PROCESS MODELLING AND LIFE CYCLE ASSESSMENT: CONVENTIONAL AND NOVALITH PROCESSING OF SPODUMENE

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ABSTRACT

Lithium is critical to the transition from a fossil-fueled to an electric economy. It is estimated that lithium demand will grow by up to 500% by 2050, compared to 2018 production. However, the cost of production will remain important, and it is critical that the increased production required for moving to an electric economy is not offset by an increase in adverse environmental impacts arising from increased production.

In this study, process modelling is combined with prospective life cycle assessment (LCA). This enables earlier and much better-informed decisions about economic and environmental sustainability. The production of lithium carbonate from spodumene is considered. The conventional route is thermal decrepitation, sulphuric acid bake, water leach, purification, and recovery of lithium. The novel (Novalith) approach is thermal decrepitation, pressure leaching with CO_2 , precipitation and purification of lithium carbonate.

To ensure holistic decision-making it is important that costs, revenue, carbon footprint, water scarcity footprint and other environmental impact categories are all considered throughout the iterative design phase. Process modelling can be used to evaluate the technical and economic feasibility of a project design, whilst life cycle assessment (LCA) can be used to quantify the environmental impacts of a production route or processing technology. LCA is a methodology to quantify environmental impacts associated with all stages of a product, process, or activity. An integrated approach is presented that enables the early consideration of economic and environmental factors when evaluating alternative technologies.

Keywords: Lithium, CO₂, water, environment, LCA, economics

INTRODUCTION

Lithium is critical to the transition from a fossil-fueled to an electric economy. It is estimated that lithium demand will grow by a few hundred percent, for electric vehicles alone, by 2050 compared to 2018 production levels¹. However, the cost of production remains important, and the required increase in production cannot come at the expense of increased adverse environmental impacts.

Process modelling combined with prospective life cycle assessment (LCA) enables earlier and much betterinformed economic and environmental decision-making. In this paper, two routes producing lithium carbonate from spodumene are examined to showcase the combination of process/economic modelling and LCA. One route is the conventional thermal decrepitation, sulphuric acid bake, water leach, purification, and precipitation of lithium carbonate. The other is a novel approach being developed by Novalith Australia, entailing thermal decrepitation, pressure leaching with CO_2 , precipitation and purification of lithium carbonate.

The purpose of process/cost modelling is to enable rational evaluation of the process or processes concerned, specifically including preliminary estimates of capital and operating costs, well before substantial costs have been incurred in the development of the process or processes concerned. The purpose of early-stage LCA is to quantify environmental impacts before irreversible decisions are made about the process.

METHODOLOGY

The two circuits chosen for this exercise were modelled using commercially available software known as Aspen Plus to generate detailed mass-energy balances that were used to calculate operating costs and exported to cost estimation software commercially known as Aspen Process Economic Analyzer, and used there to generate preliminary estimates of the capital costs of the process equipment for each circuit. This methodology has been presented before¹.

LCA is a scientific methodology to assess global environmental impacts associated with a product or process life cycle. LCA is a comprehensive and reliable tool that enables environmentally informed decision-making throughout all stages of a project's or product's life. LCA makes it possible to evaluate indirect impacts arising from a product or processing system over its entire life cycle, providing information that otherwise may not be considered. A wide range of environmental impacts can be captured scientifically and quantitatively. This holistic approach generates information on how decisions made at one stage of the life cycle might have consequences elsewhere, enabling informed decisions and avoiding the mere shifting of an environmental burden². It must be noted that LCA is a powerful tool to determine impacts at a global scale, however, it is less suitable for determining local impacts that are commonly investigated using environmental (and social) impact assessment studies.

LCA can use process data to quantify the various environmental impacts. One source of this data, which is not available when the operations under consideration do not yet exist, is actual operating plants. When the plant is yet to be built, process modelling³ can be used to generate plausible preliminary data. An important caveat here is that, while process modelling is a very useful tool for project evaluation, it is beyond risky to use it in isolation. The assumptions used (for example recoveries, reagent consumptions, solid-liquid separation efficiencies) must be verified experimentally before major expenditure such as detailed engineering design is undertaken, and certainly before a decision is made to construct the actual plant. The exercise presented here uses process modelling to generate preliminary data for the two processing options examined.



