# PROCESS MODELLING AND LIFE CYCLE ASSESSMENT: A CASE STUDY ON PRIMARY LITHIUM PRODUCTION

By

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#### ABSTRACT

Lithium is considered a critical metal to enable the transition from a fossil fuelled to an electric economy. It is estimated that lithium demand can grow up to 500% by 2050, compared to 2018 production. An increase in a demand could lead to higher lithium prices, meaning that previously considered uneconomic assets might become economically sustainable. However, when moving to an electric economy it is critical the improvement in downstream performance is not offset by an increase in environmental impacts from raw material extraction and refining.

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 environmental impacts of technology options. LCA quantifies environmental impacts associated with all stages of a product, process, or activity.

In this study, process modelling paired with prospective LCA modelling is explored, the thesis being that such pairing enables earlier and much better-informed decisions about economic and environmental sustainability. Extraction of lithium from a salar brine is considered, followed by further processing into lithium hydroxide monohydrate via two options, namely the conventional solar evaporation route and a novel route using direct lithium extraction to separate lithium from the salar brine without evaporation, followed by selective lithium solvent extraction to concentrate the lithium into a pure lithium product. An integrated approach is presented that examines economic and environmental factors in evaluating the alternative technologies.

Keywords: Lithium, CO<sub>2</sub>, water, environment, LCA, economics

#### INTRODUCTION

For the current drive towards electrification is to succeed, demand for the metals needed to make storage batteries must become vast. The lithium-ion battery, in various forms, is the leading contender for vehicle batteries, and the global demand for lithium in 2050 is expected to be almost ten times that of 2017<sup>(1)</sup>. This implies that many new lithium extraction projects must arise, along with the environmental challenges associated with all new mining ventures.

Holistic decision-making requires that costs, revenue, carbon footprint, water scarcity footprint and other environmental impact categories are all considered. Traditionally, life cycle assessment (LCA) is based on data from operating plants, but that data cannot be generated before the plant is operating. Leaving LCA to later in the development sequence when operating (or pilot-plant) data can be used means that technical decision making has already happened, and reversing major decisions is costly in terms of time and money. It would be preferable to have LCA input earlier in the project so that major decisions need not be reversed or adverse environmental consequences locked in. Process modelling can be used to evaluate the techno-economic feasibility of a project, whilst life cycle assessment (LCA) can be used to quantify its environmental impacts. LCA is a methodology for quantifying environmental impacts associated with all stages of a product, process, or activity that enables earlier and better-informed decisions about the economic and environmental sustainability of the project concerned.

The exercise presented here explores the pairing of techno-economics and LCA. Extraction of lithium from a salar brine by two technical routes is considered, with the lithium being extracted and recovered as lithium carbonate or lithium hydroxide, using conventional solar evaporation or direct lithium extraction without solar evaporation. An integrated approach is presented that examines economic and environmental factors for the alternative technologies.

## METHODOLOGY

Life cycle assessment (LCA) is a scientific methodology to assess global environmental impacts associated with the life cycle of a product or process. Beyond this generic definition, LCA is a comprehensive and reliable tool that enables environmentally informed decision-making throughout all the stages of a project. Life cycle assessment 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 enabling informed decisions that avoid, for example, simple shifting of an environmental burden<sup>(2)</sup>. It must be noted that LCA is a powerful tool to determine impacts at a global scale, but it is less suitable for determining local impacts that are commonly investigated using environmental (and social) impact assessment studies.

LCA uses process data to quantify 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 modelling can be used to generate plausible preliminary data<sup>(4)</sup>. 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 the preliminary data required to techno-economic evaluation and LCA for the two processing options examined.

Principles as outlined under ISO 14040<sup>(7)</sup> and ISO 14044<sup>(8)</sup> standards series were used in this study. They outline a four-step process, as shown in Figure 1.

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

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

The life cycle assessment study presented here takes a cradle to gate approach. This means that the impacts are accounted for from resource extraction up to where the lithium product is ready for shipment to customers. The system boundaries used in this study are presented in Figure 2. The results of this life cycle assessment study are considered to be relevant input for rational decision making and ranking processing options but are not intended to communicate comparative assertions to the general public.



