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NICKEL SULFATE FOR LITHIUM-ION BATTERIES – HOW ALTERNATIVE PRODUCTION PATHWAYS IMPACT GREENHOUSE GAS INTENSITY

By

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ABSTRACT

Estimates of the increase in nickel production that is required to meet demand over the next decade range between 1.0 and 2.5 Mtpa. These forecasts incorporate a conservative prediction that 45 - 60% of this growth will be needed just to satisfy the projected electric vehicle market. For this market, a large part of this nickel demand is expected to be in the form of high purity nickel sulfate that is required to produce lithium-ion batteries.

One of the drivers of the projected growth in electric vehicle (EV) production is the demand for reduced transport greenhouse gas (GHG) emissions. A key contributor to lifetime EV GHG emissions is the GHG intensity of the EV lithium-ion battery pack. In turn, the major contributor to the GHG intensity of the battery pack is the GHG emissions associated with the production of metals used in the battery cathode (especially nickel and cobalt).

Nickel exhibits a wide diversity of ore types, mineralogy and processing technologies, which translates into a wide variation in environmental impacts associated with nickel sulfate production. Therefore, when studying the GHG emissions intensity of nickel used in lithium-ion batteries it is important to also understand the feed ore type, mineralogy and processing routes. Yet, despite this importance, there appears to have been little consideration of the GHG emissions footprint associated with different routes for producing the lithium-ion battery precursors (especially nickel sulfate).

To further our understanding of these issues, Clean TeQ set out to undertake a streamlined GHG life cycle assessment on the basis of the ISO 14040 series of standards, that compares the GHG emissions intensity of our proposed Sunrise process to possible alternative nickel sulfate processing routes.

Keywords: Nickel Sulfate, nickel pig iron, NPI, ferronickel, matte, Clean TeQ, Sunrise, Continuous Resin in Pulp, Ion Exchange, Electric Vehicles, EV, Lithium-Ion Battery, Greenhouse, GHG, Life Cycle Assessment, Carbon Dioxide

INTRODUCTION

The primary objective of this work was to use environmental Life Cycle Assessment (LCA) methodology to quantify and compare the greenhouse gas emissions (CO_2e) associated with the major hydrometallurgical and pyrometallurgical (smelting and refining) processes used for nickel recovery from sulfide and laterite ores, plus the Clean TeQ Sunrise process, as shown in Figure 1.

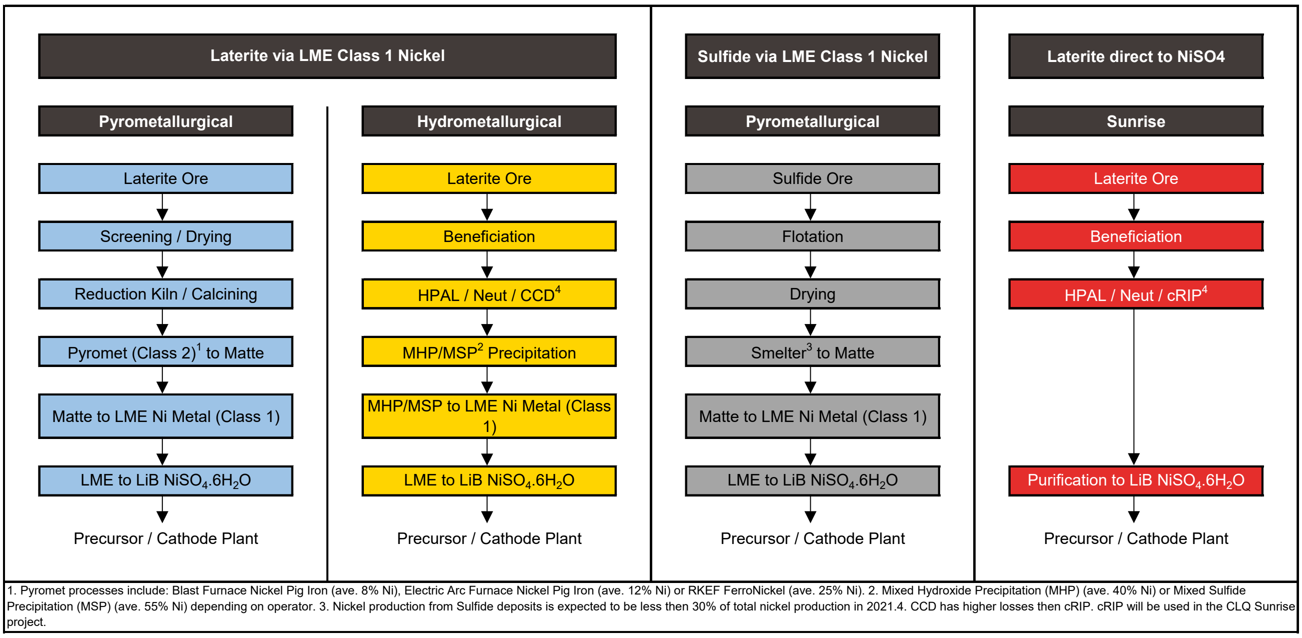

Figure 1: Nickel Processes Examined

Importantly, the world is becoming increasingly dependent on nickel laterite ores to satisfy future nickel (and to a lesser extent, cobalt) demand growth. High-grade sulfide ores are relatively scarce and those that are developed have a relatively short mine life. The substitution of sulfide for laterites ores has been a consistent trend for the past two decades, and this trend is expected to continue. This places a large responsibility on the mining industry to demonstrate high capability and efficiency using hydrometallurgical processing routes.