Principles as outlined under ISO 14040⁴ and ISO 14044⁵ standards series were applied in this study. These outline a four-step process, as shown in Figure 1.

Figure 1 – Life Cycle Assessment Stages

The scope of a life cycle assessment study in the resource sector can be either:

• Cradle-to-gate: a partial life cycle assessment study of a product life cycle, from resource extraction to a defined end gate (e.g. lithium chemical delivered to the market).

• Gate-to-gate: a partial life cycle assessment study of a product life cycle, from factory entry gate to a defined end gate (e.g. lithium chemical delivered to the market).

• Cradle-to-grave or cradle-to-cradle: complete life cycle assessment study on the product life cycle, from resource extraction throughout the use phase and evaluating end-of-life impacts (grave) or recycling pathways (cradle).

The LCA presented here takes a cradle-to-gate and gate-to-gate approach. For the cradle-to-gate scenario, the impacts are accounted for from the point of extraction and production of spodumene concentrate to the final product, being battery-grade lithium carbonate produced and ready for shipment to customers. For the gate-to-gate scenario, the impacts of the spodumene concentrate have been excluded. Two scenarios are modelled:

(1) the production of lithium carbonate via the conventional sulphation route, with sodium sulphate as a coproduct, and

(2) the production of lithium carbonate via the Novalith process.

The system boundaries used in this study are presented in Figure 2. The results of this LCA study are considered to be relevant input for rational decision-making and ranking processing options. The results of the study are not intended to communicate comparative assertions to the public.



Figure 2 – System Boundary Applied in this Lithium Carbonate Life Cycle Assessment Study

LIFE CYCLE IMPACT ASSESSMENT

The life cycle impact assessment categories evaluated in this study are climate change and water use.

Climate change

Climate change is the term generally used to mean an increasing global temperature arising from the effect of "greenhouse gases" (GHG) 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 on economic activity, and one of the most difficult to control because of its global scale⁶. The environmental profiles characterisation model is based on factors developed by the UN's Intergovernmental Panel on Climate Change. Factors are expressed as GWP (Global Warming Potential) over various time horizons, the most common historically being 100 years, measured in the reference unit, **kg CO₂ eq.**

The GHG 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.

Water use

The AWARE method is applied to quantify the environmental performance of products and operations regarding fresh water. This method was developed by Water Use in Life Cycle Assessment (WULCA), a working group of the United Nations Environment Programme (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC) Life Cycle Initiative, on a water scarcity midpoint method for use in LCA and for water scarcity footprint assessments. This approach is based on the available water remaining per unit of surface area in a given watershed after human and ecosystem demands have been met, relative to the world average. The resulting characterisation factor ranges between 0.1 and 100 and can be used to calculate water scarcity footprints⁷. A value close to 0.1 means that plenty of water is available in that region, whilst a water scarcity of 100 means that water in that region is extremely scarce. Units of the characterisation factor are dimensionless, expressed in **m³ world eq. per m³**. It is important to note that this impact relates to the potential for water deprivation to humans or ecosystems, rather than direct water use by the project. Another way to think about this is that it is a life cycle impact assessment value, not an inventory flow. The water stress index for the project in development is assumed to be **2.4 m³ world eq. per m³**.

Allocation

If a system produces multiple products, it is required to divide the impacts between those products that represent the distribution of the impacts between those products and the benefits of those products in a fair way. This is defined as allocation and should follow a stepwise approach⁸. For the scenario assessing the impact of lithium carbonate produced via the conventional sulphation circuit, sodium sulphate is produced. One scenario has assumed the sodium sulphate is sold. The impacts of this scenario have been distributed via system expansion. For the Novalith circuit, no co-products are produced, meaning no allocation is required.

SPODUMENE

Rationally comparing two process options for processing spodumene requires them to use the same feed. The spodumene selected as feed for the study is shown in Table 1.

α-LiAlSi ₂ O ₆	70.84	Mg₅Al₄Si₃O18H8	2.09
Fe ₂ O ₃	1.93	CaCO₃	1.74
SiO ₂	7.44	KAl ₃ Si ₃ O ₁₂ H ₂	7.54
NaAlSi ₃ O ₈	6.43	$AI_2Si_4O_{12}H_2$	1.99

Table 1 – Spodumene composition, mass %.

