Life Cycle Assessment for the production of Lithium Hydroxide Monohydrate battery-grade

LITHIUM ARK

1st International Circular Hydrometallurgy Symposium
September, 2024

Who are we?

Peter Ehren & **Macarena González** bring over **40+ combined years** of experience in the lithium industry. Two Companies:

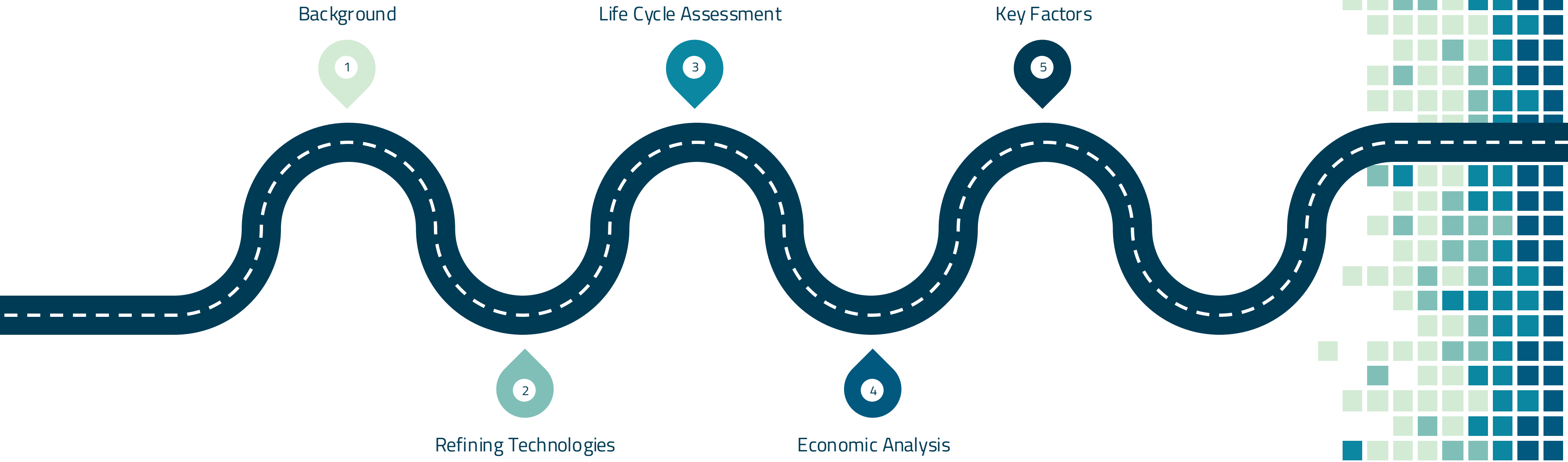
Process & Environmental Consultancy (2007): provides technological- and ESG-based solutions to address a range of challenges in the Lithium sector (lithium-experts.com):

- Worked with the leading companies in the lithium space
- With a strong focus on challenges in extraction & refining
- Spanning projects from lab-scale to full-scale production
- Lithium sourced from brines (DLE and solar evaporation) hard rock and sedimentary rock (clay)
- Visited many of the most significant lithium projects in the world.

Lithium Ark (2021): A clean tech company that:

- Offers Blue and Green+ Lithium Refining – two novel pathways.
- Helps companies transition from Black/Grey Refining to Blue/Green Refining

ROADMAP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1. Background

Lithium Sources

- Brines
- Ores (Spodumene)
- Clays

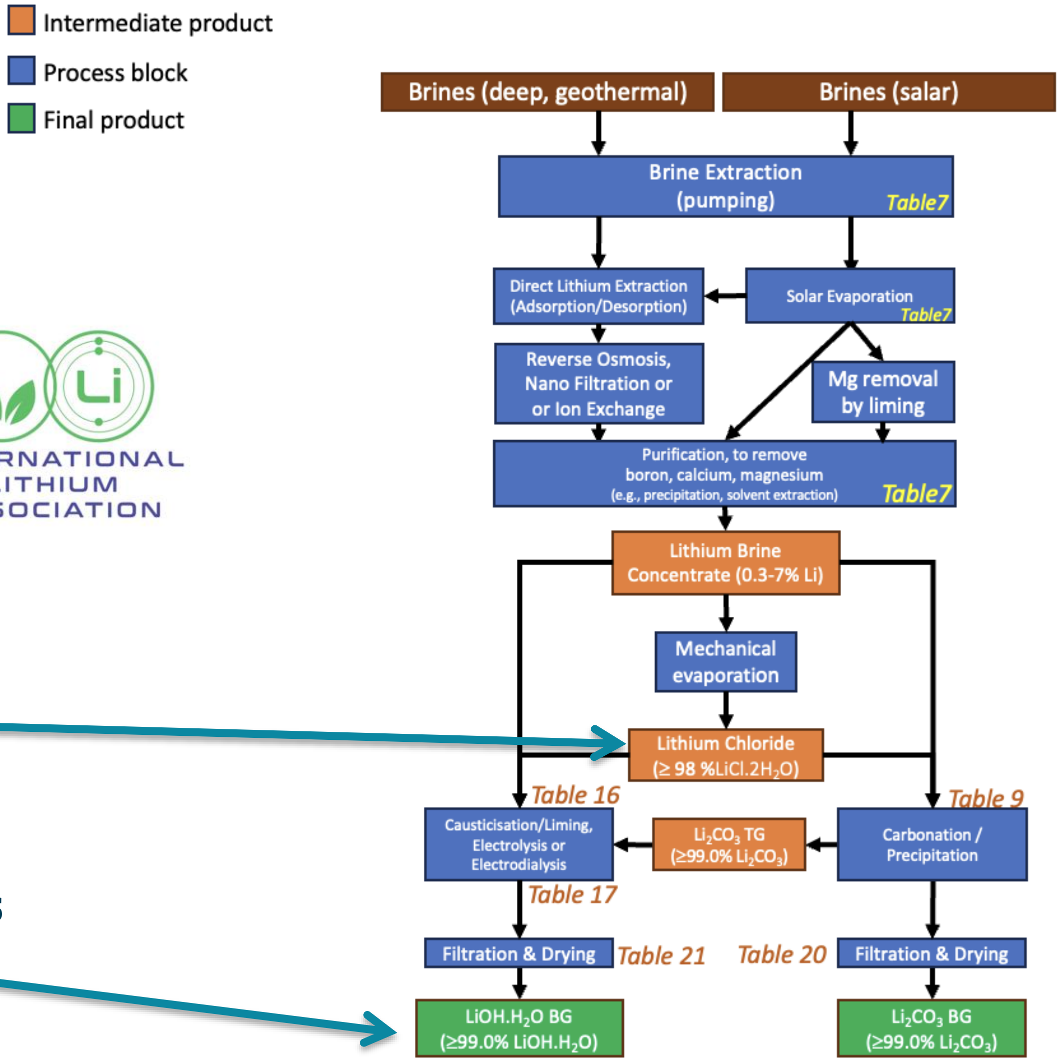
Salar de Olaroz, Argentina (Arcadium Lithium)

Talison Lithium's Greenbushes Mine (iLiA, 2024).

Ioneer, Nevada (Ioneer.com)