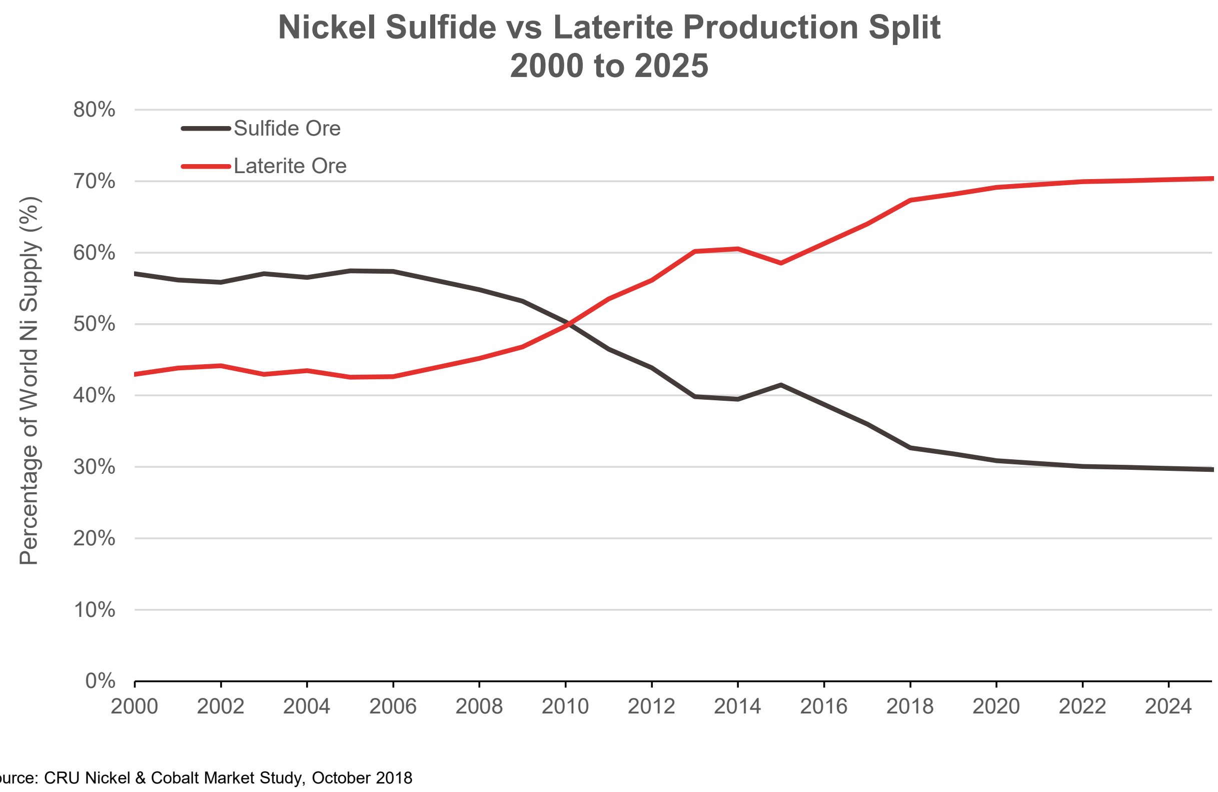

Figure 2: Nickel Sulfide vs Laterite Production Split

If electric vehicles are to be a net benefit to society, they must be designed around the battery. Raw materials (from mining and processing) in the battery leave the biggest GHG footprint on the supply chain. Original Equipment Manufacturers (OEMs) need measurable embodied greenhouse gas emissions ("carbon footprint") data for all their raw materials to benchmark performance and improve their designs. Nickel and cobalt are the major contributors to an electric vehicle's carbon footprint, which varies widely depending on the source of metal and the processing route. See Figure 2 for Volkswagen's estimate on the contribution of battery CO_2e emissions to the overall emissions in manufacturing an electric vehicle. This paper will outline how the battery components impact CO_2e emissions.