Figure 1 – LCA stages



Figure 2 – System boundaries applied in this LCA study

## LIFE CYCLE IMPACT ASSESSMENT

While there are other factors as well, 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" released by human activity. There is 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<sup>(6)</sup>. The environmental profiles characterization 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 CO<sub>2</sub> eq.

The Greenhouse Gas Protocol identifies three "scopes" of GHG emissions which have been included in this study. It should be noted, however, 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 (such as 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 (for example 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 UNEP-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 any given watershed after human and ecosystem demands have been met, relative to the world average. The resulting characterization factor ranges between 0.1 and 100 and can be used to calculate water scarcity footprints<sup>(9)</sup>. 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 characterization factor are dimensionless, expressed in m<sup>3</sup> world eq. per m<sup>3</sup>. It is important to note that this impact relates to the potential of 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 this exercise is assumed to be 40 m<sup>3</sup> world eq. per m<sup>3</sup>.

#### ALLOCATION

A difficulty in LCA is that, if a system produces multiple products, the impacts have to be divided between those products such that the distribution of the impacts between those products and the benefits of those products are allocated fairly; this is called allocation. It should follow a stepwise approach<sup>(8)</sup> and is not always easy. The two production pathways described in Figure 2 do not have any co-products, meaning that no allocation is required in the exercise presented here.

#### PROCESSES

This study extends a previous exercise<sup>(2)</sup>, in which the extraction of lithium from a salar brine and from lithium bearing clay was examined. The source is the same salar brine as before (Table 1) and two processing options are examined:

- The conventional solar evaporation route from the previous exercise (the solar evaporation route).
- A novel route entailing the use of a lithium-ion sieve and lithium-selective solvent extraction (the DLE-SX route).

Mg	4826
Ca	415
Na	487500
К	24900
Li	1960

#### Table 1 – Hypothetical brine, ppm

#### Solar evaporation

The brine is concentrated by solar evaporation in a series of large ponds, causing mainly sodium chloride (initially) and potassium chloride (subsequently) to crystallize and settle to the bottom of the evaporation ponds. The settled salts are harvested periodically and disposed of on dumps. Depending on the composition of the brine, other salts such as calcium sulphate, borates and double salts can also crystallize. If the brine contains more than a small amount of magnesium, a lithium-magnesium double salt can crystallize, causing loss of lithium. In such cases the brine is treated with lime at some suitable point in the evaporation sequence, precipitating the magnesium as hydroxide and replacing it with calcium, to avoid that form of lithium loss. The first part of this circuit is illustrated in Figure 3 and the second in Figure 4.

Brine from the wellfield is limed, the resulting mixture of gypsum and magnesium hydroxide is settled out and the remaining brine is concentrated by solar evaporation. The solar evaporation is modelled as two steps, first crystallizing out sodium chloride and then crystallising out sodium and potassium chloride. (The two pond icons shown, of course, each represent multiple solar ponds.)

Hydrochloric acid is added to the evaporated brine to lower the pH and the acidified brine is warmed by heat exchange with steam, then passed through solvent extraction to remove the bulk of the boron. The boron-loaded organic phase is stripped with aqueous sodium hydroxide and the resulting strip solution is disposed of in a waste pond.



Magnesium hydroxide, gypsum

Figure 3 – Conventional circuit processing salar brine





The boron-depleted brine is dosed with sodium carbonate to precipitate the bulk of the remaining calcium and magnesium, the precipitate being settled and filtered. The filter cake is washed with water and disposed of. The filtrate is passed through two ion exchange steps, first to remove residual calcium and magnesium, then to remove residual boron. In these ion exchange steps, the loaded resin is stripped with dilute hydrochloric acid and regenerated with dilute sodium hydroxide. The spent reagents are disposed of in the waste pond.

The purified brine is concentrated further by evaporation against condensing steam, with some of the remaining sodium chloride crystallizing and being removed. The concentrated brine is dosed with sodium carbonate, precipitating lithium carbonate that is recovered by thickening. Part of the thickener underflow is

recycled to the precipitation step as seed and the balance is filtered. The filter cake is washed with water and the filtrate is recycled to the Ca/Mg precipitation step in the front end of the circuit to bleed out impurities (Ca, Mg, B).