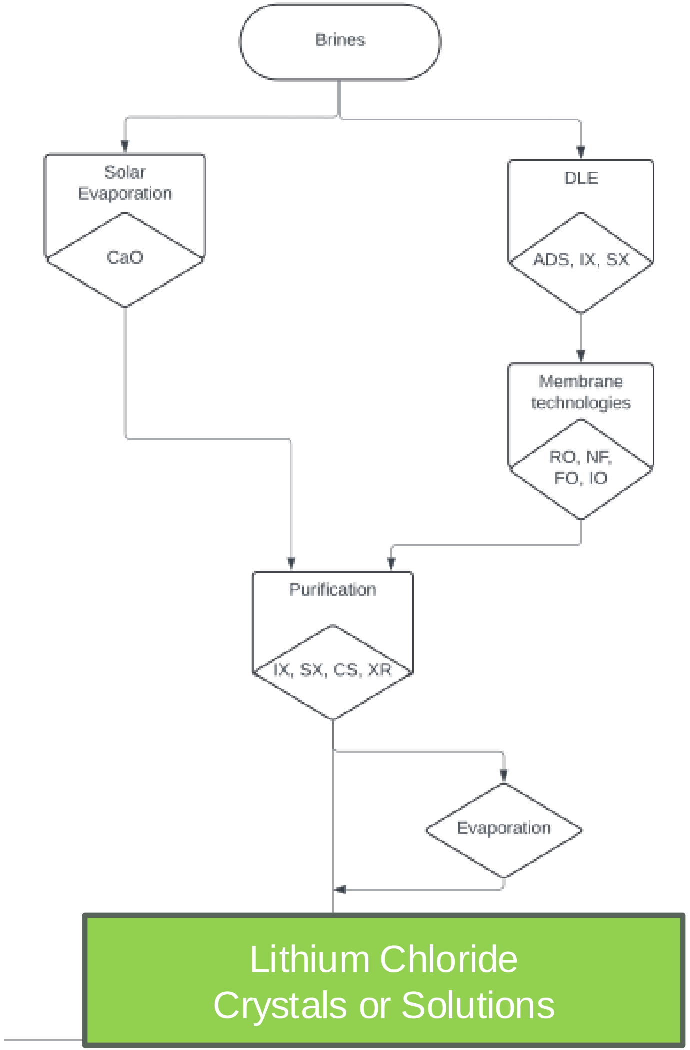
Lithium Chloride

Lithium battery-grade Products

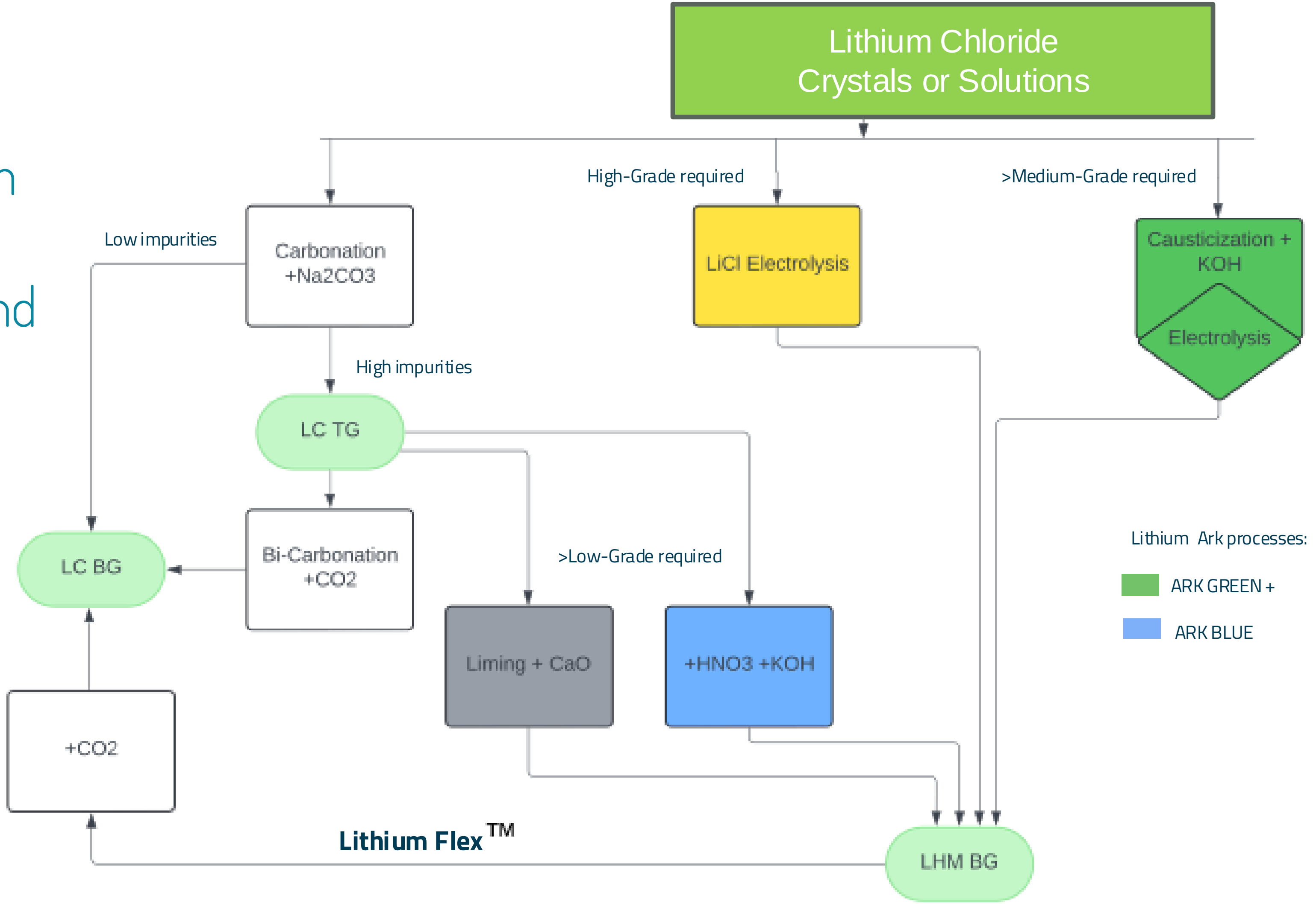


ILiA,2024

All roads go through Lithium Chloride



From Lithium Chloride to Carbonate and Hydroxide



2. Refining Technologies

Caustization with Potassium Hydroxide (Ark Green+)

ARK GREEN+: Pathway to Zero-Carbon, Zero-Waste Conversion

- Lithium Chloride is converted into LiOH by adding KOH.
- Potassium Chloride (KCl) and battery-grade Lithium Hydroxide (LiOH) are easily crystallized from solution.
- KCl is 100% recycled back into KOH via electrolysis, making the reagent fully circular.
- Electrolysis generates HCl (Acid), useful in brine processing.

Lithium Chloride (Feedstock)

Crystallization

Lithium Hydroxide (Battery Grade)

(Optionally)

Lithium Carbonate (Battery Grade)

Just add CO_2

Potassium Hydroxide (KOH)

KCl-Electrolysis

Potassium Chloride (KCl)

Hydrochloric Acid (HCl)
Or Clorine gas

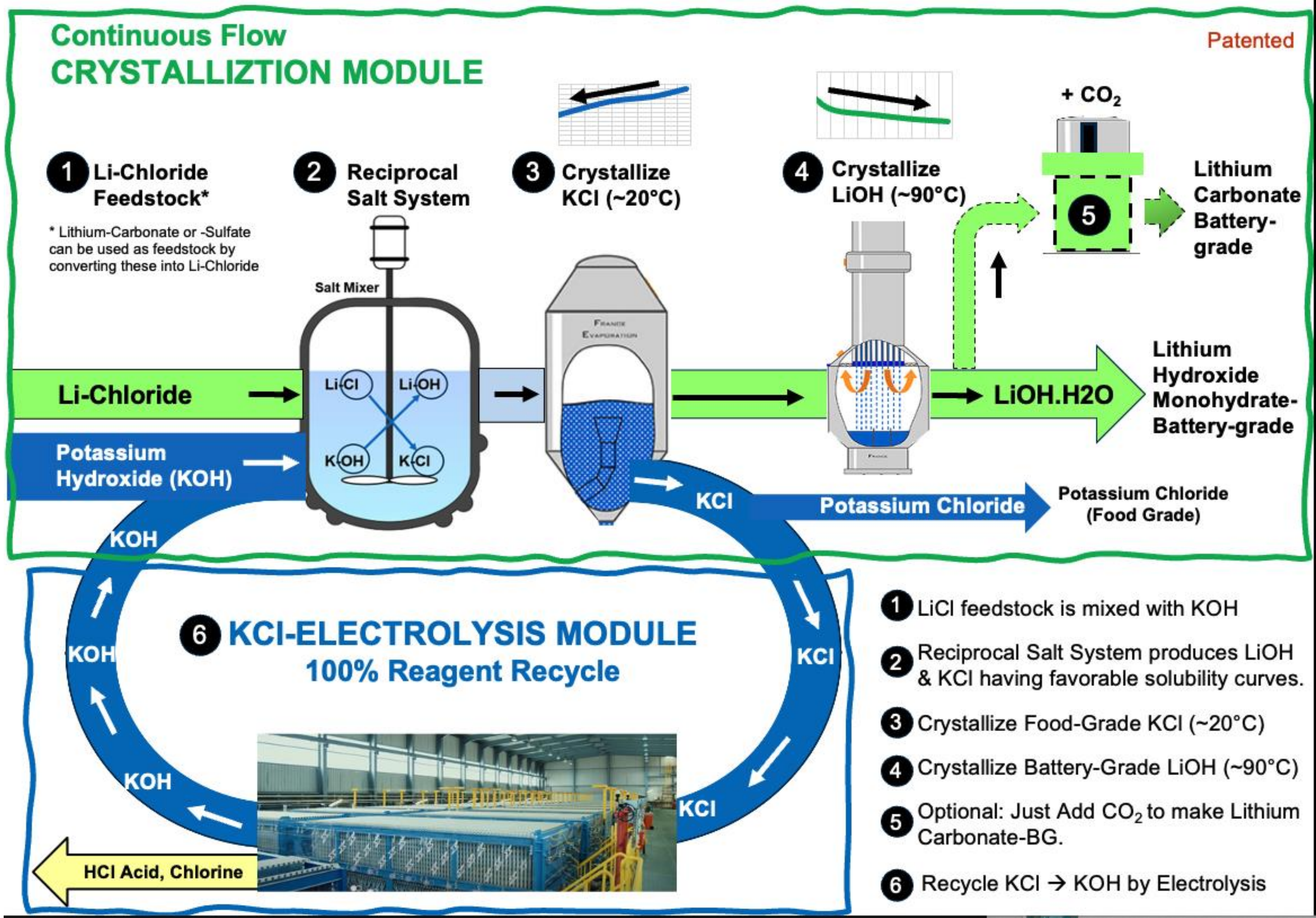
Green+ Refining:

- NO Reagent Sourcing
- NO Reagent Transport
- NO Reagent Impurities
- NO Waste Generated
- **Lowest** CO2 emission
- **Unmatched** OPEX/MT

Caustization with Potassium Hydroxide
(Ark Green+)