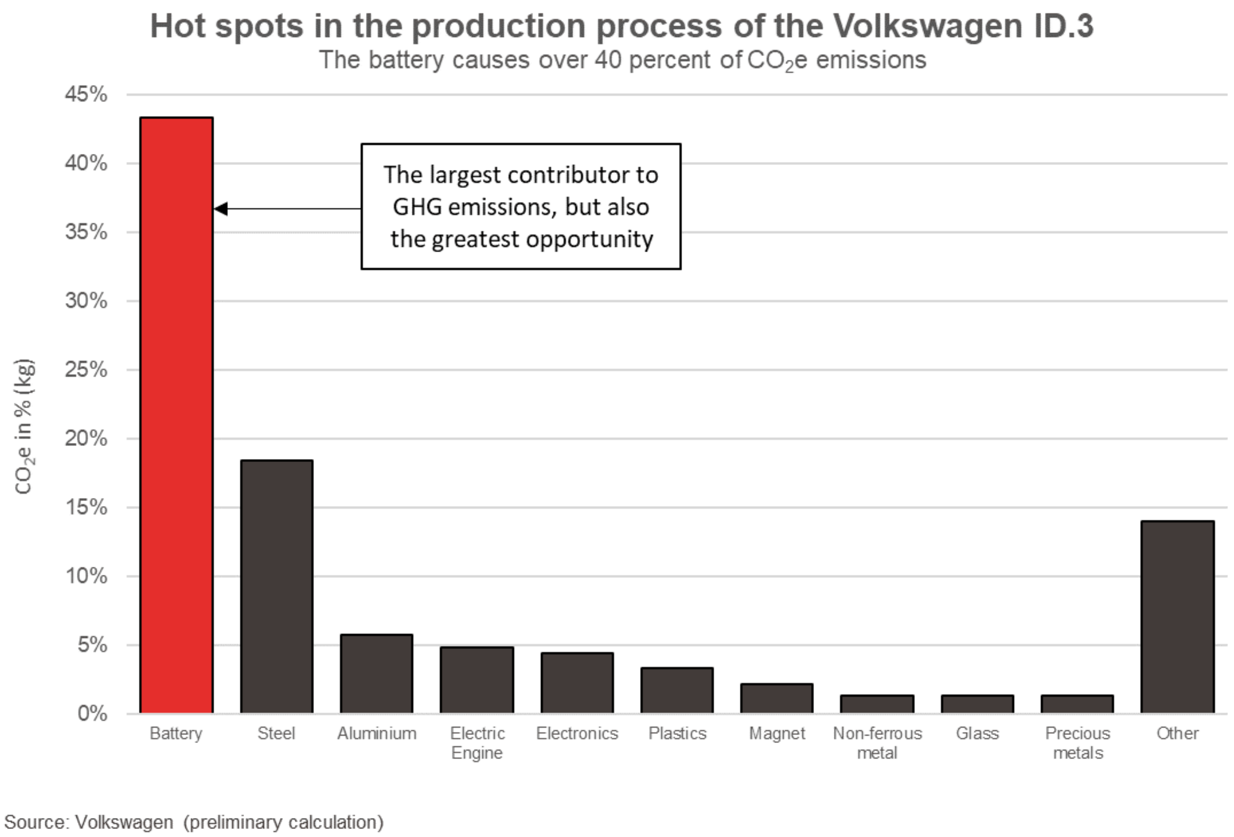

Figure 2: Carbon Dioxide release for Volkswagen

METHODOLGY

The Sunrise Process

It was agreed early in this work that we wanted to be as transparent as possible on both the methodology and the exact basis for any GHG analysis. Applicable literature references were found for the other processing methods, however for the current process being developed by Clean TeQ for the Sunrise project in NSW, as shown in Figure 3, we had to conduct the assessment from our engineering design.