The washed filter cake is mixed with water and carbon dioxide at ambient temperature and somewhat elevated pressure (about 3 bar). The carbon dioxide reacts with the carbonate, forming bicarbonate and thereby redissolving the lithium. The addition of  $CO_2$  is manipulated to re-dissolve the lithium carbonate while leaving impurities such as calcium carbonate undissolved. The bicarbonate solution is filtered, and the solid impurities are discarded. The filtrate is heated and depressurised, causing the aqueous bicarbonate to revert to carbonate and carbon dioxide, re-precipitating purified lithium carbonate that is recovered and washed with water in a centrifuge, then dried. The primary centrate is recycled to the redissolution step. The wash centrate and fresh water are used to dissolve solid sodium carbonate to make up the near-saturated solution of sodium carbonate that is used to precipitate lithium carbonate from the solution ex evaporation.

# DLE-SX

The chemistry of processing salar brines via solar evaporation requires essentially all the divalent cations in the brine to be replaced with sodium. Where calcium hydroxide is used to remove magnesium, the magnesium is replaced by calcium that is later replaced with sodium, thus the magnesium is ultimately also replaced with sodium. The ratio of divalent cations to lithium determines the amount of sodium needed to replace the divalent cations, and the cost of the sodium accounts for an appreciable part of the overall cost of extracting lithium from salar brine. There is chemistry that selectively removes lithium in the presence of divalent cations, based on materials called lithium-ion sieves, one example being solid meta-titanic acid, which can selectively absorb lithium from brines containing high levels of calcium, magnesium and other cations<sup>(11,12)</sup>. The essential chemistry (bold denoting the solid phase) is:

$$H_2TiO_3 + H_2O + Li^+ \leftrightarrow LiHTiO_3 + H_3O^+$$

The crystal structure of the solid phase is such that the "holes" are small enough to allow only lithium or protons into the lattice, thus making the equilibrium highly selective for lithium.

Figure 5 and Figure 6 illustrate a circuit exploiting this chemistry. Incoming brine is mixed with recycled solution from the ion exchange purification stage and filtrate from the first precipitation of lithium carbonate, then passed through two counter-current stages of loading, where the lithium is absorbed into the lattice of the  $H_2TiO_3$  sorbent, releasing protons. The loading reactors are held close to neutral (pH 7) by the addition of sodium or ammonium hydroxide. The resulting loaded sorbent (a mixture of  $H_2TiO_3$  and LiHTiO<sub>3</sub>) is washed with water in a counter-current decantation train, then stripped in a recirculating solution of lithium chloride (from the first thickener in the subsequent counter-current decantation train) that is held at about pH 2 by addition of concentrated hydrochloric acid into the circulating solution. The regenerated  $H_2TiO_3$  is washed with water in a second counter-current decantation train, then recycled to the loading reactors.

A bleed from the circulating strip solution is filtered to capture and remove any entrained solids, the ensuing small loss of sorbent being replaced by fresh sorbent added to the stripping reactor. The pH of the resulting solids-free solution is raised, and ion exchange is used to remove the residual entrained divalent cations (mainly Ca<sup>2+</sup>) not washed off the loaded sorbent in the counter-current decantation train preceding the stripping step. The resin is stripped with hydrochloric acid and regenerated with sodium hydroxide. The spent strip acid is recycled to the feed tank ahead of the ion exchange section. The spent regenerant is recycled to the feed tank ahead of the loading reactors via another counter-current decantation train.

The resulting purified solution of lithium chloride goes to the circuit illustrated in Figure 6. This circuit exploits a solvent extraction system that very selectively extracts lithium from solutions also containing other monovalent cations like sodium and potassium. The prime requirement is that the feed solution be free of divalent cations because these are extracted ahead of lithium. The preceding Li-ion sieve circuit extracts lithium and rejects divalent cations very selectively but does not concentrate the lithium overly and the lithium brine produced necessarily contains sodium cations.