CONVENTIONAL CIRCUIT

Figure 2 illustrates the conventional circuit, which has been described in the literature^{9,10}. Incoming spodumene concentrate is first heated to 1050°C in a rotary kiln, converting the α -spodumene to β -spodumene. The requisite energy is supplied by burning fuel (natural gas, represented by methane) in air.



Figure 2 – Conventional Circuit.

The flows of solids and gas are counter-current, allowing for some pre-heating of the incoming air and cooling of the hot calcine. Table 2 shows the stoichiometry used to represent the calcination.

Table 2 – Calcination Chemistry.

 $\begin{array}{l} \alpha \mbox{-LiAlSi}_2O_6 \rightarrow \beta \mbox{-LiAlSi}_2O_6 \\ Mg_5Al_2Si_3O_{18}H_8 \rightarrow 5MgSiO_3 + Al_2O_3 + 2SiO_2 + 4H_2O \\ CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2 \\ 2KAl_3Si_3O_{12}H_2 \rightarrow K_2SiO_3 + 3Al_2O_3 + 5SiO_2 + 2H_2O \\ Al_2Si_4O_{12}H_2 \rightarrow Al_2O_3 + 4SiO_2 + H_2O \end{array}$

The hot calcine is cooled, mixed with concentrated sulphuric acid and baked at about 200°C, then cooled and leached with water. The sulphate salts formed in the acid bake dissolve fully, except for calcium sulphate, which dissolves to the extent dictated by its limited solubility in water. The water-leached slurry is filtered, and the filter cake is washed with water and discarded. Table 3 shows the acid-bake chemistry.

The filtrate from the water leach is oxidised with air and neutralised with calcium carbonate to oxidise any ferrous iron to ferric iron and precipitate the iron and aluminium as hydroxides. The resulting slurry is filtered, the filter cake is washed with water and discarded, and the filtrate is neutralised further with slaked lime to precipitate magnesium hydroxide. The resulting slurry is dosed with sodium hydroxide and sodium carbonate, raising the pH beyond what is achievable with lime and precipitating the residual magnesium as magnesium hydroxide and the residual calcium as calcium carbonate. The precipitated solids are filtered off, rinsed with water and discarded. The wash filtrate is recycled to the upstream lime slaking step.

Table 3 – Acid-Bake Chemistry.

$2\beta\text{-LiAlSi}_2O_6 + H_2SO_4 \rightarrow Li_2SO_4 + 2HAlSi_2O_6$	
$Fe_2O_3 + 3H_2SO_4 \rightarrow Fe_2(SO_4)_3 + 3H_2O$	
$2\text{NaAlSi}_3\text{O}_8 + 4\text{H}_2\text{SO}_4 \rightarrow \text{Na}_2\text{SO}_4 + \text{Al}_2(\text{SO}_4)_3 + 4\text{H}_2\text{O} + 6\text{SiO}_4$	
$MgSiO_3 + H_2SO_4 \rightarrow MgSO_4 + H_2O + SiO_2$	
$CaSiO_3 + H_2SO_4 \rightarrow CaSO_4 + H_2O + SiO_3$	
$K_2SiO_3 + H_2SO_4 \to K_2SO_4 + H_2O + SiO_4$	
$AI_2O_3 + 3H_2SO_4 \rightarrow AI_2(SO_4)_3 + 3H_2O$	

The primary filtrate from the purification sequence is dosed with sodium carbonate to precipitate lithium carbonate that is recovered by filtration, washed with water and collected as the required product. The wash filtrate is used to dissolve the incoming sodium carbonate, the dissolved sodium carbonate returning to the precipitation of lithium carbonate. The primary filtrate is dosed with sulphuric acid to decompose carbonates to carbon dioxide that is removed in a vacuum degassing step, then cooled to crystallise sodium sulphate decahydrate (Glauber's Salt). The remaining solution is recycled. The Glauber's Salt is remelted and the melt is further evaporated, crystallising sodium sulphate that is captured, dried and removed from the circuit.

