So you have lithium – now what?

Mike Dry

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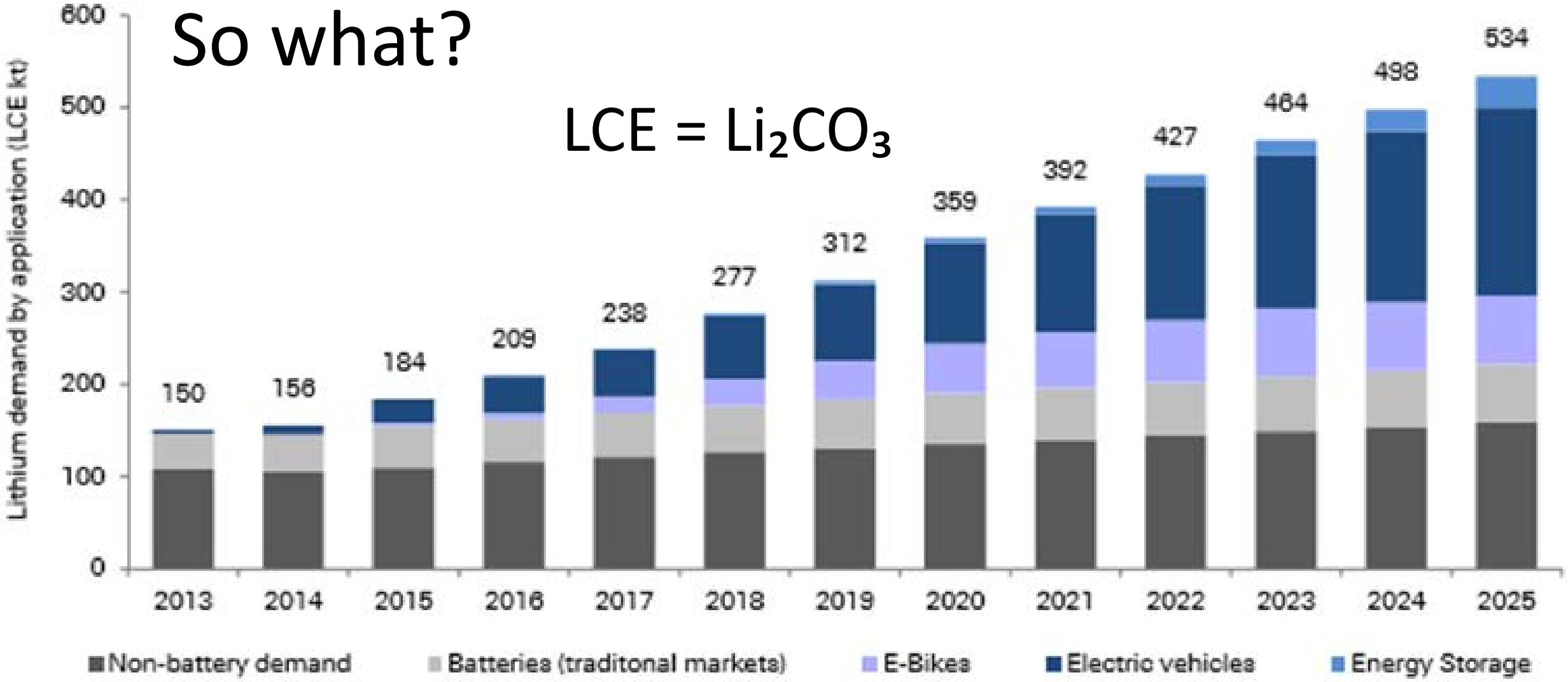
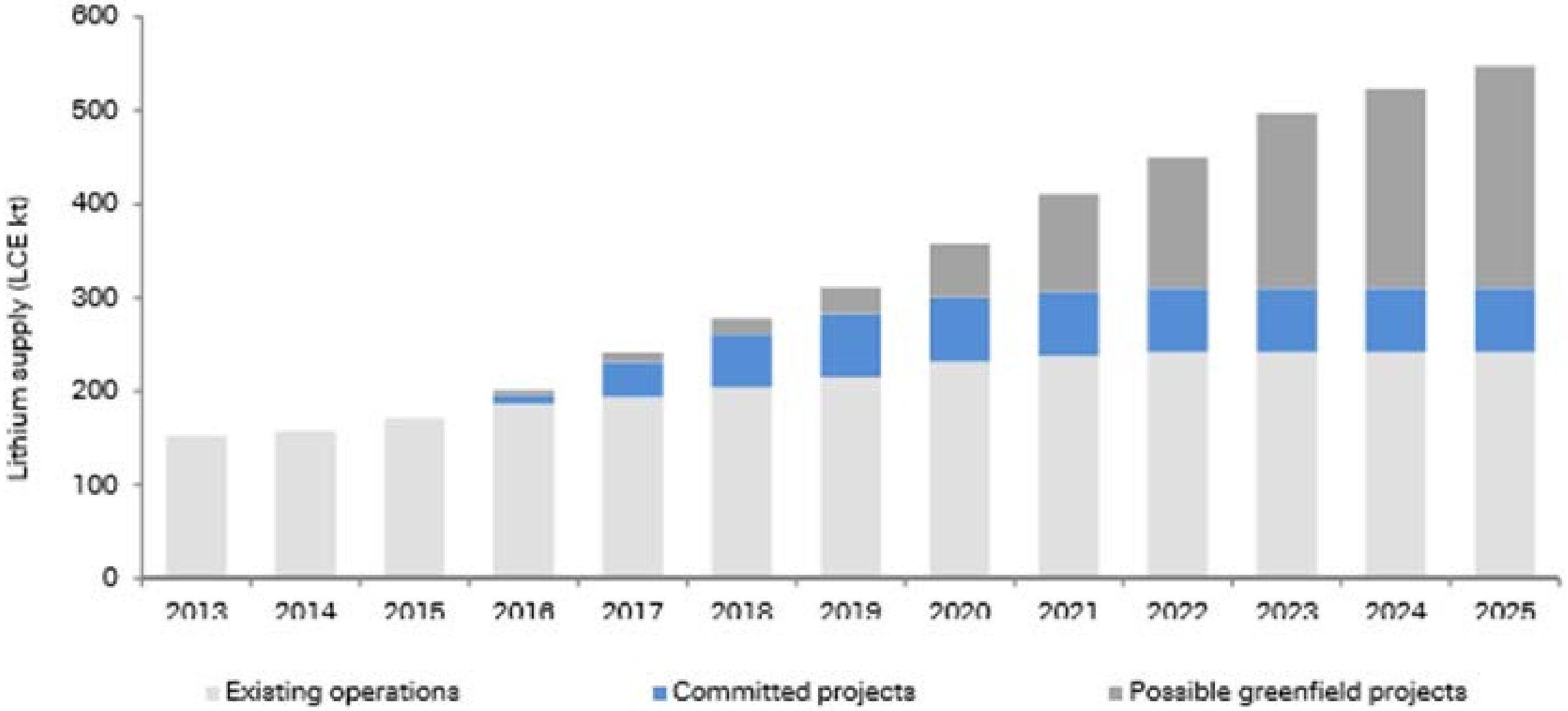
So what?