LiCl + KOH <=> LiOH + KCl

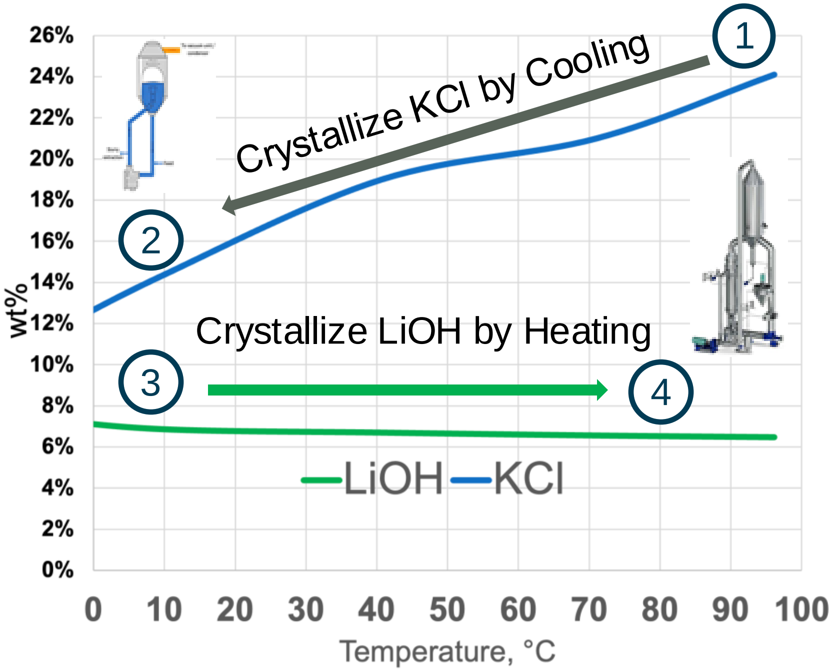
Lithium Chloride | Potassium Hydroxide | Lithium Hydroxide | Potassium Chloride



1. LiCl feedstock is mixed with KOH
2. Reciprocal Salt System produces LiOH & KCl having favorable solubility curves.
3. Crystallize Food-Grade KCl (~20°C)
4. Crystallize Battery-Grade LiOH (~90°C)
5. Optional: Just Add CO_2 to make Lithium Carbonate-BG.
6. Recycle KCl → KOH by Electrolysis

Green+ Refining: Crystallization to Achieve High-Purity

Our process uses crystallization equipment and processing common in the **chlor-alkali** industry to separate high-purity crystals of Lithium Hydroxide (LiOH) & Potassium Chloride (KCl) from the salt mixture.



The inverse slopes of the two solubility curves are exploited:

Potassium Chloride (KCl) is separated, purified and crystallized by cooling (20°C) without co-crystallization of Lithium Hydroxide (LiOH).

Then,

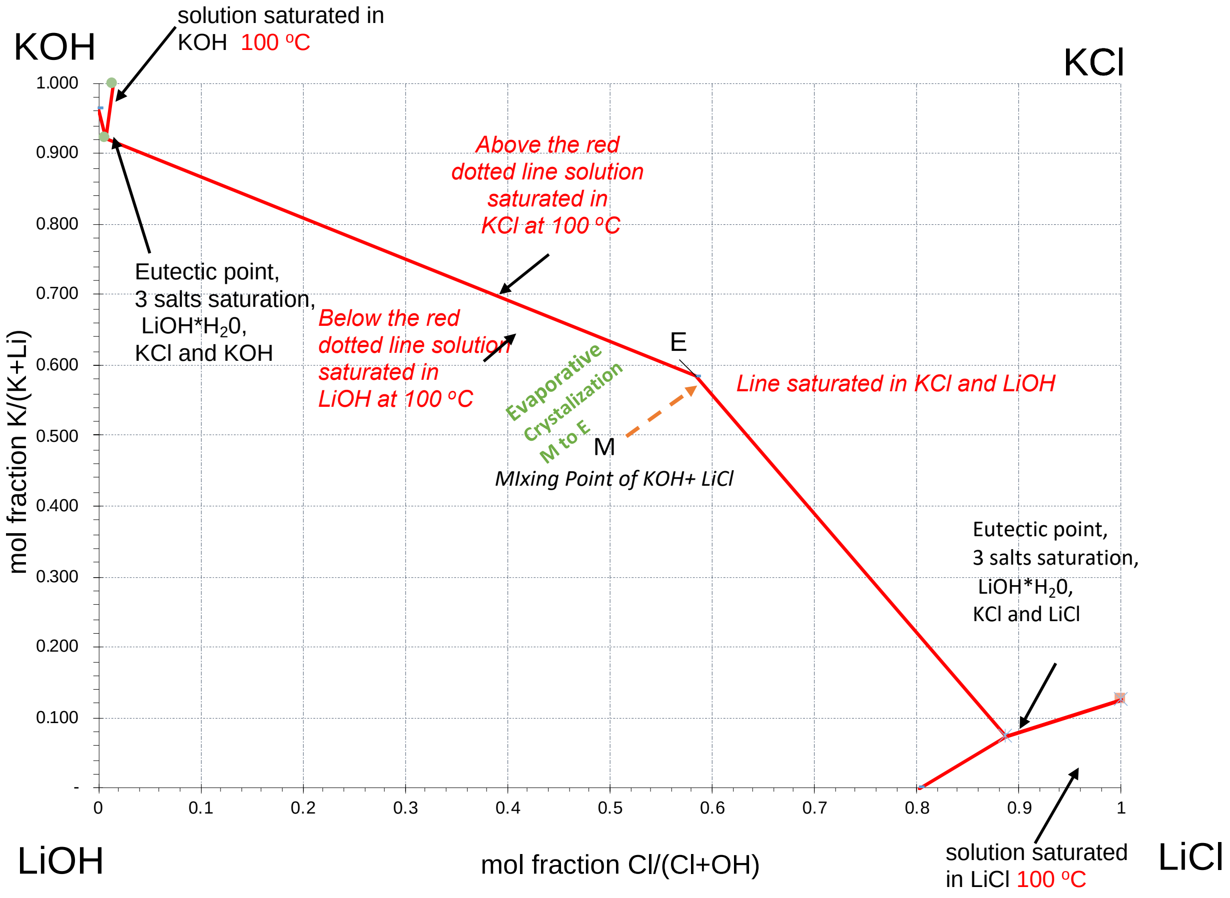
Lithium Hydroxide (LiOH) is separated, purified and crystallized by evaporative heating (90°C) without co-crystallization of KCl.

All other impurities remain in solution to be later purged

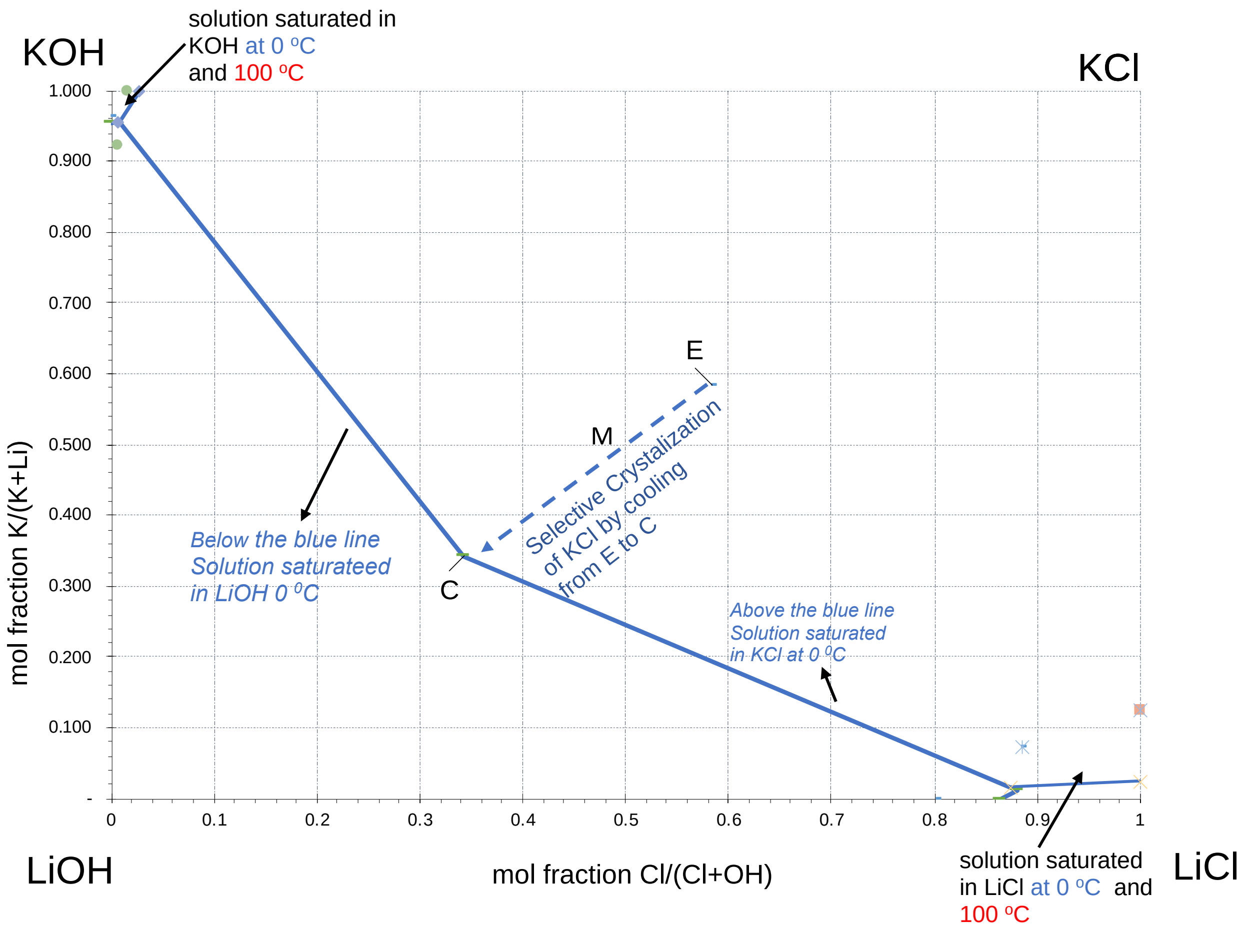
What is a reciprocal salt system?