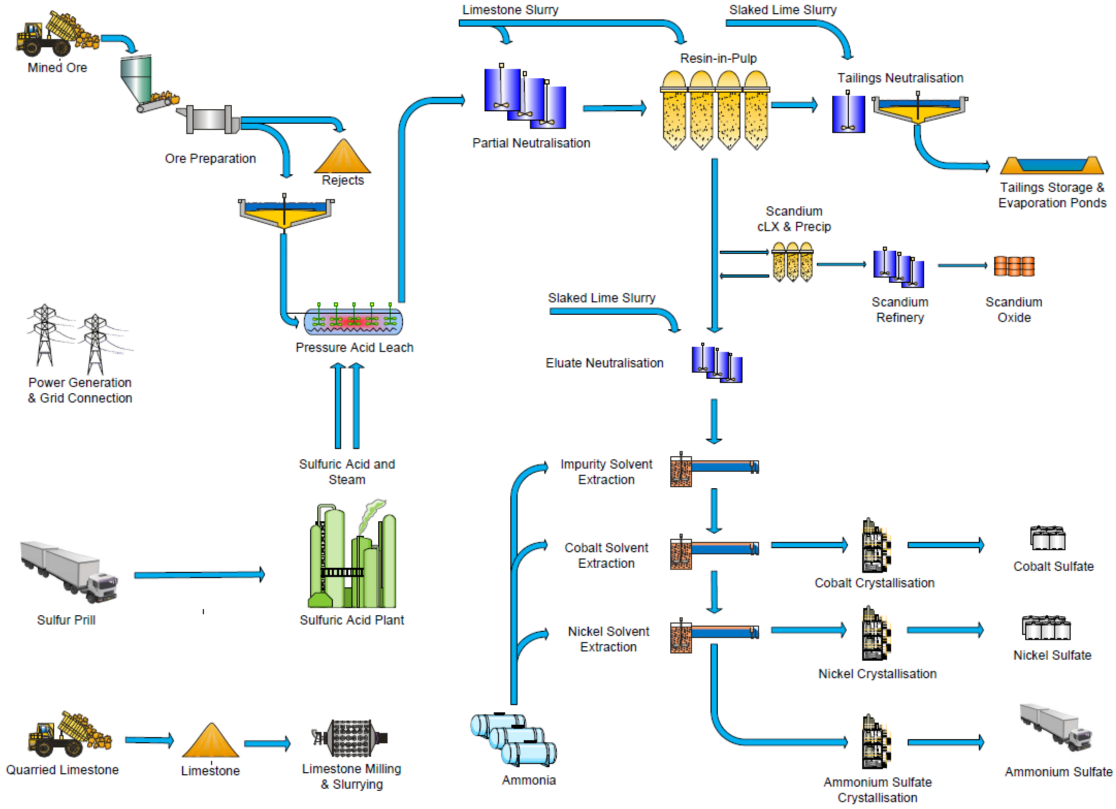

Figure 3: Clean TeQ Sunrise process flow diagram

LCA Basis

To ensure a clear basis was used for benchmarking we applied the principles from the ISO 14040[1] and ISO 14044[2] series of standards. The standards outline a four-step process for undertaking LCA, as shown in Figure 3.

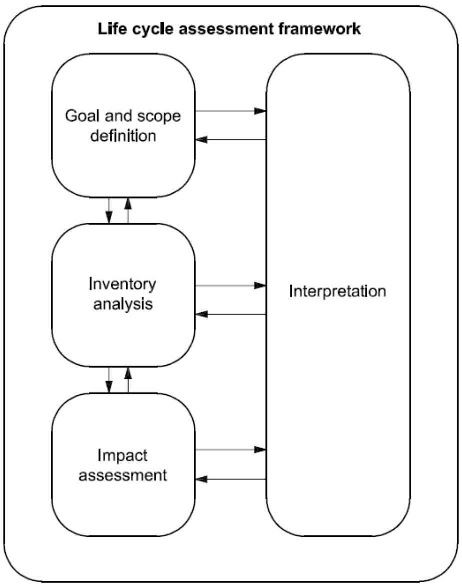

Figure 4: LCA Stages

The scope of an LCA – i.e. which life cycle stages are included – can vary:

- Cradle-to-gate: partial product life cycle from resource extraction (cradle) through production to the factory gate (i.e. before it is transported to the consumer).
- Cradle-to-grave or cradle-to-cradle: complete product life cycle from resource extraction (cradle) through production to the factory gate, distribution to the customer, use and final disposal at end-of-life (grave) or recycling into new products (cradle).

In the transport sector, the above options are often referred to as well-to-tank and well-to-wheel.

For the Clean TeQ Sunrise development a cradle-to-gate basis was used (up to the point where saleable nickel sulfate is produced), with the same basis used for benchmarking, as outlined in Figure 4. For Sunrise an additional check was conducted on including transport of final product to port. Due to time constraints it was decided not to include an external peer-review step, as required by ISO 14040, so instead the results from our analysis would be defined as a streamlined LCA.