$LCE = Li_2CO_3$



Source: Deutsche Bank



Source: Deutsche Bank

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Sources of Lithium

- Hard rock deposits
  - Spodumene $LiAlSi_2O_6$
  - Lepidolite $K_2Li_2Al_4Si_7O_{21}(OH,F)_3$
  - Petalite $LiAlSi_4O_{10}$
- Li-bearing clays
- Brines
  - Geothermal
  - Continental (Salar)
  - Oilfield

Estimated Lithium Quantities

Region	Thousand tonnes Li	
	Brine	Ore
South America	8800	4
North America	2588	327
China	2000	500
Australia	-	160
Europe/Middle East	2000	10
Russia	-	130

Garrett, D.E. Handbook of lithium and natural calcium chloride

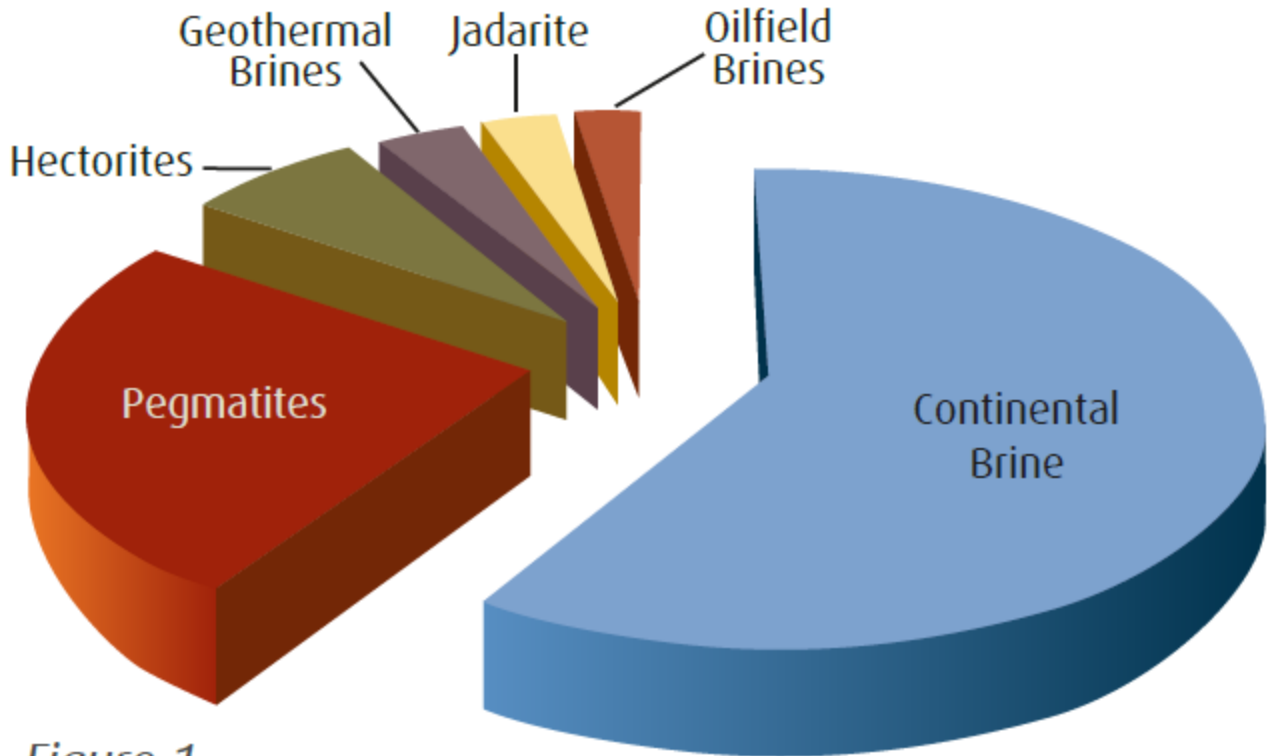
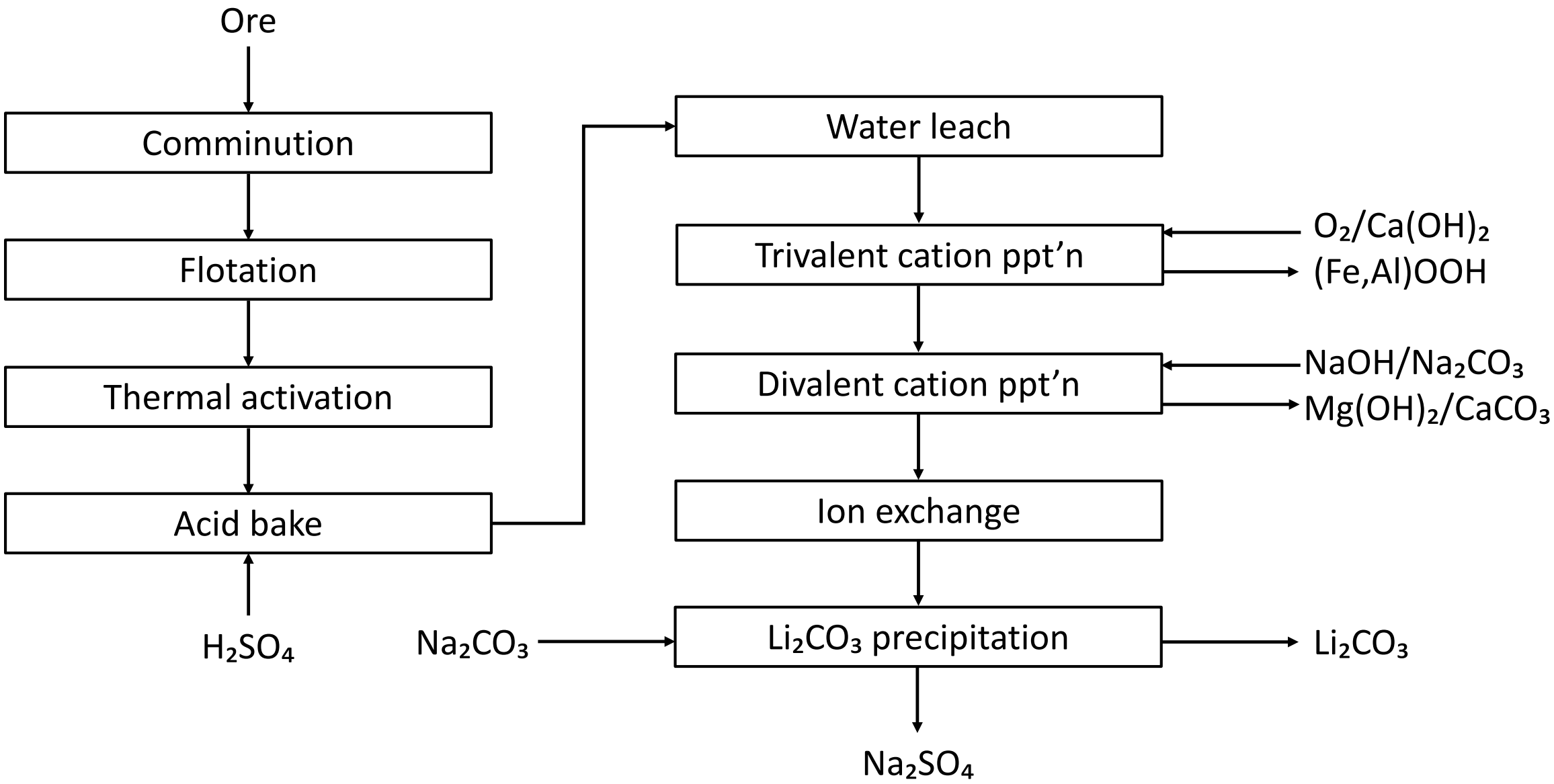
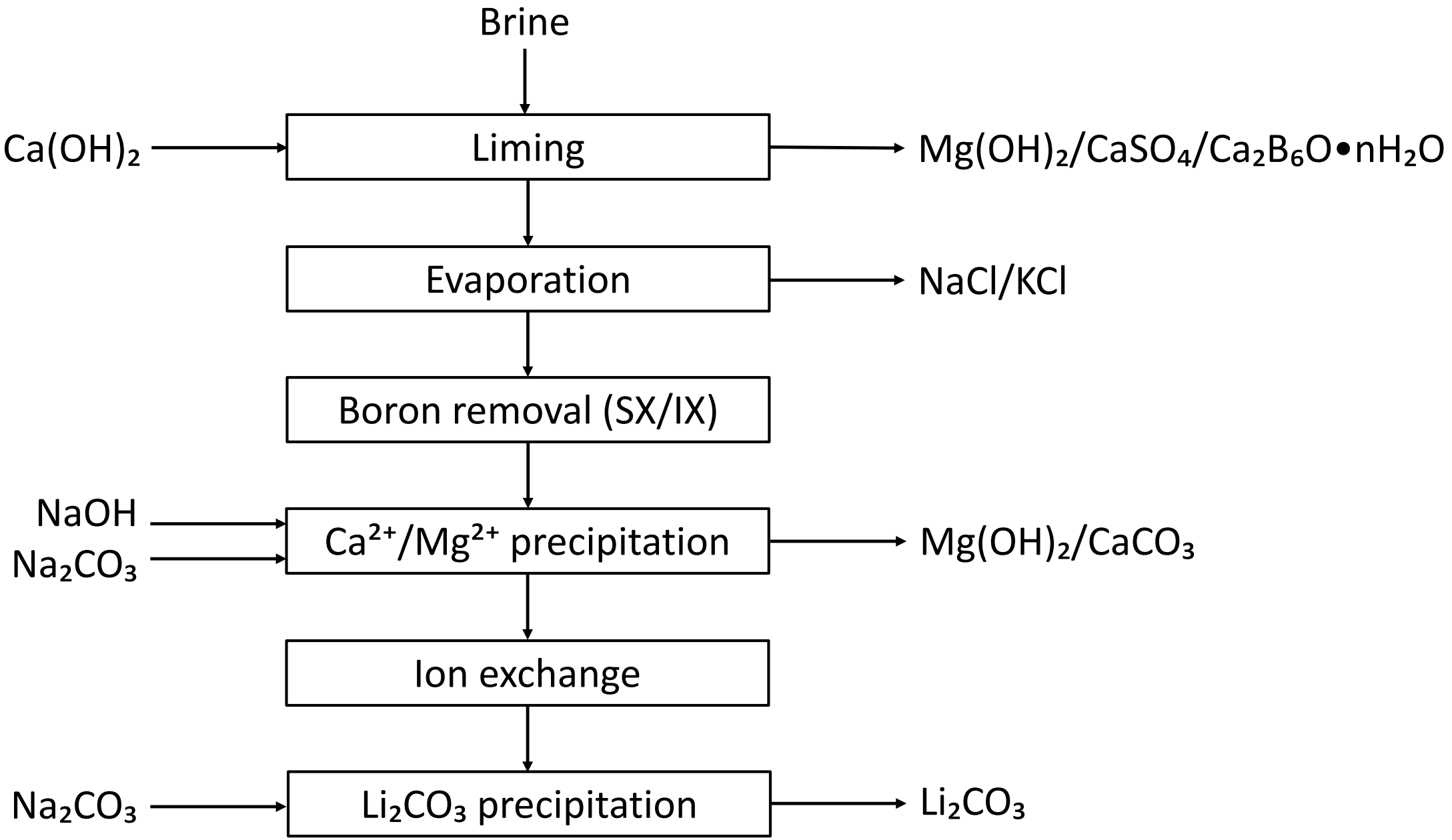