The incoming LiCl brine is contacted with the organic solvent, the Li cations being extracted completely and very selectively. The pH is held at neutral by the addition of sodium hydroxide. The loaded organic solvent is then stripped with recycled sulphuric acid from the subsequent electrolysis step, in which the loaded strip liquor is passed to the anode side of a chlor-alkali type electrolysis cell. Oxygen is evolved at the anodes, releasing protons and thus regenerating sulphuric acid. Hydrogen is evolved at the cathode, generating OH<sup>-</sup> ions that are balanced by Li<sup>+</sup> ions passing through the cation selective membrane. The anolyte, atter supplementation for minor losses with sulphuric acid and water (to replace the water decomposed by the production of oxygen and hydrogen) is recycled to the stripping step of the solvent extraction sequence. The catholyte is evaporated to crystallize lithium hydroxide monohydrate that is recovered by centrifugation and washing with part of the condensate from the evaporation step. The wash centrate and the balance of the condensate ex the evaporation step are recycled to the cathode side of the electrolysis stage. The washed lithium hydroxide is dried and becomes the product, or (not shown) can be treated with CO<sub>2</sub> to make high-grade lithium carbonate.









While admittedly still in their infancy, both the Li-ion sieve technology and the Li-selective solvent extraction technology have been tested reasonably extensively, up to pilot plant scale and engineering evaluations. For the purposes of the exercise presented here, these technologies are accepted as sound, but obviously both would require substantially more work to become commercial practice.

# **TECHNO-ECONOMIC RESULTS**

The approach used for generating estimates of the capital and operating costs associated with the process routes in this exercise was to develop and analyse process models (mass-energy balances) for each, then to estimate the capital costs. The techniques used are presented in detail elsewhere<sup>5</sup>. Published data was used to estimate the capital costs.

#### Variable operating costs

Table 2 and Table 3 list the variable operating costs calculated for the two routes examined. The DLE-SX route would seem to have an advantage of about 30 percent over the established route, at an electricity cost of \$0.05/kWh. At \$0.1/kWh that advantage drops by about 5 percent.

Solar evaporation	Amount	Cost, \$
Lime (\$60/t CaO)	3596 kg	216
Hydrochloric acid (\$200/t 32% HCl)	4633 kg	927
Sodium hydroxide (\$450/t NaOH)	1630 kg	367
Sodium carbonate (\$300/t Na <sub>2</sub> CO <sub>3</sub> )	21 kg	6
Utility steam (\$20/t)	495 kg	10
Electricity (\$0.05/kWh)	48 kWh	2
Fresh water (\$2/m³)	53 m³	107
Sub-total reagent/utility cost per tonne L0	1635	
Li <sub>2</sub> CO <sub>3</sub> precipitation and refining	Amount	Cost, \$
Sodium carbonate (\$300/t Na <sub>2</sub> CO <sub>3</sub> )	2238 kg	671
Carbon dioxide (\$50/t CO <sub>2</sub> )	42 kg	2
Utility steam (\$20/t)	5526 kg	111
Electricity (\$0.05/kWh)	52 kWh	3
Fresh water (\$2/m³)	15 m³	29
Sub-total reagent/utility cost per tonne L	816	
Combined reagent/utility cost per tonne I	2451	

Table 2 –	Solar	evaporation	variable	costs	ner	tonne	I CF
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## Capital and fixed operating costs

For both routes examined, the capacity was assumed to be 40 kilotons per year, with the product expressed as lithium carbonate equivalent (LCE). When the product is lithium carbonate, one tonne of product is one tonne LCE. When the product is lithium hydroxide monohydrate, one tonne of the product is 880.4 kg LCE. For this exercise, the capital cost associated with the solar evaporation route was taken from published information on the production of lithium carbonate from the Cauchari-Olaroz Salars in the Jujuy Province of Argentina<sup>(14)</sup>. For the route using lithium-ion sieve technology, selective solvent extraction and electrolysis, the capital cost was extrapolated from published information on the Lanxess Smackover project<sup>(15)</sup>.

Table 4 lists the capital and fixed operating costs for the solar evaporation circuit. Table 5 shows the calculation of the capital cost for the Li-ion sieve route. The Standard Lithium project had three phases, capacity and cost of each as listed. Plotting the capital costs versus the design capacities for the three phases gives the plot shown in Figure 7, and fitting a power function through the data points gives the equation shown in the box on that graph. A capital cost for the Li-ion sieve route was calculated by scaling the costs for each phase - multiplying each capacity by 40000/209000 and using the equation in Figure 7 to calculate a scaled capital cost for each phase, then totalling the three numbers so calculated. The production wells were assumed to be the same for both cases.