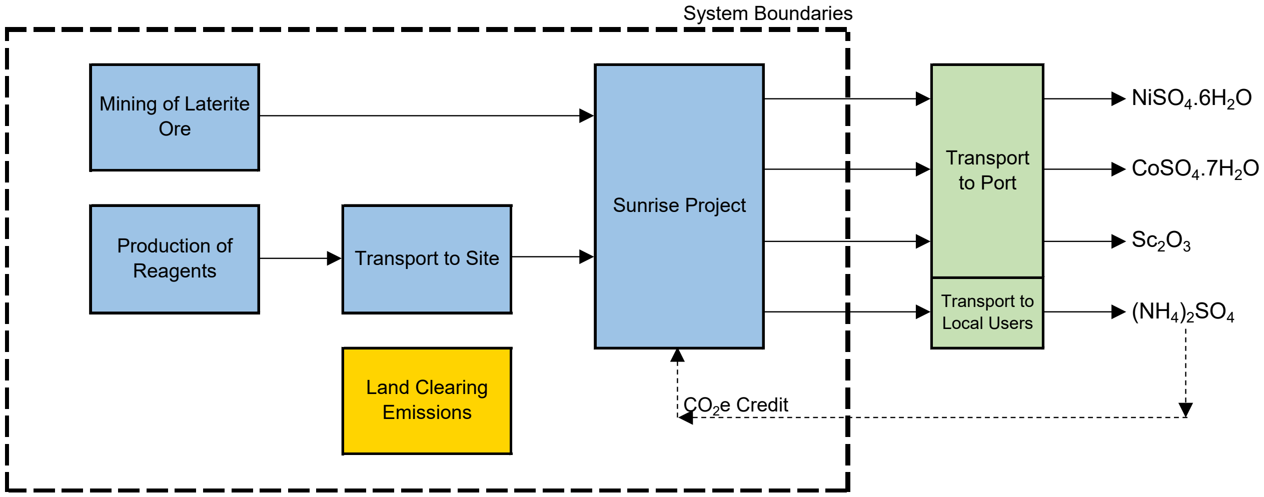

Figure 5: System boundaries applicable to the Clean TeQ Sunrise project in this LCA

The GHG emissions of the Sunrise process and its products are determined by considering all direct and indirect emission sources. In carbon accounting this scope is referred to as including all scope 1, 2 and 3 emission sources, which are defined as:

- Scope 1: All Direct Emissions from the process, including fuel combustion.
- Scope 2: Indirect Emissions from electricity purchased and used by the process.
- Scope 3: All Other Indirect Emissions from activities related to the process, occurring from sources that are not directly owned or controlled, e.g. reagent production, etc.

Allocation

As Figure 5 shows, the Sunrise process results in multiple products. In order to compare greenhouse gas emissions on the basis of 1 tonne of contained nickel equivalent (the reference unit), the model needs to find a way to allocate the impacts and benefits between the various co-products. In LCA terminology, this is referred to as the allocation problem. The ISO 14044 hierarchy was followed:

1. Avoid allocation
    a. By dividing the process into two or more sub-processes
    b. By expanding the system boundaries to include additional functions related to the co-products
2. Apply allocation based on underlying physical relationships between products or functions
3. Where physical relationships alone cannot be established, allocation will be based on economic relationships.

As the nickel production process generates various co-products with different properties it is most appropriate that the share in total value is used to allocate process impacts to each co-product, i.e. the economic value. For Sunrise the following was used:

Table 1: Product prices used for this LCA

Product	Value
Nickel – Ni as $NiSO_4.6H_2O$	8.50 USD/lb 1.90 USD/lb
Cobalt – Co as $CoSO_4.7H_2O$	22.5 USD/lb 4.72 USD/lb
Scandium – Sc as Sc_2O_3	2,301 USD/kg 1,500 USD/kg

For ammonium sulfate we have used system expansion in our default analysis. This means that we have determined a typical production process for ammonium sulfate and subtracted this from the Clean TeQ system boundaries to address this differential with alternative processing routes.

Metal prices can fluctuate significantly depending on global economic factors such as supply and demand and volatility of exchange rates. It should be noted that the above prices are indicative only for the purposes of allocating GHG impacts between products, and do not represent a forecast or estimate of future prices.

Greenhouse Gas Equivalence

This streamlined LCA focused on greenhouse gas (GHG) emissions only. The main characterised greenhouse gases are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (dinitrogen monoxide; N_2O). The climate change indicator is presented in kilograms of CO_2 equivalent units (CO_2e).

The equivalent factors (Global Warming Potentials; GWPs) describe how potentially severe each greenhouse gas is in relation to the reference gas CO_2. They are derived from the Intergovernmental Panel for Climate Change (IPCC) Fourth Assessment Report (AR4), using a 100-year time horizon(3). This report forms the basis for emissions factors used in Australia's national energy and greenhouse reporting regulations.

Key Choices and Assumptions

Key choices and assumptions within this LCA are presented in the following table.

Table 2: Key choices and assumptions

Choices and assumptions	Impact on the Sunrise process LCA
Value of products	The value of the products determines how the impacts of the process are attributed to various co-products.
Reagents	Life cycle inventory (LCI) data are generally available for basic materials and chemicals, less so for specific chemicals. Where LCI data for a reagent are not available, generic processes based on a reagent's Material Safety Data Sheet (MSDS) and using organic chemicals or inorganic chemicals as a proxy for unknown ingredients. The contribution of these minor reagents to the footprint is small. We therefore expect that using proxies only has a minor impact on the LCA results.
Sulfur for sulfuric acid plant	Clean TeQ's Sunrise process includes an on-site sulfuric acid plant. In this study, the sulfur is sourced from Canada, where excess sulfur is available from unconventional gas production. The embodied emissions associated with sulfur are based on an ecoinvent v3 process for Canadian sulfur from unconventional gas. The impacts of processing are allocated to the different co-products. The source data for sulfur can have a significant impact on results. Sulfur is transported by ship to NSW, via train to Trundle, then via truck to site.
Limestone for Neutralisation	A limestone quarry is located 70 km from site, with associated mining, crushing and transport to site included in this analysis.
Process Emissions	Emissions from slurry neutralisation and trace gases from the sulfuric acid plant are estimated and included.
Major Diesel Users	Estimates on annual diesel consumption were included for mining, process and maintenance vehicles, intermittent diesel generators and intermittent diesel boilers.
Transport of minor reagents	It has been assumed all minor reagents are transported by truck (28 t load) over a 450 km one-way distance. This is roughly the distance from Sydney to the Sunrise project site. Actual transport distances may vary and will only be known when the supplier contracts are locked in. The impact of transport is negligible and is very unlikely to materially affect the results.
Land clearing / disturbed area	Emissions from land clearing are calculated based on the total disturbed area. Due to the way in which mining progresses, the area of disturbed land varies over time. A simplified approach has been used, whereby the maximum disturbed area is used as an indication for the total disturbed area. In effect, this ignores any land rehabilitation that is currently planned and budgeted to take place and is therefore conservative.
Electricity grid factors	The electricity grid factors for New South Wales are based on NGA 2019 data(4). The greenhouse gas intensity is 0.90 t CO_2e/MWh. [scope 2 (0.81) + scope 3 (0.09)]