Figure 1:

Geologic Source of Global Lithium Resource. Estimates from Keith Evans (2009).


Ore
Comminution
Flotation
Thermal activation
Acid bake
H2SO4
Water leach
Trivalent cation ppt'n
O2/Ca(OH)2
(Fe,Al)OOH
Divalent cation ppt'n
NaOH/Na2CO3
Mg(OH)2/CaCO3
Ion exchange
Na2CO3
Li2CO3 precipitation
Li2CO3
Na2SO4


Brine
Ca(OH)2
Liming
Mg(OH)2/CaSO4/Ca2B6O•nH2O
Evaporation
NaCl/KCl
Boron removal (SX/IX)
NaOH
Na2CO3
Ca2+/Mg2+ precipitation
Mg(OH)2/CaCO3
Ion exchange
Na2CO3
Li2CO3 precipitation
Li2CO3

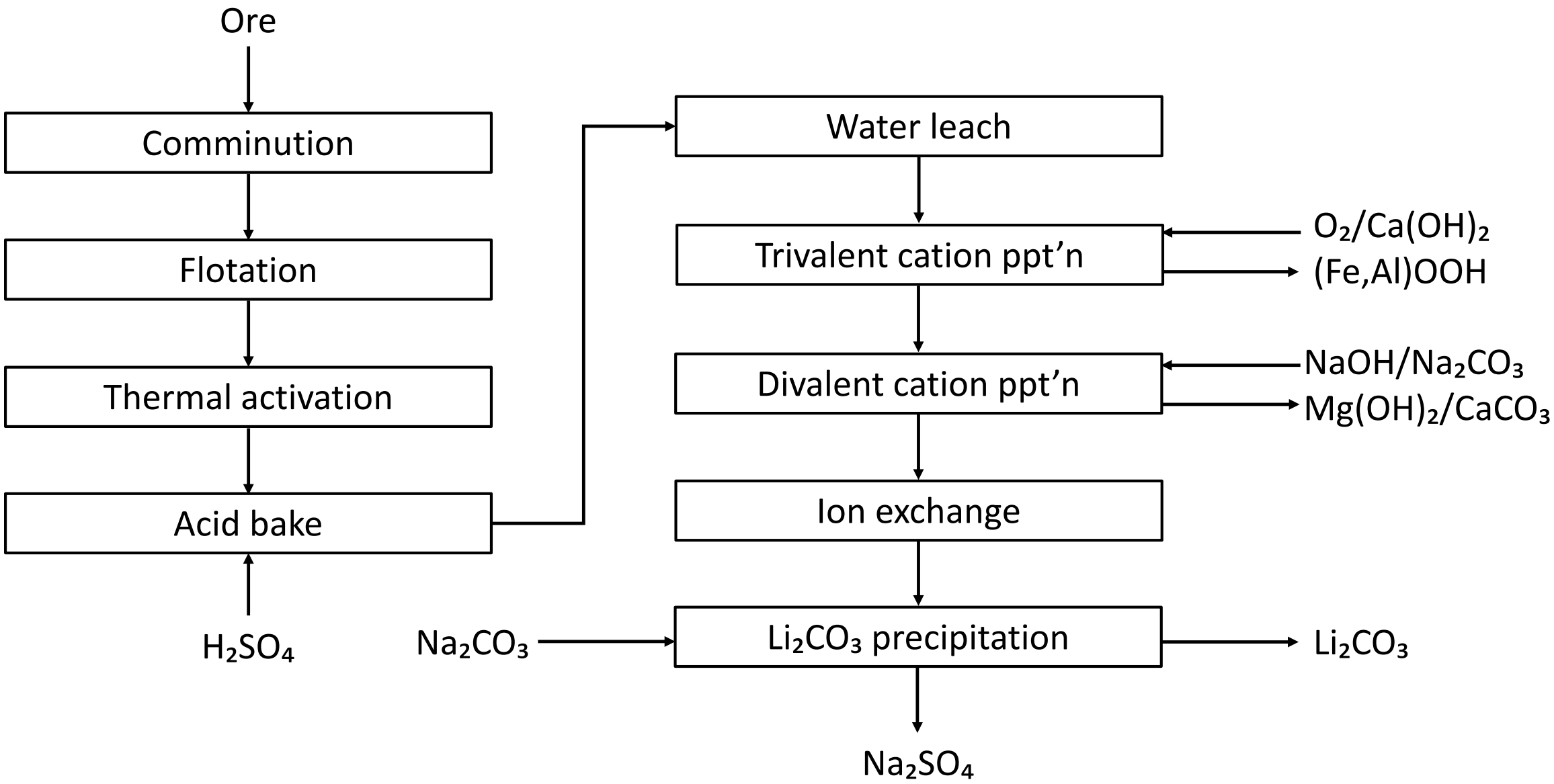
Precipitation in Evaporation

- NaCl
- NaCl KCl
- NaCl KCl **$KLiSO_4$**
- NaCl $KCl•MgSO_4•2¾H_2O$ **$Li_2SO_4•H_2O$**
- NaCl **$Li_2SO_4•H_2O$** $KCl•MgCl_2•6H_2O$
- $MgCl_2•6H_2O$
- $MgCl_2•6H_2O$ **$LiCl•MgCl_2•7H_2O$**

$$Ca(OH)_2 + Mg^{2+} \longrightarrow Ca^{2+} + Mg(OH)_2$$

$$Ca(OH)_2 + SO_4^{2-} \rightarrow CaSO_4 + 2OH^-$$

Figure 1.60 One of SQM's salt (halite) solar ponds, with a salt disposal pile in the background (courtesy of SQM SA).