NOVALITH CIRCUIT

The Novalith circuit is illustrated in Figure 3. The chemistry of the dissolution step is shown in Table 4. The incoming spodumene concentrate is calcined as in the conventional circuit, converting the α -spodumene to β -spodumene. After cooling, calcine is mixed with make-up and recycled reagents, milled, and activated, making the β -spodumene more reactive towards aqueous carbon dioxide. The details of the activation step remain, for the present, proprietary to Novalith.

Table 4	- N	ovalith	chemistr	y
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2β-LiAlSi₂O₆ + CO₂ + H₂O → 2Li⁺ + 2HCO₃⁻ + aluminosilicate MgSiO₃ + CO₂ → MgCO₃ + SiO₂ CaSiO₃ + CO₂ → CaCO₃ + SiO₂

The activated solids are mixed with water and pumped, via feed-product heat exchange and a pre-heater, into a leaching reactor and reacted with carbon dioxide and water at high pressure and moderate temperature, dissolving the lithium carbonate into aqueous lithium bicarbonate. Mineral carbonation occurs in this reactor mainly for the lithium, and to a small extent for the impurities in the spodumene feed, e.g. a very small amount of calcium silicate is converted to calcium carbonate. The exit slurry is cooled and filtered, the filter cake is washed with water, and the washed filter cake is discarded.

The filtrate is purified through ion exchange, removing any residual divalent cations (primarily calcium) then concentrated by reverse osmosis. The concentrated solution is evaporated to release CO_2 and precipitate lithium carbonate which is recovered by filtration. The vapour is re-compressed and partially condensed in the hot side of the evaporator. The condensate is recycled as process water. The remaining vapour is cooled, condensing out more water that is also recycled as process water, and the remaining vapour (now mainly CO_2) is recompressed and recycled to the autoclave.

The filter cake is centrifuged, washed with water and dried, exiting as the lithium carbonate product. The filtrate and centrate solutions are combined, evaporatively concentrated to manage the overall water balance, and recycled. The condensate from this evaporation step is recycled as process water



Figure 3 – Novalith Circuit.

COMPARISON

The amounts of the various reagents and utilities consumed in each circuit were extracted from the massenergy balances emanating from the two process models. These quantities, the unit costs used and the resulting operating costs are summarised in Table 5 and Table 6. The conventional circuit consumes a little more spodumene than the Novalith circuit because there is a little lithium in the sodium sulphate by-product. The Novalith circuit does not generate sodium sulphate.

Item	Amount	\$/t Li ₂ CO ₃
Spodumene (\$500/t)	7540 kg	3770
Fuel, approximated as CH ₄ (\$350/t)	274 kg	96
Sulphuric acid, as 100% H_2SO_4 (\$180/t)	3994 kg	719
Limestone, as 100% CaCO ₃ (\$60/t)	1193 kg	72
Lime, as 100% CaO (\$180/t)	17 kg	3
Sodium hydroxide, as 100% NaOH (\$500/t)	43 kg	21
Sodium carbonate, as 100% Na ₂ CO ₃ (\$300/t)	2879 kg	864
Steam (\$10/t)	33485 kg	325
Water (\$5/t)	46956 kg	235
Electricity (\$0.06/kW/b)	2416	152
	kWh	152
Feed, reagent & utility co	6257	

Table 5 – Feed, Reagents and Utilities, Conventional Circuit.

Table 6 – Feed, Reagents and Utilities, Novalith Circuit.

Item	Amount	\$/t Li ₂ CO ₃	
Spodumene concentrate (\$500/t)	7122 kg	3561	
Fuel, approximated as CH ₄ (\$350/t)	295 kg	103	
Carbon dioxide, as 100% CO ₂ (\$34/t)	3 kg	0.1	
Activation reagent (\$350/t)	1208 kg	423	
Process water (\$5/t)	2060 kg	10	
Cooling water make-up (\$5/t)	35033 kg	175	
Utility steam (\$10/t)	13346 kg	129	
Electricity to compression (\$0.06/kWh)	2864 kWh	181	
Electricity to pumping (\$0.06/kWh)	922 kWh	58	
Feed, reagent & utility cost, \$/t LCE			

Techno-economics

The capital costs listed in Table 7 are based on a production capacity of 20 thousand tonnes per year of lithium carbonate. The capital and operating costs lead to the cash flow analyses shown in Figure 4. Granted, the conventional circuit is commercially proven, and the Novalith circuit is not yet proven. However, there would appear to be more than enough potential economic benefit to justify further development of the Novalith circuit.