The fixed operating costs were assumed to be the same for both routes, and to be those of the solar evaporation route. Table 6 shows the fixed operating costs.

## **Cash flow calculations**

Cash flow calculations boil the various costs and revenues down to a set of simple numbers that show the relative economics of the options examined. The revenue for the two process routes would be the selling prices of lithium carbonate and lithium hydroxide monohydrate, respectively. Setting values for these numbers is not a trivial exercise. The values assumed for this exercise are thought to be plausible but are not claimed to be accurate; they are used only because cash flow modelling deals with revenues as well as costs, and therefore requires selling prices. Table 7 lists the assumptions used in the cash flow calculations.

LiSTR	Amount	Cost, \$
Sodium hydroxide (\$450/t NaOH)	1099 kg	495
Hydrochloric acid (\$200/t 32% HCl)	3204 kg	641
Make-up Li <sub>2</sub> TiO <sub>3</sub> (\$8000/t)	9 kg	74
Electricity (\$0.05/kWh)	6 kWh	0
Fresh water (\$1.61 per m³)	13 m³	25
Sub-total reagent/utility cost	1236	
Li SX-EW and LiOH crystallization	Amount	Cost, \$
Sodium hydroxide (\$450/t NaOH)	1119 kg	503
Sulphuric acid (\$200/t H <sub>2</sub> SO <sub>4</sub> )	46 kg	12
Utility steam (\$20/t)	83 kg	2
Natural gas (\$400/t)	0.4 kg	0
Electricity (\$0.1/kWh)	1818 kWh	91
Fresh water (\$0.43 per m³)	12 m³	25
Sub-total reagent/utility cost per	633	
Combined reagent/utility cost	1868	

# Table 3 – DLE-SX, variable costs per tonne LCE

#### Table 4 – Capital and fixed operating costs, solar evaporation route

Production wells	S50 million
Solar evaporation ponds and lithium carbonate plant	S565 million
Annual maintenance (3% of capex)	\$16 million/y
Manpower, other fixed costs	\$24 million/y

# Table 5 – Capital and fixed operating costs, Li ion-sieve route

LiSTR data			At 40 kt/y LCE
Phase 1	9700 tpa LCE	\$137 million	\$181 million
Phase 2	8200 tpa LCE	\$129 million	\$169 million
Phase 3	3000 tpa LCE	\$84 million	\$110 million
Total	20900 tpa LCE	\$350 million	\$460 million
Production wells			\$50 million

# Table 6 – Fixed operating costs

Annual maintenance (3% of capex)	\$16 million/y
Manpower, other fixed costs	\$24 million/y



Figure 7 – Capex versus capacity, Standard Lithium project Table 7 – Assumptions used for cash flow calculations.

Corporate tax rate	20%	Production in year 1	25%
Estimated capital cost	\$600 M	Production in year 2	50%
Capital expenditure in year -1	50%	Production in year 3	75%
Capital expenditure in year 0	50%	Production after year 3	100%
Selling price for Li <sub>2</sub> CO <sub>3</sub>	S30000/t	Selling price for LiOH•H <sub>2</sub> O	S36000/t

The capital and operating costs calculated for this exercise lead to the cash flow calculations presented next. Figure 8 shows the internal rates of return calculated for the two process routes. While both appear to offer attractive rates of return, the DLE-SX route appears to be stronger than the solar evaporation route.

Figure 9 shows the results of NPV (net present value) calculations for the two circuits, assuming a discount rate (annual cost of capital) of 10% in both cases on the left and 15% for the DLE-SX route on the right. The DLE-SX route appears to be superior at the same cost of capital as the solar evaporation route, but because the DLE-SX route is still unproven it might be prudent to assign it a higher cost of capital to account for the added technical risk compared to the other circuit that is well established. Making the cost of capital 5% higher for the unproven route essentially eliminates its advantage in terms of the NPV.