- Comprises of two salts and water, where the two salts do not share a common ion.
- These salts yield two new salts, an interaction known as a double decomposition, thereby forming a reciprocal salt pair.
- May be illustrated using a pyramid with a square base, with water at the top and each of the four salts located at the corners.
- The reactions within a reciprocal salt system must reach a state of equilibrium, where the rates of the forward and reverse reactions are equal. It is reversable.
- It is NOT a Salt Metathesis or precipitation reaction, which is a type of double-replacement reaction, where metathesis occurs between two inorganic salts where they exchange ions to form an insoluble precipitate.

The Jänecke projection



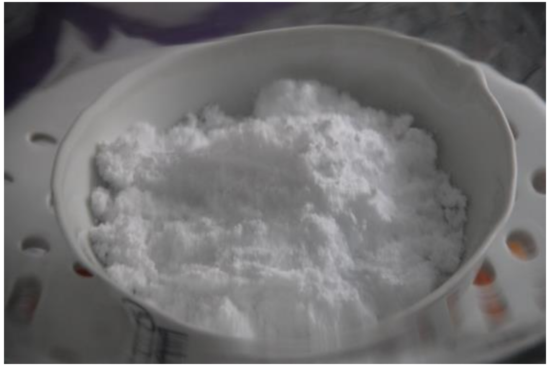
The Jänecke projection



Experimental Method

IBZ, 2024

GEA, 2023



LiOH H2O

KCL

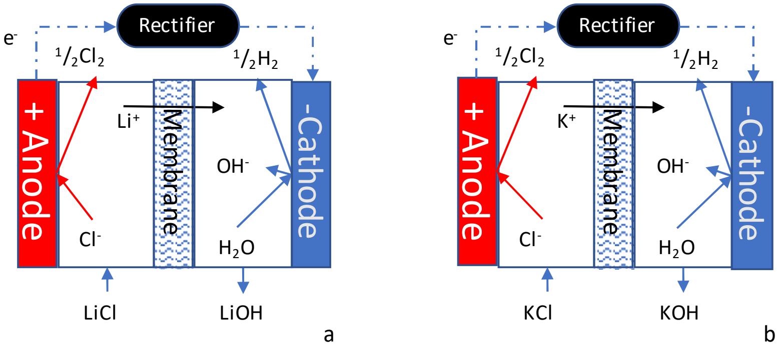
Lithium Chloride Electrolysis (Lithium Electrolysis)

$$\text{Dissolution of LiCl:} \quad LiCl \rightarrow Li^{+} + Cl^{-}$$

$$\text{At the Cathode (Reduction):} \quad 2H_2O+ \rightarrow H_2 + OH^{2-}$$

$$\text{At the Anode (Oxidation):} \quad 2Cl^{-} \rightarrow Cl_2 + 2e^{-}$$

LiCl Electrolysis

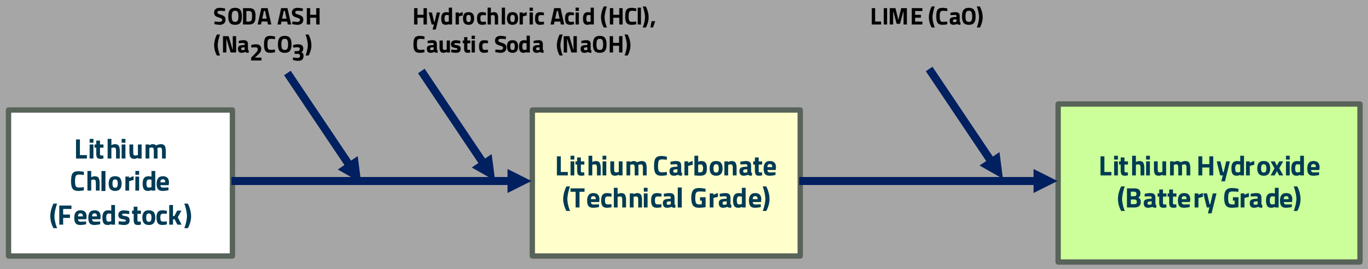


Ark Green+

Advantages of KCl-Electrolysis over LiCl-Electrolysis

	POTASSIUM Chloride Electrolysis	LITHIUM Chloride Electrolysis
Description	Electrolyzes Potassium Chloride (KCl) back into Potassium Hydroxide (KOH) to be used as Reagent.	Electrolyze Li-Chloride Feedstock directly into Lithium Hydroxide.
Current Efficiency	**98%**	70%
Energy Consumption (kWh/MT LiOH)	3300 kWh	7300 kWh
Current Density	6000 A/m^2	2400 A/m^2
OPEX/MT	**Low**. < ½ Power Consumption	High
CAPEX	**Low**. < ½ Equipment CAPEX	High
Industrially-Scaled	**Yes**. 2 Million Tons Annually	No

GREY REFINING (Conventional):
A Carbon-Intensive, Financially Wasteful Pathway



Reagents are Highly Problematic:

- Reagent Cost ↑
- Transport Cost ↑
- Unavoidable CO_2 Emissions
- Reagent Impurity Impacts Lithium Purity
- Lithium Losses **>6%**

Grey Refining:

- Costly Reagent Use
- High $CaCO_3$ & NaCl Waste
- High CO_2 Emission
- High OPEX/MT

Liming with Calcium Oxide (CaO) (Grey Refinery)

$$Li_2CO_3 \rightarrow 2Li^+ + CO_3^{2-}$$

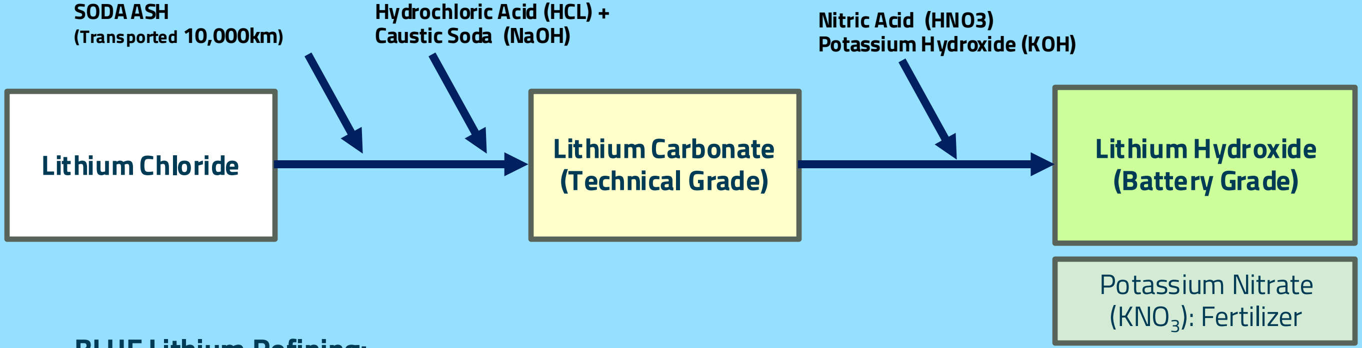
$$Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^-$$

$$CO_3^{2-} + Ca^{2+} \rightarrow CaCO_3\,(s)$$

$$Li_2CO_3\,(s) + Ca(OH)_2\,(s) \rightarrow 2LiOH\,(aq) + CaCO_3\,(s)$$

ARK BLUE Lithium Refining: A Zero Waste Pathway

- Lithium Carbonate-TG is converted directly into LiOH by adding Nitric Acid & Potassium. Hydroxide (KOH).
- Potassium Nitrate (KNO_3) and battery-grade Lithium Hydroxide (LiOH) are easily crystallized from solution.
- BLUE Lithium generates two valuable products: LiOH-BG and Potassium Nitrate (KNO3).



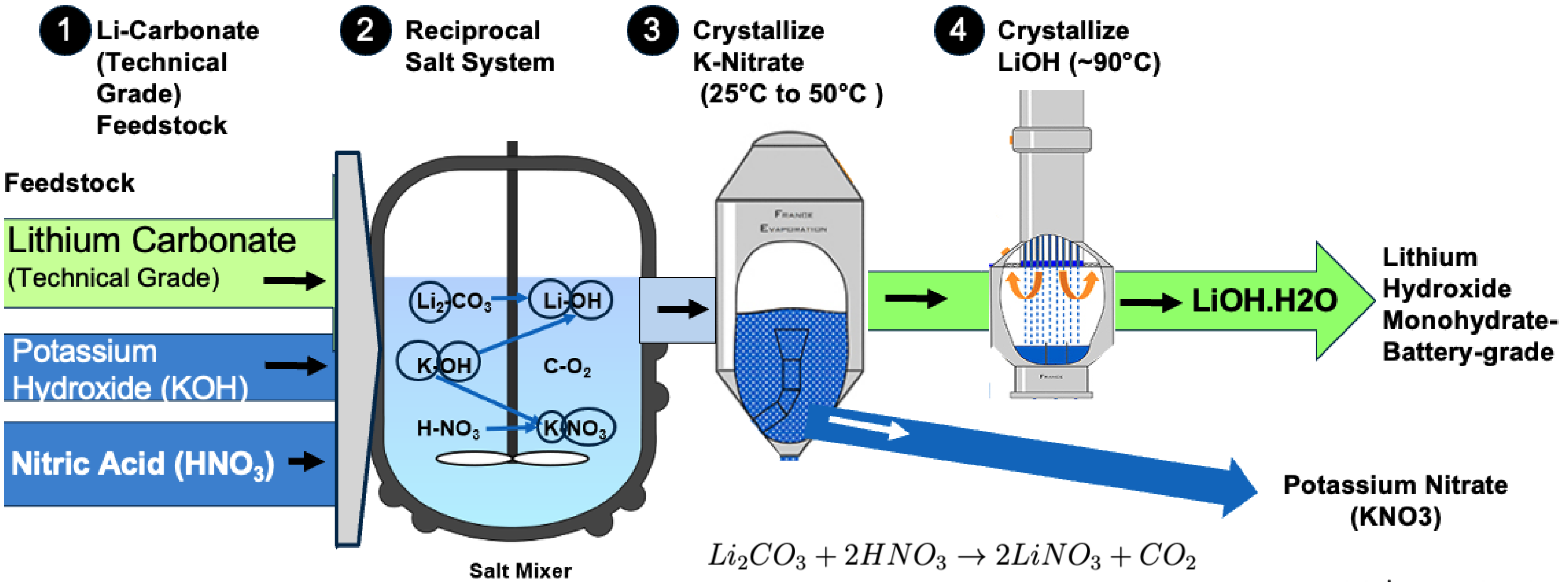
BLUE Lithium Refining:

- Produces two valuable products: LiOH-BG & Potassium Nitrate (KNO_3) – a high value fertilizer. used in greenhouses essential in plant growth.
- Lowest Net OPEX/MT, when the value of KNO_3 credited back to OPEX
- Lowest CAPEX of all Lithium Refining options.
- Zero waste.
- Less CO2 emission than conventional refinery.

+HNO3 + KOH (Ark Blue)

Continuous Flow
CRYSTALLIZTION MODULE

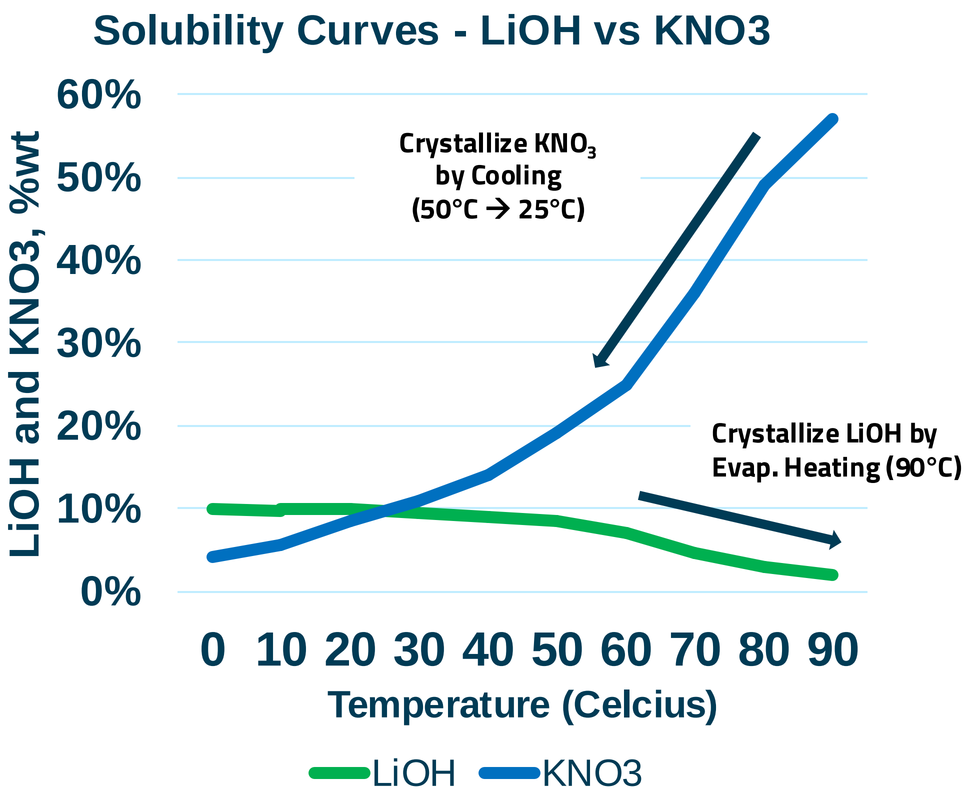
Patented



$$Li_2CO_3 + 2HNO_3 \rightarrow 2LiNO_3 + CO_2$$

$$2LiNO_3 + 2KOH \rightarrow 2KNO_3 + 2LiOH$$

BLUE™ Refining: Crystallization to Achieve High-Purity



The inverse slopes of the two solubility curves are exploited:

Potassium Nitrate (KNO_3) is separated, purified and crystallized by cooling, without co-crystallization of Lithium Hydroxide (LiOH).

Then,

Lithium Hydroxide is separated, purified and crystallized by evaporative heating, without co-crystallization of Potassium Nitrate (KNO_3).

All other impurities remain in solution to be later purged.

3. Life Cycle Assessment

Research Questions

- How can we best summarise the complexity of pathways for the production of battery-grade lithium? Identify and summarise the various routes available for producing Li2CO3 and LiOH.
- What are the environmental impacts of the primary process routes for Lithium Carbonate Equivalents (LCE)?
- What are the environmental impacts of the primary processing pathways for the production of battery-grade Lithium Hydroxide Monohydrate?

Life Cycle Assessment: Methods

Methodology

- Scope 1, 2 and 3 emissions.
- 2016 ReCiPe Hierachist Midpoint (100 years GWP).
- Field and Literature Data.

Guidelines

- ISO14040 and ISO14044 standards.
- International Lithium Association Product Carbon Footprint of Lithium Products Guidance (ILiA, 2024).
- Intergovernmental Panel on Climate Change (IPCC, 2013).

- Cradle-to-Gate. End Point in The Netherlands.
- Transportation included.
- Mass balance.
- Waste (Salt tailing), Emissions to Air (CO_{2eq}).
- Heat and Electricity on and off-site.

LiOH H2O LCA

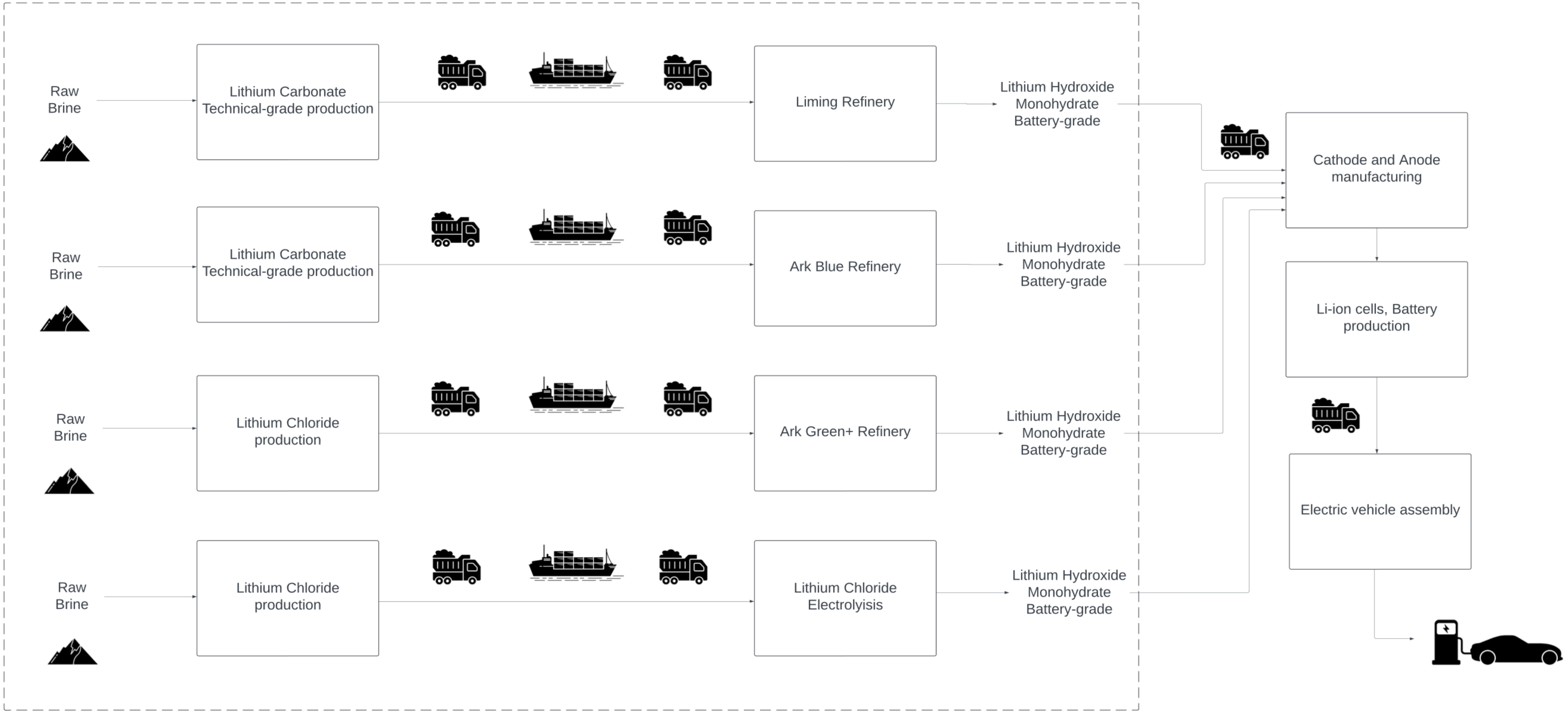
- Location at Brightlands Chemelot Campus, The Netherlands.
- Dutch and/or European supply reagent use.