Item	Conventional	Novalith
Purchased Equipment	32	59
Equipment Setting	0.5	1
Piping	15	24
Civil	2	3
Steel	0.4	0
Instrumentation	7	7
Electrical	6	6
Insulation	1	1
Other	29	36
G and A Overheads	3	4
Contract Fee	43	4
Contingencies	18	26
Total estimated capital	117	170

Table 7 – Preliminary capital cost estimates for 20 kt/y LCE, US\$ million



Figure 4 – Internal Rate of Return Versus Project Year.

LCA

Table 8 and Table 9 list the flows exiting each circuit.

Table 8 – Exit Flows, Conventional Circuit, kg/tonne Li₂CO₃.

Decerintian	Vapour		L	Calida	
Description	CO ₂	CO ₂ Total		Total	Solids
Flue gas ex calciner	810	7205			
Vent ex acid bake	0	15			
Vent ex Fe oxidation	522	1740			
Vent ex lime slaking	0	0			
Vent ex purification	0	0			
Vent ex decarbonation	546	1686			
Vent ex Na ₂ SO ₄ drier	0	633			
Vent ex Li ₂ CO ₃ drier	1	245			
Water leach residue			801	804	7234
Fe/Al residue			206	207	1859
Ca/Mg/Mn residue			5	5	44
Li carbonate			0	0	1002
Na sulphate			3	3	3877

Description	Vapour		Liquid		Calida
Description	CO ₂	Total	H₂O	Total	Solius
Flue gas ex calcination	765	6809			
Vent ex activation	0	585			
Bicarbonation leach residue	-	-	1822	1822	7319
Waste solutions ex IX	-	-	0.06	0.07	-
Vent ex Li ₂ CO ₃ drier	1	245	-	-	0

Table 9 – Exit Flows, Novalith Circuit, kg/tonne Li₂CO₃.

Climate Change

Figure 5 shows the climate change impact for producing battery-grade lithium carbonate via the conventional circuit, where sodium sulphate is assumed to be a product. The total climate change impact is then calculated to be 14.9 kg CO_2 eq. per kg Li_2CO_3 . Contribution analysis figures aggregate contributors making up less than 1% of the impact category total as 'other'.

- The main contributor to climate change impact is the spodumene concentrate.
 - o 3.8 kg CO₂ eq. per kg Li₂CO₃ which equates to 20.5% of the climate change impact.
 - The primary impact of spodumene concentrate in Australia is the use of diesel in the mining fleet and electricity generation.
- The total contribution of energy used in the process is 6.2 kg CO₂ eq. per kg Li₂CO₃.
 - Utility steam contributes 4.5 kg CO₂ eq. per kg Li₂CO₃, which equates to 24.3% of the total climate change impact.
 - Electricity to pumping contributes to <0.1 kg CO₂ eq. per kg Li₂CO₃, and is incorporated in "Other".
 - Electricity to compression contributes to 0.3 kg CO₂ eq. per kg Li₂CO₃.
 - \circ Electricity to run refrigeration contributes to 1.3 kg CO₂ eq. per kg Li₂CO₃ which equates to 7.0% of the total climate change impact.
- The use of reagents in the process, which in total contribute 8.4 kg CO₂ eq. per kg Li₂CO₃, of which the main contributors are as follows:
 - Sodium carbonate (Li purification) contributes 3.6 kg CO₂ eq. per kg Li₂CO₃.
 - Sulphuric acid contributes 0.7 kg CO₂ eq. per kg Li₂CO₃.



Climate Change

Contribution Analysis (Conventional Route - Na2SO4 co-product)

Figure 5 – Climate Change Contribution Analysis for Lithium Carbonate Produced from Spodumene Concentrate via the Conventional Circuit (Sodium Sulphate as Co-Product).