Figure 8 – IRR calculations



#### Figure 9 – NPV calculations

# LIFE CYCLE IMPACT ASSESSMENT RESULTS

The above cash flow calculations ignore the impact of the LCA results, which are as follows.

## Climate Change

Figure 9 shows the climate change impact for producing lithium hydroxide monohydrate via the conventional solar evaporation route. The total climate change impact is calculated to be 14.7 kg CO<sub>2</sub> eq. per kg LCE (lithium carbonate or equivalent).

- Total contribution of energy used in the process is 5.8 kg CO<sub>2</sub> eq. per kg LCE:
  - o Steam, raised using of natural gas, contributes 5.7 kg CO<sub>2</sub> eq. per kg LCE.
  - Electricity contributes 0.1 kg CO<sub>2</sub> eq. per kg LCE.
- The use of reagents in the process, which in total contribute 9.1 kg CO<sub>2</sub> eq. per kg LiOH•H<sub>2</sub>O, of which the contribution is as follows:
  - $\circ$  Lime contributes 4.3 kg Co<sub>2</sub> eq. per kg LCE
  - $\circ$  Hydrochloric acid contributes 1.3 kg CO<sub>2</sub> eq. per kg LiOH•H<sub>2</sub>O.
  - Sodium hydroxide contributes 0.3 kg  $CO_2$  eq. per kg LiOH•H<sub>2</sub>O.
  - Sodium carbonate contributes 2.9 kg  $CO_2$  eq. per kg LiOH•H<sub>2</sub>O.

The relative impact of direct  $CO_2$  emissions from the process to the atmosphere is negligible compared to the embodied impact of steam and reagents used in the process.



Figure 9 – Climate change contribution for the solar evaporation route

Figure 10 presents the climate change impact for the DLE-SX route. The total climate change impact for this route is 6.1 kg  $CO_2$  eq. per kg LCE. The climate change impact is made up of the following factors:

- More than half of the climate change impact of lithium hydroxide produced via this route comes from the embodied impact of sodium hydroxide used in the process, which contributes 2.9 kg CO<sub>2</sub> eq. per kg LCE.
- Electricity, assumed to be produced on site from natural gas, contributes 1.2 kg CO<sub>2</sub> eq. per kg LCE.
- Hydrochloric acid used for direct lithium extraction contributes 0.9 kg CO<sub>2</sub> eq. per kg LCE.
- Direct hydrogen gas emissions from the production process contributes 0.3 kg CO<sub>2</sub> eq. per kg LCE.



# Climate Change

Figure 10 – Climate change contribution for the DLE-SX route

Comparing the results presented in Figure 9 and Figure 10, note that, overall, the DLE-SX route has fewer items contributing to the climate change impact. This could have to do with the lower technology readiness level of the DLE-SX route, in that its requirements for energy and consumables might be increase as the technology evolves further. Conversely, it is plausible that the DLE-SX route is really the better of the two.

A significant difference between the two routes is that in the DLKE-SX route, there being no evaporation of the salar brine, the lithium-depleted brine is returned to the salar. This does not contribute to the climate change impact but could conceivably affect the lithium content of the salar brine over time. The total waste from the DLE-SX route is much lower than the total waste from the solar evaporation route, per unit of lithium product, if the depleted brine returned to the salar is not considered a waste stream.

Figure 11 shows the climate change impact results for the solar evaporation and the DLE-SX routes, classified into scope 1, 2 and upstream scope 3 emissions. Scope 3 emissions make up most of the impact for both routes, which is a good example of why it is essential to use a life cycle assessment approach rather than just greenhouse gas inventory analysis. For the solar evaporation route, the upstream scope 3 emissions make up 67% of the total climate change impact. For the DLE-SX route, the scope 3 emissions account for 72% of the total climate change impact (of a smaller total than for the solar evaporation route). An interesting difference between the two routes is the relative contribution of scope 1 and scope 2 emissions. For the solar evaporation route, scope 1 emissions make up 33% of the climate change impact, whilst scope 1 emissions make up only 7% for the DLE-SX route. For the DLE-SX route, scope 2 emissions account for 21% of the total climate change impact, which for the solar evaporation route is less than 1%.