Benchmarking Basis

In order to benchmark our Sunrise process against alternative nickel processing routes, we had to normalise all results against the amount of nickel contained in the final nickel sulfate product. However:

- Traditional nickel processing routes produce different end products (e.g. ferronickel, nickel pig iron, mixed hydroxide, LME-grade metal) but for this analysis the different production routes have been normalised to produce through to a battery-grade nickel sulfate.
- Large variations occur across different regions, due to operating strategies, the type of power available (with large variations in GHG intensity), waste management, etc.
- Due to the nature of multi-output processes, the relative and total value of co-products can have a significant impact on the results. It is possible, and in some cases likely, that allocation between valuable co-products has had a significant effect on the carbon footprint intensities in literature data. However, this may not always be clear from the information provided. Even when values have been provided it may not always be possible to adjust for this effect without access to the underlying model.
- Even if we wanted to harmonise the results, there is generally not enough detail in the sources to be able to do so with confidence. This is a major limitation for comparing literature values.

When interpreting the GHG emissions intensity comparison between Clean TeQ Sunrise and other processes the factors influencing the benchmarking basis above should be considered.

LCA RESULTS

Sunrise Project

The environmental profile of the Clean TeQ Sunrise project and its products is detailed below

Table 3: GHG emissions and intensity of the Clean TeQ project, expressed for various indicators

Sunrise project		**Unit**	**Value**
Total cradle-to-gate		**t CO_2e/year**	**571,457**
	Scope 1 emissions (incl. land clearing)	*t CO_2e/year*	*265,577*
	Scope 2 emissions	*t CO_2e/year*	*165,844*
	Scope 3 emissions	*t CO_2e/year*	*140,036*
GHG intensity of Sunrise products		**Unit**	**Value**
Ni (per kg nickel metal contained)		kg CO_2e/kg	17.2
Co (per kg cobalt metal contained)		kg CO_2e/kg	45.4
Sc (per kg scandium metal contained)		kg CO_2e/kg	2,107

Note: In absolute terms this equates to 355,264 t CO_2e/year for Ni, 202,383 t CO_2e/year for Co and 13,812 t CO_2e/year for Sc

The hot spot analysis considers the key contributors to the results of the LCA, providing valuable insights into the data and offering opportunities for improvement in environmental performance.