Figure 6 presents the climate change impact of lithium carbonate produced via the Novalith circuit. This production route's total climate change impact is 10.5 kg CO2 eq. per kg Li2CO3. The climate change impact is made up of the following factors:

- Spodumene concentrate equates to 34.7% of the climate change impact, at 3.6 kg CO₂ eq. per kg Li₂CO₃.
- Electricity accumulates to 25.0% of climate change impacts, at 2.6 kg CO₂ eq. per kg Li₂CO₃.
- Utility steam contributes to 17.3% of climate change impacts, at 1.8 kg CO₂ eq. per kg Li₂CO₃.



Figure 6 – Climate Change Contribution Analysis for Lithium Carbonate Produced from Spodumene Concentrate via the Novalith Circuit.

Comparing the results presented in Figures 5 and 6 shows that, overall, the conventional route has a higher total climate change than that of the Novalith route. The major differences between the conventional route and the Novalith route are the direct emissions, energy requirements, and reagents used. The conventional route has a higher impact due to the exhaust gases produced during the calcination and purification stages, which vent CO_2 into the atmosphere.

The Novalith circuit is an electrified process totalling 3.8 kWh per kg Li₂CO₃, with the greatest electricity demand required for the compression of recycled carbon dioxide. As a result, the composition of the electricity source (e.g. renewable electricity vs. fossil-fuel sources) for the Novalith process can have a large influence on the total climate change impact. In comparison, the conventional sulphation route sources energy from steam, generated by a natural gas boiler, and electricity from the Western Australian grid.

As for the reagents, the conventional route requires more reagent input than the Novalith route, due to the neutralisation and purification stages of the process. As seen in Figure 5, sodium carbonate is one of the main reagents contributing to the climate change impact for the conventional route, compared to Figure 6, where the activation reagent has the largest contribution. This is due to the amount of sodium carbonate used in the process; a total of 2.2 kg of sodium carbonate per kg Li₂CO₃ for the conventional route. The embodied impact of producing sodium carbonate is driven by its manufacturing process, which entails the dissolving of ammonia and carbon dioxide followed by calcination (Solvay process), which requires a large amount of thermal energy.

A key difference between the conventional route and the Novalith route is that the conventional route has the co-product of sodium sulphate. The conventional route where sodium sulphate is considered an economically viable co-product and has the climate change impact of 14.9 kg CO₂ eq. per kg Li₂CO₃. The Novalith route, however, has a lower climate change impact of 10.5 kg CO₂ eq. per kg Li₂CO₃, which is approximately 30% lower than the conventional sulphation process.

Figure 7 shows the climate change impact results for the conventional circuit and the Novalith circuit classified into scope 1, 2 and upstream scope 3 emissions. Scope 3 emissions make up the majority of the impact for both routes. This highlights the value of using a LCA approach, rather than just a GHG inventory analysis. For the conventional route, the upstream scope 3 emissions make up 56% of the total climate change impact. For the Novalith route, the scope 3 emissions account for 54% of the total climate change impact. A notable

difference is the relative difference between the emissions of scope 2 and particularly scope 1. For the conventional route, the scope 1 emissions make up 32.9%, compared to the scope 1 emissions of the Novalith route, which contribute 21% of the total emissions. For the conventional route, scope 2 emissions make up 11.2% of the total emissions, and with Novalith the scope 2 emissions make up 25%.



Figure 7 – Climate Change Impact for Lithium Carbonate Produced via the Different Pathways Broken Down into Scope Emissions.

Water Use

Figure 8 presents the water use calculated for lithium carbonate via the conventional route, totalling 19.4 m³ world eq. per kg Li₂CO₃. This total water use calculation accounts for direct freshwater use on-site and embodied water impacts of consumables used.



Water Scarcity Footprint

Figure 8 – Water Contribution Analysis for Lithium Carbonate Produced from Spodumene Concentrate via the Conventional Route.

In this case, water captured from recycled condensate is taken into account. Of the total water out, 87% exits as water vapour to the atmosphere, and the rest in residue to be disposed of. The non-agricultural water scarcity footprint of the study area is 2.4 m³ world eq. per m³. This indicates that the region where the project is has 2.4 times less available water remaining per area than the world average.