Functional Unit: 1kg Lithium Product

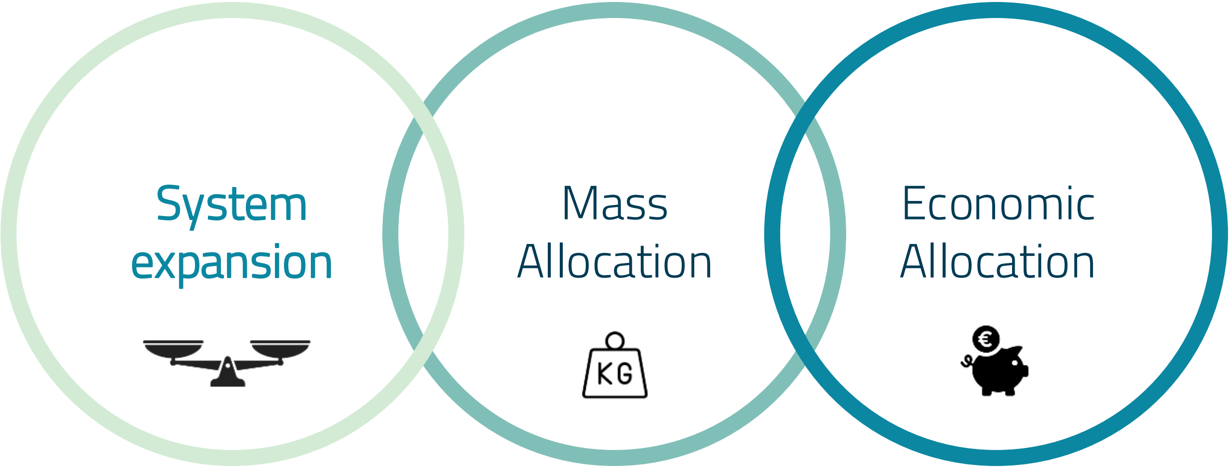
Lithium Product	Product grade	CAS Number
Lithium carbonate (Li_2CO_3)	> 99.0% Li_2CO_3 (> 18.6% Li) (anhydrous)	554-13-2
Lithium hydroxide monohydrate ($LiOH.H_2O$)	> 99.0% $LiOH.H_2O$ (> 16.3% Li)	1310-65-2

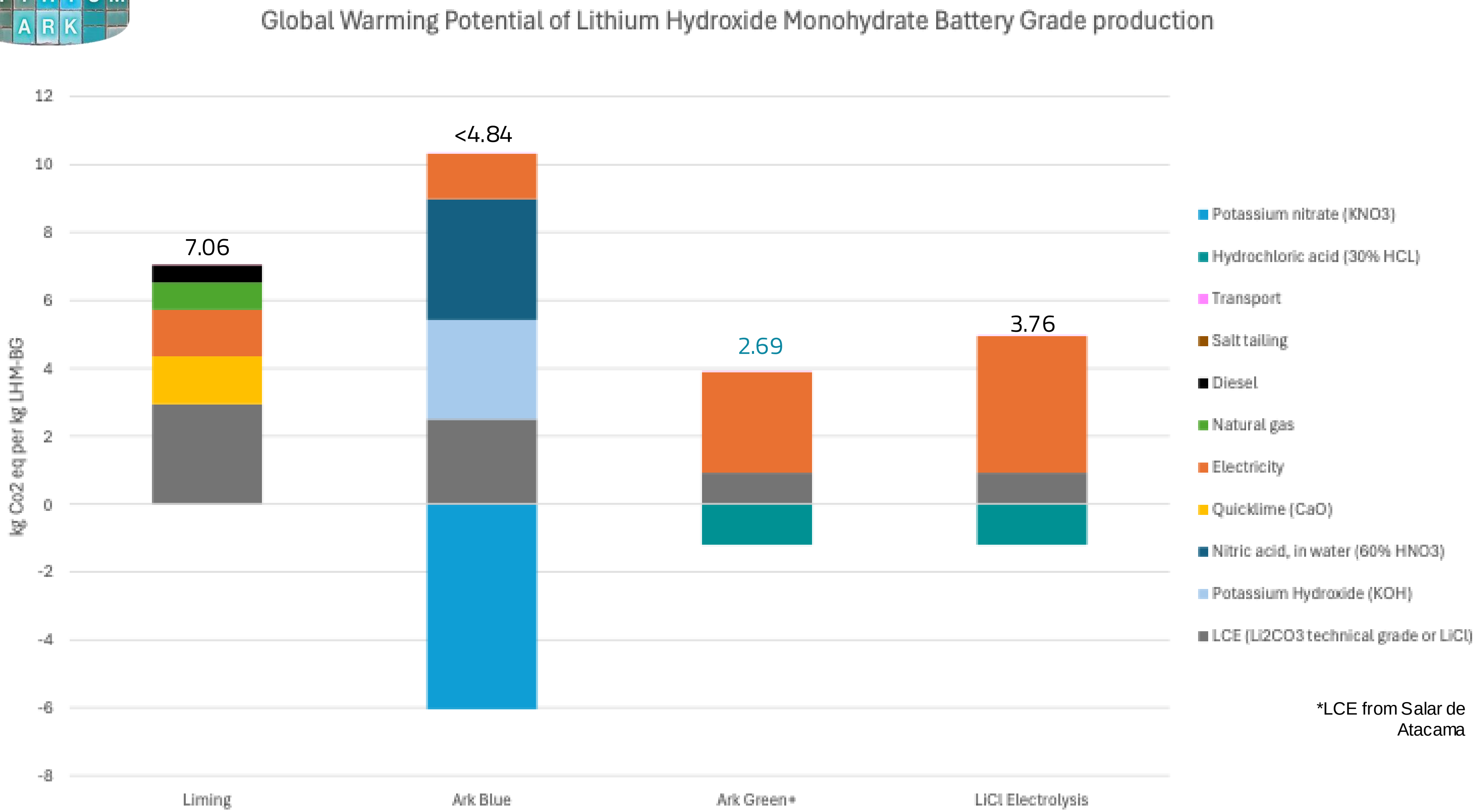
Functional Unit : 1 kg Lithium Hydroxide Monohydrate battery-grade product.

System Boundary

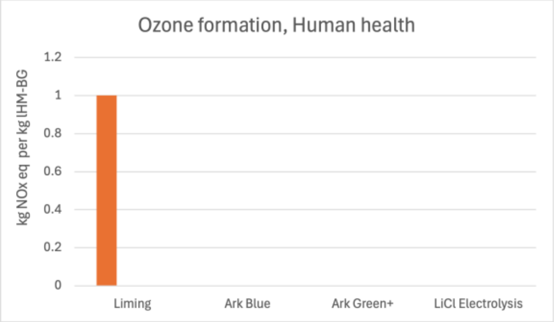


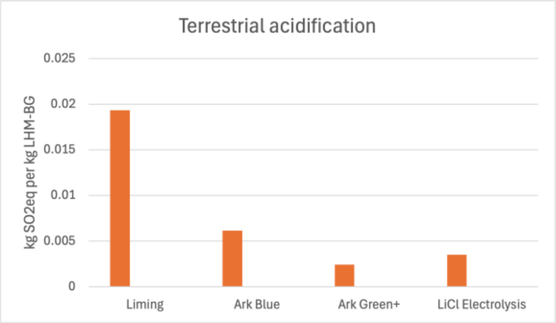
Existing Allocations

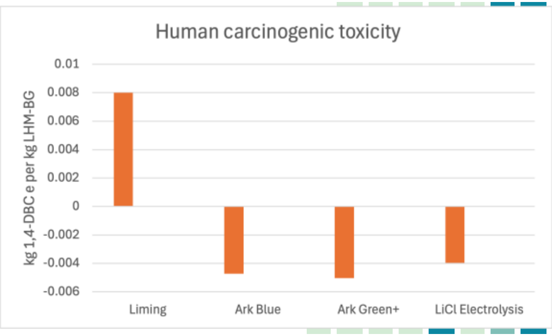


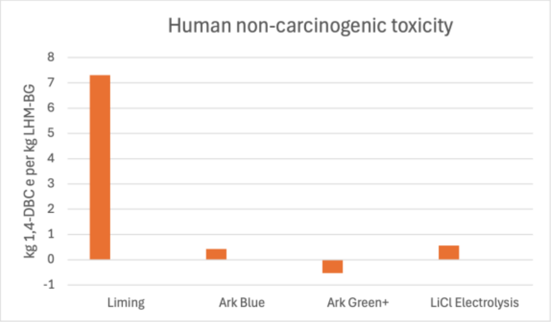

Global Warming Potential of Lithium Hydroxide Monohydrate Battery Grade production
kg Co2 eq per kg LHM-BG
12
10
8
6
4
2
0
-2
-4
-6
-8
7.06
<4.84
2.69
3.76
Liming
Ark Blue
Ark Green*
LiCl Electrolysis
Potassium nitrate (KNO3)
Hydrochloric acid (30% HCL)
Transport
Salt tailing
Diesel
Natural gas
Electricity
Quicklime (CaO)
Nitric acid, in water (60% HNO3)
Potassium Hydroxide (KOH)
LCE (Li2CO3 technical grade or LiCl)
*LCE from Salar de Atacama