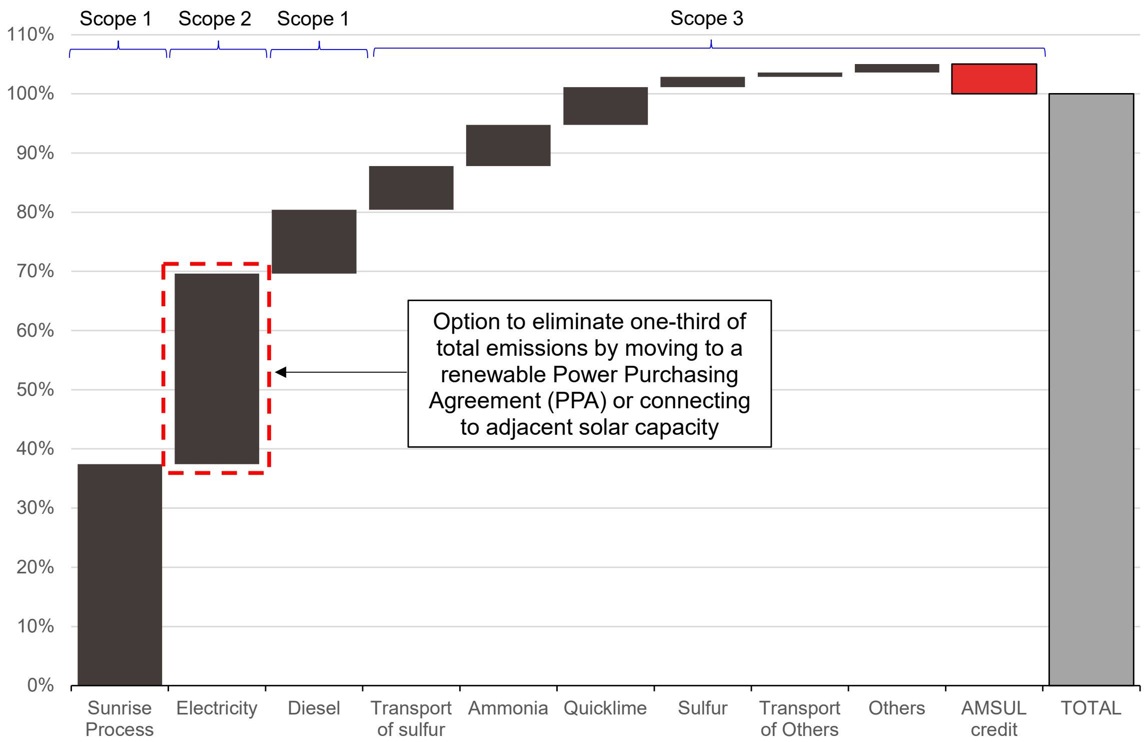

Figure 6: Contribution of key inputs and processes to climate change impacts

See below a summary of the reagents and utilities on a per unit consumption basis, excluding transport / diesel, and excluding associated chemical production (via processing), for example with Limestone and Quicklime (shown separately as Sunrise Process in Figure 6).

Table 4: Analysis of Reagents and Utilities

Reagent / Utilities	Value	Units	% of total
Power	0.90	t CO_2e / MWh of Power	63.8%
Ammonia	1.93	t CO_2e / tonne of NH_3	15.7%
Quicklime	1.04	t CO_2e / tonne of CaO	14.0%
Sulfur	0.04	t CO_2e / tonne of Sulfur	3.9%
SMBS	1.19	t CO_2e / tonne of $Na_2S_2O_5$	0.6%
Flocculant	2.61	t CO_2e / tonne of Flocculant	0.5%
Caustic	1.90	t CO_2e / tonne of NaOH	0.4%
Soda Ash	0.88	t CO_2e / tonne of Na_2CO_3	0.3%
Limestone	0.002	t CO_2e / tonne of $CaCO_3$	0.3%
Resin	0.001	t CO_2e / L of Resin	0.2%
Extractant	2.85	t CO_2e / tonne of Extractant	0.1%
Diluent	0.001	t CO_2e / L of Diluent	0.1%
Hydrochloric Acid	1.29	t CO_2e / tonne of HCl	0.1%
Hydrated Lime	0.90	t CO_2e / tonne of $Ca(OH)_2$	0.1%

Benchmarking

Benchmarking results and reference of the major processes are listed in Table 5.

Table 5: Overview of GHG intensities of nickel processing routes

Primary Process	Primary Process (kg CO_2e/kg Ni)			Matte to LME	LME to $NiSO_4$	TOTAL (kg CO_2e/kg Ni)			References
	Min	Ave	Max	Ave	Ave	Min	Ave	Max	
Clean TeQ Sunrise (renewables)	-	11.7	-	-	-	-	11.7	-	-
Sulfide Pyromet	8.1	12.9	17.7	-	1.2	9.3	14.1	18.9	8,11,12,15,17
Clean TeQ Sunrise (grid)	-	17.2	-	-	-	-	17.2	-	-
Laterite Hydromet (Australia)	22.7	24.1	25.5	-	1.2	23.9	25.3	26.7	11,13,17
Laterite Hydromet (Indonesia)	-	25.5	-	-	1.2	-	26.7	-	Conversion of above using black coal power.
Laterite Pyromet (Rotary Kiln Electric Furnace)	25.7	34.8	43.8	5.5	1.2	32.4	41.5	50.5	11,15,17
Laterite Pyromet (Blast Furnace)	-	71.0	-	5.5	1.2	-	77.7	-	6,8,11,12,17
Laterite Pyromet (Electric Arc Furnace)	-	99.0	-	5.5	1.2	-	105.7	-	11,15,17
Nickel Institute 2020 LCA Report Results (data from 2017)									
Class 1 LME (Laterite / Sulfide)	-	13.0	-	-	-	-	-	-	18
Nickel Sulfate (Laterite / Sulfide)	-	24.5	-	-	-	-	-	-	18
Laterite Pyromet (RKEF)	-	45.0	-	-	-	-	-	-	18
Nickel Institute 2015 LCA Report Results (data from 2011)									
Class 1 LME (Laterite / Sulfide)	-	7.9	-	-	-	-	-	-	21
Laterite Pyromet (RKEF)	-	32.0	-	-	-	-	-	-	21

Note that the technology for conversion of FeNi or NPI to battery-grade sulfate (via matte) has not been proven at industrial scale, may not be economically viable and may add further GHG emissions which have not been accounted for in this study.