The main contribution to the water impact is from sodium carbonate for Li purification, totalling 11.1 m³ world eq. per kg Li_2CO_3 . This is due to the embodied impacts of sulphuric acid production. Furthermore, -4.5 m³ world eq. per kg Li_2CO_3 has been removed, as this is the impact associated with sodium sulphate which has been removed from the system via system expansion.

Figure 9 presents the water use calculated for lithium carbonate via the Novalith route, totalling 7.4 m³ world eq. per kg Li_2CO_3 . The activation reagent is the main contributing factor in this case, with 4.8 m³ world eq. per kg Li_2CO_3 . This is due to the embodied impact of producing the activation reagent being a water-intensive process. For the Novalith route, 60% of the water leaving the circuit exits as vapour to the atmosphere, the rest in discarded residue.



Water Scarcity Footprint

Figure 9 – Water Contribution Analysis for Lithium Carbonate Produced from Spodumene Concentrate via the Novalith Route.

Sensitivity Analysis

Three sensitivity analyses were performed on the primary assumptions. The scenarios include:

- 1. Sodium sulphate as a waste this analysis looks at the scenario where lithium becomes so abundant that the sodium sulphate co-product is no longer economically viable and therefore becomes a waste product.
- 2. Novalith renewable energy this scenario examines the current Western Australian grid mix versus a more renewable energy mix, in this case; a 70% renewable grid mix.
- 3. Gate-to-Gate this sensitivity scenario looks at the base case conventional route and the base case Novalith route, where the system boundary has removed the cradle and hence the impacts of spodumene concentrate. Therefore, only the impacts of processing the lithium carbonate are considered.

Figure 10 depicts the base case scenarios, plus sensitivity analyses 1-2 as described above. The Novalith circuit has a 30% lower impact than the conventional base case circuit with 10.5 kg CO_2 eq. per kg Li_2CO_3 and 14.9 kg CO_2 eq. per kg Li_2CO_3 , respectively. However, having a clean electrical grid (at least 70% renewables) for Novalith has a significant decrease of 23.7% of the climate change impact. This graph also shows that the conventional route can have a 12.9% increase in the climate change impact where sodium sulphate is considered a waste product compared to the conventional base case scenario.



Figure 10 – Climate Change Contribution Sensitivity Analysis for Lithium Carbonate Produced.

Figure 11 presents the climate change impact of the base case scenarios when the impact of spodumene concentrate is excluded. The conventional route processing has a larger processing impact than the Novalith route.



Climate Change Contribution Analysis - Gate-to-Gate Scenario

Figure 11 – Climate Change Contribution Gate-to-Gate Analysis for Lithium Carbonate Produced.

CONCLUSIONS

This paper shows how a combination of life cycle assessment based on process modelling and technoeconomic evaluation allows early quantification and investigation of the relationship between mineral resource project economics and environmental impacts before substantial development expenditure has been incurred. The example used is the production of lithium carbonate from spodumene concentrate in a conventional circuit and in the novel Novalith circuit.

The techno-economic analysis indicates that the Novalith route offers distinctly better economics than the conventional route, making its ongoing development a rational decision.

Depending on the production pathways, the climate change impact can range from 8.0-16.9 kg CO_2 eq. per kg Li_2CO_3 produced. The water use impact of the two circuits is shown to range between 7.4-19.4 m³ world eq. per kg Li_2CO_3 . For climate change impact, the Novalith circuit has the lowest climate change impact, particularly if the energy can be sourced from at least 70% renewable energy, highlighting the benefits of a more electrified process and a clean electricity mix. For the water use impact, the Novalith circuit has a lower water use impact of 7.4 m³ world eq. per kg Li_2CO_3 . This impact would further increase if impacts of sodium sulphate are included in the conventional route, rather than excluded through system expansion. This increase is due to the electricity and energy requirements for the crystallisation and waste treatment of sodium sulphate. It must be noted that the impact values of the two circuits can change depending on the process location, energy sources, material consumption and process route.

This study shows the value of using and integrating life cycle assessment methods into the early development phase of a project phase, particularly capturing the upstream scope 3 emissions. This enables environmentally informed decisions that can be used to understand and mitigate environmental impacts while the development phase of the project is still flexible.

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