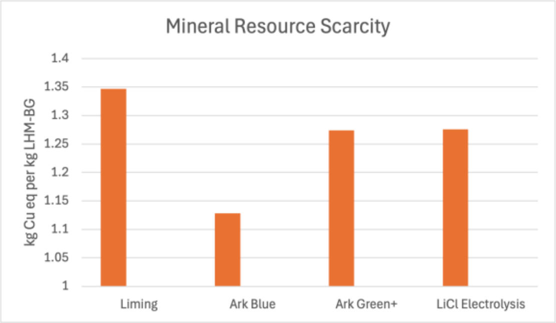
Environmental Impacts

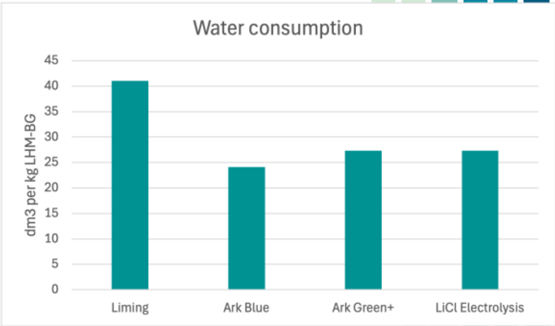




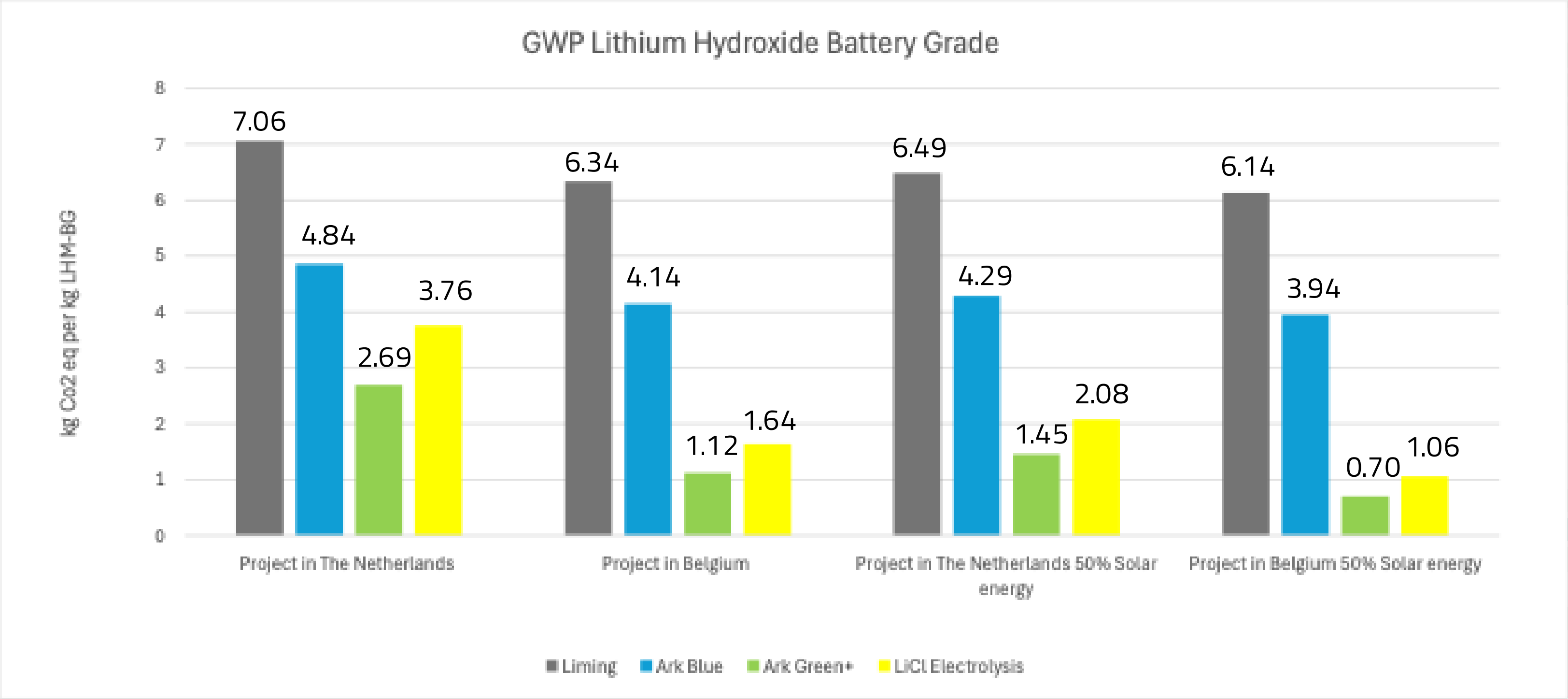






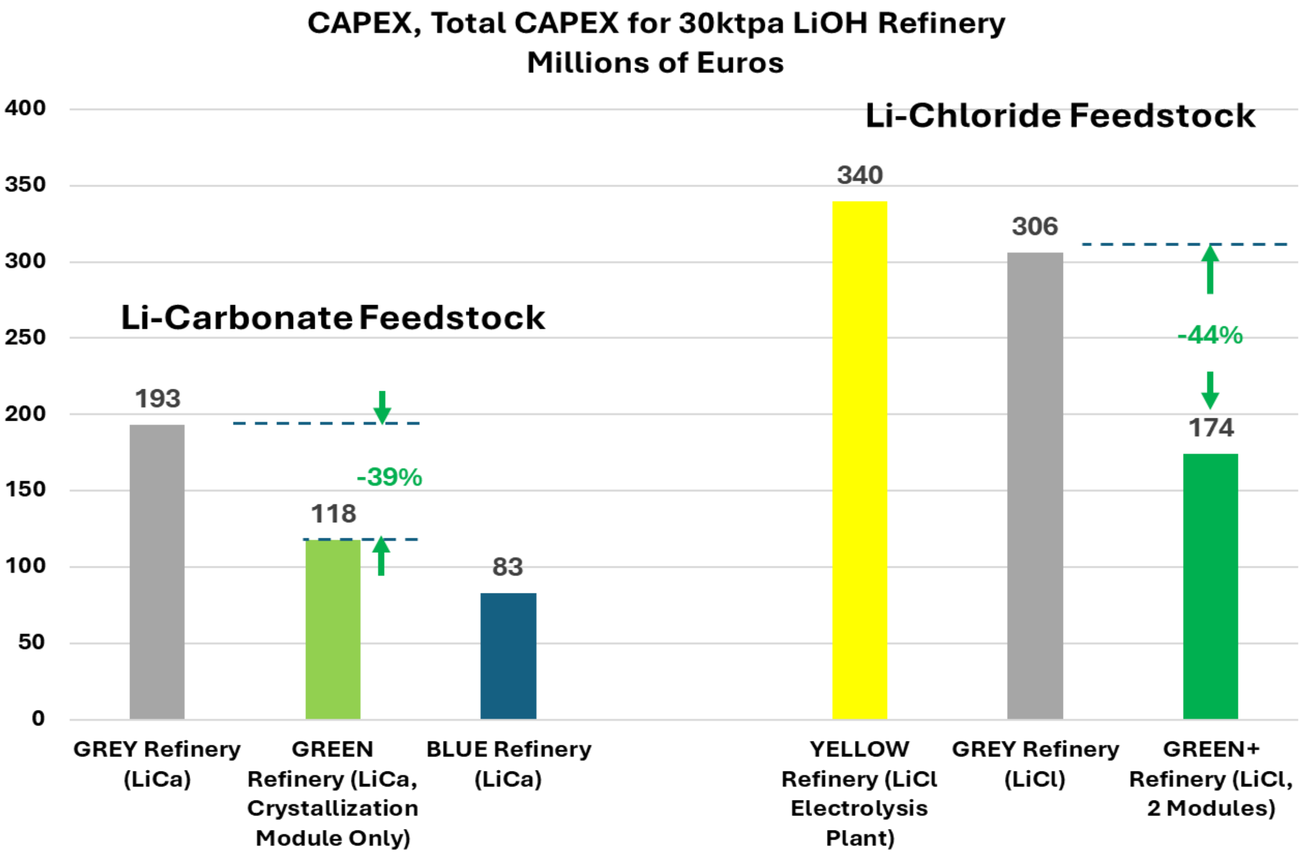


Scenario Analysis: GWP



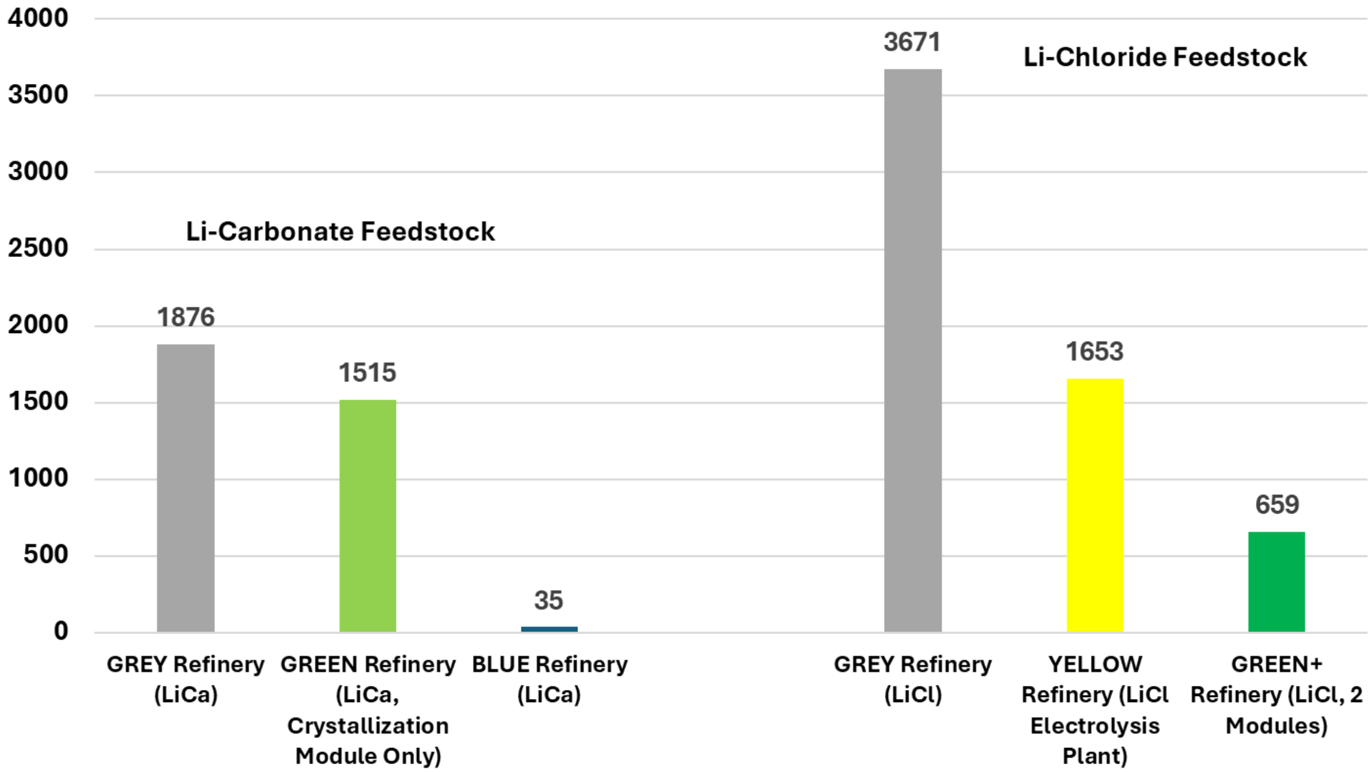
4. Economic Analysis

Comparison: CAPEX



Blue, **Green** and **Green⁺** Refinery Types are proprietary Process Technologies of Lithium Ark

Comparison: Reagent and Energy costs/MT of LHM



Net OPEX is the direct cost to produce each MT of LHM, including reagent, direct labour and energy, minus the market value of beneficial co-products, such as HCl, KCl-Food Grade, and/or Potassium Nitrate.

5. Key Factors

Key Factors to decarbonize Lithium Refining

✓ Eliminate the need for Soda Ash.

- Eliminate costly reagent transport.
- Eliminate impurities (in the Soda Ash) from contaminating the refining of battery-grade Lithium chemicals.

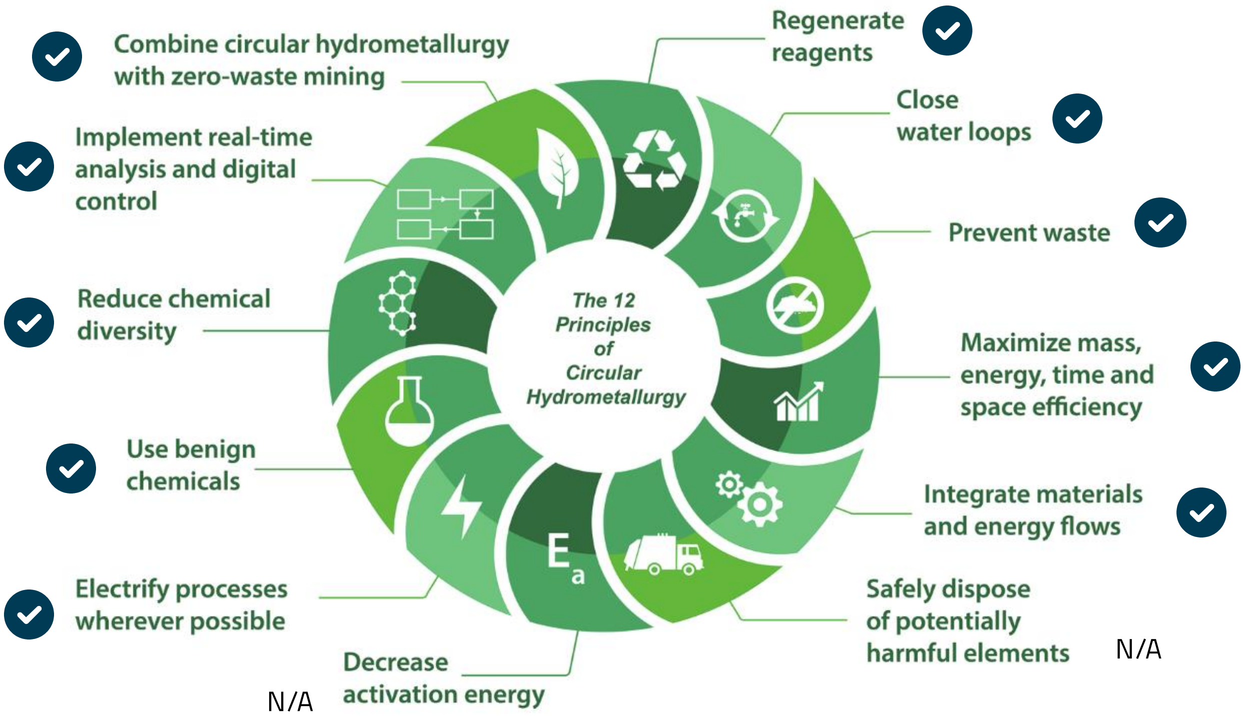
✓ Replace Lithium Carbonate (Li_2CO_3) with Lithium Chloride (LiCl).

- Chloride (Cl_2) has a higher value vs carbon from carbonate.

✓ Provide Refineries the flexibility to produce Lithium Carbonate-BG by simply adding CO_2 to LHM.

✓ Source Green / Renewable energy from the grid.

12 Principles of Circular Hydrometallurgy Ark Green+



Binnemans, K. , Jones, PT. 2022

Advantages for DLE Plants to sell Li-Chloride vs Li-Carbonate

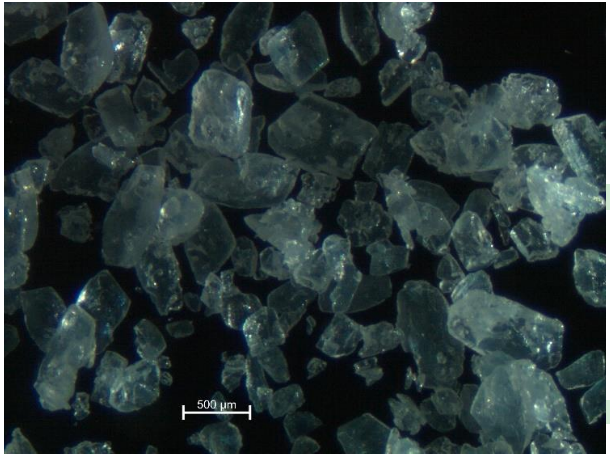
	Lithium Chloride (LiCl)	Lithium Carbonate (Li_2CO_3)
Environmental	Opens the door to **zero** waste & **zero** CO_2 emissions by Green+ Refineries making LHM/LCE.	Inherent Carbon in Li_2**C**O_3 makes CO_2 emissions inevitable.
CAPEX	Lowered CAPEX by <u>not</u> building lithium carbonate plant.	High CAPEX (adds US$150 to $250 million @ 30kpta capacity)