It is difficult to compare the previous results with the Nickel Institute LCA data[18][21], as there is no separation in the results between laterite and sulfide ore. Due to this direct comparison is not possible, however as a sanity-check no significant issues are identified.

Cobalt and scandium were not a specific part of this benchmarking, however two references were found in review to compare Sunrise values to:

- The Cobalt Development Institute[19] identified a value of 38.0 kg CO_2e/kg Co, which compares reasonably with the Sunrise estimate of 45.4 kg CO_2e/kg Co. As cobalt is generally a by-product it is a difficult metal to benchmark.
- The high impact associated with Scandium is due to its relatively high value. Similar results can be found in literature[20] which puts scandium oxide (Sc_2O_3) at 6,332 kg CO_2e/kg (~4,130 kg CO_2e/kg scandium contained). Note: the price of scandium oxide used in the literature reference was $US7,200 per kg, and because it was part of a different multi-output process, a direct comparison is not possible without further investigation.

LITHIUM-ION BATTERY IMPACT

In all lithium-ion battery GHG intensity studies read by the authors the impact of nickel and cobalt on the overall GHG intensity appears to have been based on the Nickel Institute LCA values from 2016[21] (using data from 2011), which also appears to match the major LCA databases like GREET, ecoinvent, etc. This dataset is heavily skewed towards nickel sulfide producers, thus providing a lower total average value than expected. If we compare the nickel and cobalt results from this study, with internal lithium-ion battery GHG models, we see the following results.

Table 6: Nickel and Cobalt impact on NMC 811 lithium-ion battery pack emissions

Process and feedstock	kg CO_2e / kWh for Ni+Co	Ni+Co as % of total pack emissions
Clean TeQ Sunrise (renewables)	**12.8**	**17%**
Nickel Sulfide Pyromet	14.8	20%
Clean TeQ Sunrise (grid)	**18.6**	**23%**
High Pressure Acid Leach (HPAL)	26.4	30%
Ferronickel (RKEF)	43.6	42%
Nickel Pig Iron (BF)	63.7	51%
Nickel Pig Iron (EAF)	85.3	58%

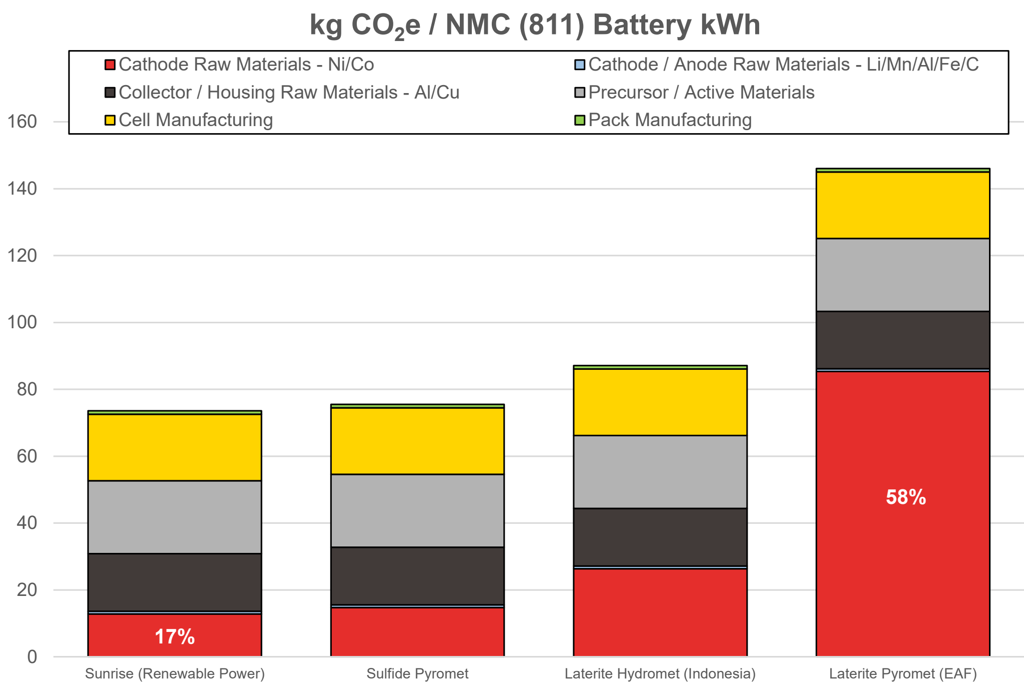

Figure 7: The environmental promise of EVs depends greatly on procurement strategy

CONCLUSIONS

The selection of nickel and cobalt used in lithium-ion battery production can have a significant impact on the overall lithium-ion battery GHG intensities and must be an important part of the decision process for OEMs and car manufacturers. If EV manufacturers want to ensure they have the lowest reasonable GHG intensities in their electric vehicles, procurement and sourcing of metal becomes a key enabler for differentiating the sustainability credentials of their products. It is the belief of the authors that a complete mine to car procurement strategy must be embraced by the industry to ensure environmental requirements are being met.

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