO 14040 and 14044. *Int. J. Life Cycle Assess.* **17**, 1087–1093 (2012).
2. Wernet, G. *et al.* The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* **21**, 1218–1230 (2016).
3. Finkbeiner, M., Tan, R. & Reginald, M. Life cycle assessment (ISO 14040/44) as basis for environmental declarations and carbon footprint of products. in *ISO Technical Committee 207 Workshop, Norway* (2011).
4. Horne, R. E., Grant, T. & Verghese, K. *Life Cycle Assessment: Principles, Practice and Prospects*. (Csiro Publishing, 2009).
5. Santero, N. & Hendry, J. Harmonization of LCA methodologies for the metal and mining industry. *Int. J. Life Cycle Assess.* **21**, 1543–1553 (2016).
6. BHP, 2020 Annual Report. https://www.annualreports.com/HostedData/AnnualReportArchive/b/LSE_BHP_2020.pdf. Accessed 24th of July 2022.
7. Nickel Institute, Nickel sulfate Life Cycle Data. https://nickelinstitute.org/media/8d9409c7c0bdfc8/lca-nickel-sulphate-july-2021.pdf. Accessed 24th of July 2022.
8. Vale Inco Ltd, External Audit of Mineral Reserves, Volume 2, Section 5, Nouvelle Caledonie Goro Project. https://www1.hkexnews.hk/listedco/listconews/sehk/2010/1202/06210_950098/e126.pdf. Accessed 24th of July 2022.
9. Intergovernmental Panel on Climate Change. *Climate Change 2013: The Physical Science*

Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (Cambridge University Press, 2014).

10. Boulay, A.-M. *et al.* The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). *Int. J. Life Cycle Assess.* **23**, 368–378 (2018).
11. Bos, U., Horn, R., Beck, T., Lindner, J. P. & Fischer, M. *LANCA® - Characterization Factors for Life Cycle Impact Assessment: Version 2.0*. (Fraunhofer Verlag, 2016).
12. Alcamo, J., Shaw, R. W. & Hordijk, L. The RAINS Model of Acidification: Science and Strategies in Europe. 30 (1991).
13. Seppälä, J., Posch, M., Johansson, M. & Hettelingh, J.-P. Country-dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator (14 pp). *Int. J. Life Cycle Assess.* **11**, 403–416 (2006).
14. corporate-body. IES:Institute for Environment & Sustainability. *International Reference Life Cycle Data System (ILCD) Handbook : general guide for life cycle assessment : detailed guidance*. (Publications Office of the European Union, 2011).

Appendix A - Life Cycle Impact Assessment Results

Table 2. Results Overview of Life Cycle Assessment Study

Impact Category	Study Results Assuming Use Of Vietnamese Grid Electricity	Study Results Assuming Use Of Hydro Powered Electricity	Units
Global Warming Potential	9.8	7.4	kg CO_2
Freshwater + Terrestrial Acidification Potential	0.10	0.08	mol H^+ eq.
Freshwater Eutrophication Potential	0.00	0.00	kg P eq.
Terrestrial Eutrophication Potential	0.29	0.26	mol N eq.
Freshwater Ecotoxicity Potential	22.01	21.84	CTU
Marine Eutrophication Potential	0.02	0.02	kg N eq.
Ionising Radiation Potential	-0.04	-0.05	kg U235 eq.
Photochemical Ozone Potential	0.07	0.06	kg NMVOC eq.
Carcinogenic Potential	0.00	0.00	CTUh
Non-Carcinogenic Potential	0.00	0.00	CTUh
Respiratory	0.00	0.00	Disease Incidence
Ozone Depletion Potential	0.00	0.00	kg CFC-11
Minerals + Metals Depletion	0.00	0.00	kg SB eq.
Fossil Energy Use	86.08	51.29	MJ
Water Use (AWARE)	454.72	454.54	kg water eq.
Land Use - Biotic Production Potential	0.40	0.40	kg
Land Use - Erosion Potential	1.8E-2	1.8E-2	kg
Land Use - Groundwater Regeneration Potential	3.1	3.1	m^3
Land Use - Mechanical Infiltration Reduction Potential	3.2	3.2	m^3
Land Use - Physicochemical Filtration Potential	0.10	0.08	m^3