Financing Challenge	Allows DLE plant to <u>internally</u> fund growth from LiCl sales, lowering need for external sources of funds.	Funding High CAPEX thru outside financing dilutes company equity.
Ramp-up Risk	No qualification of battery-grade lithium is required. Faster uptime = quicker pay-back.	High. Adds 18+ months to qualify battery-grade lithium and ramp up.
Skilled Labor Requirement	Medium Difficulty	High Difficulty: DLE and Lithium Carbonation plant.

Standardizing Li-Chloride Specifications

		Solution	Crystal
LiCl	%	42	98
H_2O	%		0.5
K	%	No Limit	No Limit
Na	ppm	1200	1400
Ca	ppm	50	100
SO_4	ppm	300	300
Fe	ppm	10	10
B	ppm	50	100
Ba	ppm	50	100
Mg	ppm	50	100
Si	ppm	20	40
NO3	ppm	10	10
Insolubels in HCl	ppm		100

Lithium Ark battery-grade lithium hydroxide

Lithium Ark Range	Unit	Range
LiOH	wt.%	56.5
CO2	wt.%	0.20 - 0.30
SO4	ppm	< 50
Si	ppm	< 50
Cl	ppm	<100
Na	ppm	<20
Ca	ppm	< 50
K	ppm	< 50
Metals	ppm	<5



The lithium ark process is ultra low in impurities, such as Si, Zn and Al as it avoids any contamination from soda ash and lime.

LITHIUM ARK

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Appendix

Key Factors to decarbonize Lithium Refining

Crystallization is the foundation of the **Green⁺** Lithium Refinery. An electrolysis module is added to increase ESG and financial performance

MAIN MODULE:

Crystallization Module (LiOH, KCl):
A straightforward crystallization plant to crystallize Lithium Hydroxide (LiOH) and Potassium Chloride (KCl). GEA Messo, world leader in crystallization processing, has **validated, tested**, and **guarantees** this module of the Greenify™ Refinery.

OPTIONAL MODULE:

Electrolysis Module (Recycle KCl → KOH):
A **plug-and-play** Potassium-Chloride (KCl) electrolysis module based on mature and commercially-proven technology. Such plants are commonly found throughout the chlor-alkali sector with a worldwide installed base of 2 Million MT/Annum of KCl-Electrolysis today.