Figure 11 – Climate change impact as scope contributions

# Carbon tax

Carbon taxes are a recent development that effectively add to the variable cost of a process, the amount depending on the carbon footprint of the process concerned. For this exercise, the assumption used is that the carbon tax will take the form of an amount at present, increasing annually into the future. The Canadian numbers<sup>(16)</sup> for this are \$50 in 2022, escalating by \$15/year from 2023 to 2030.

Figure 12 shows the impact of carbon tax on the IRR and NPV calculations as before. The symbols are the curves with the carbon tax and the lines are the NPV or IRR without the carbon tax. At the preliminary level of this exercise, the carbon tax makes no appreciable difference to the IRR for either process, while the NPV calculation indicates that the carbon tax does affect the economics of the conventional route to a small extent. This agrees qualitatively with the relative magnitudes of the two carbon footprints shown in Figure 11.



Figure 12 – Effect of C tax on IRR and NPV

# Water Use

Figure 13 presents the water use calculated for lithium hydroxide monohydrate via the solar evaporation route, totalling at 24.0 m<sup>3</sup> world eq. per kg LCE. This total water use calculation accounts for direct use of fresh water on site, and embodied water impacts of consumables used. Water evaporated from the brine is considered as water used, as per the AWARE methodology which states that evaporated water is considered used. It is the direct H<sub>2</sub>O emissions evaporated to air that account for most of the water impact: 20.3 m<sup>3</sup> world eq. per kg LCE. This value is relatively high due to the high water-scarcity footprint, which amplifies this value by a factor of 40. The relative water use impact of reagents such as hydrochloric acid and sodium carbonate is higher than the relative water use contribution from fresh water. By far the bulk of the water use, however, is evaporation from the solar ponds.



Figure 13 – Water use contribution for the solar evaporation route

Figure 11 presents the water use for the DLE-SX route. The water use for this route is one quarter of the value calculated for the solar evaporation route: 7.7 m<sup>3</sup> world eq. per kg LCE. Direct water emissions to air are much lower for this route, which can be attributed to the fact that the depleted brine brine returns to the aquifer and, in the AWARE methodology, is not considered used. The largest contributor to the water use impact is sodium hydroxide, which contributes 3.1 m<sup>3</sup> world eq. per kg LCE. That value is identical to the total freshwater input and direct water emissions that contribute to the water use impact via this route.





Bringing the water footprint into the relevant business (cash flow) calculations is not currently possible in the same way as carbon tax brings the CO<sub>2</sub> footprint into these calculations. This is quite probably an aspect of

LCA that could be handled like CO<sub>2</sub>, which would require consensus between the various stakeholders that may or may not be achievable – practioners of LCA might do well to add this to their efforts.

# CONCLUSIONS

This paper explores the pairing of life cycle assessment and techno-economic evaluation to quantify and investigate the relationship between mineral resource project economics and environmental impacts when considering the production of lithium from a salar brine.

The techno-economic analysis indicates that direct extraction plus selective solvent extraction of lithium from the brine is potentially superior to the established route of solar evaporation, etc. However, adding a 5% risk premium to the cost of capital to allow for the technical risk associated with the novel process eliminates its apparent economic advantage. The 5% risk premium is a pure guess, meant to show the impact of such an assumption. What suc a risk premium should actually be is beyond the scope of this paper.

Depending on the production pathways, the climate change impact can range between 5.5 and 19.3 kg  $CO_2$  eq. per kg LiOH•H<sub>2</sub>O. The water use impact of the routes shown to range between 7.6 and 26.0 m<sup>3</sup> world eq. per kg LiOH•H<sub>2</sub>O. Both for the climate change and water use impacts, the direct lithium extraction and electrolysis had the lowest impact and the solar evaporation route the highest.

At the levels used in this study, the carbon tax has a negligible impact on the economics of both process routes. That could mean that neither emits enough  $CO_2$  to matter particularly, or, more probably, that the carbon tax levels are too low to appreciably influence the choice between these two process routes.

It is important to note that LCA results from any one project are not transferrable to other projects. Site specific factors play a major role.

The study shows the value of integrating life cycle assessment metrics into the early development phase. This enables environmentally informed decisions, that mitigate environmental impacts while the process flexibility is high.

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