Ore
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Divalent cation ppt'n
NaOH/Na2CO3
Mg(OH)2/CaCO3
Ion exchange
Na2CO3
Li2CO3 precipitation
Li2CO3
Na2SO4

$$\alpha\text{-}LiAl(SiO_3)_2 \rightarrow \beta\text{-}LiAl(SiO_3)_2$$

$$LiAl(SiO_3)_2 + 2H_2SO_4 \rightarrow Li^+ + Al^{3+} + 2SO_4^{2-} + 2H_2O + 2SiO_2$$

$$2Al^{3+} + 3SO_4^{2-} + 3CaO + 3H_2O \rightarrow 3CaSO_4 + 2Al(OH)_3$$

$$CaSO_4 \leftrightarrow Ca^{2+} + SO_4^{2-}$$

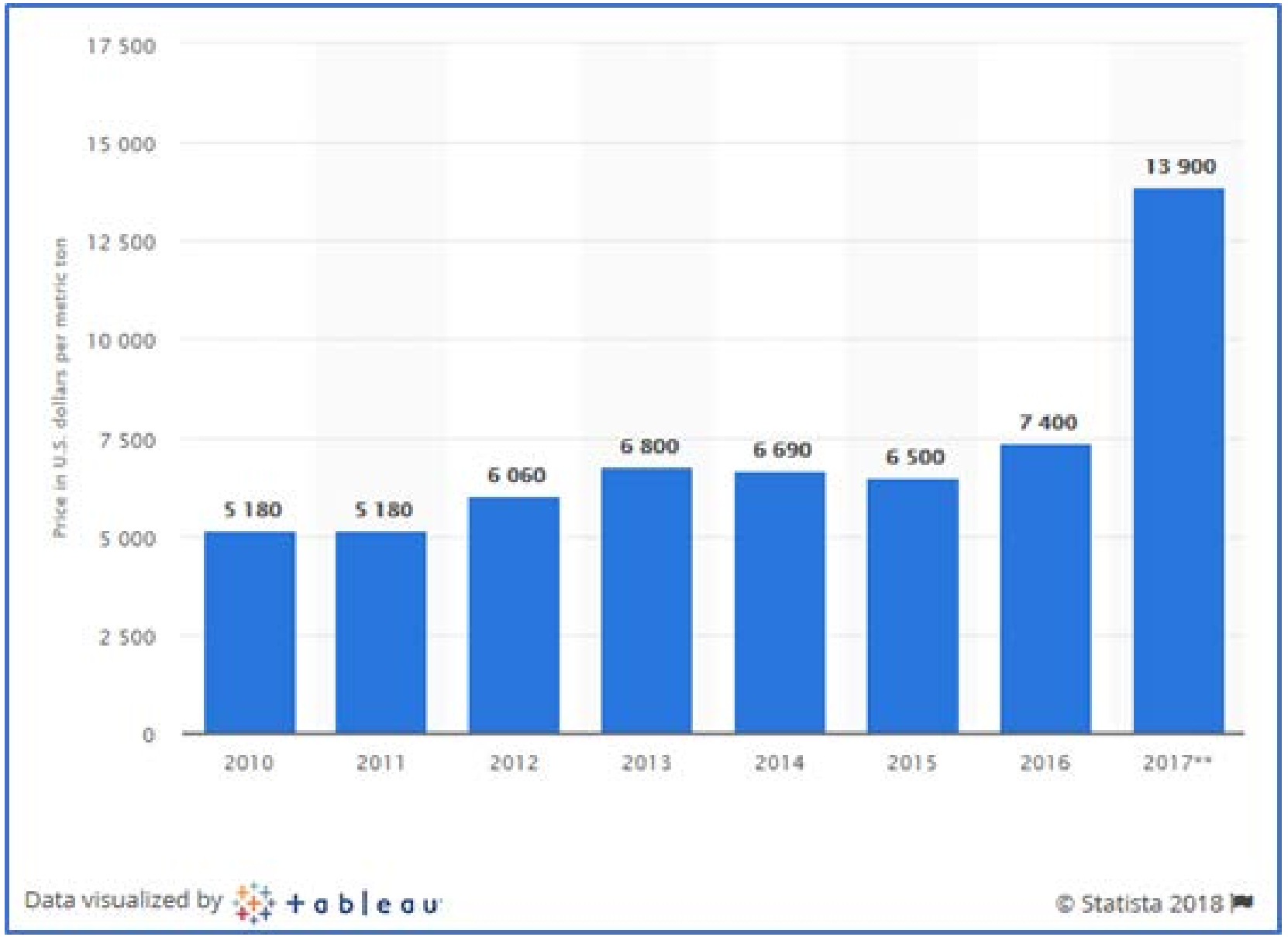
$$Ca^{2+} + Na_2CO_3 \rightarrow CaCO_3 + 2Na^+$$

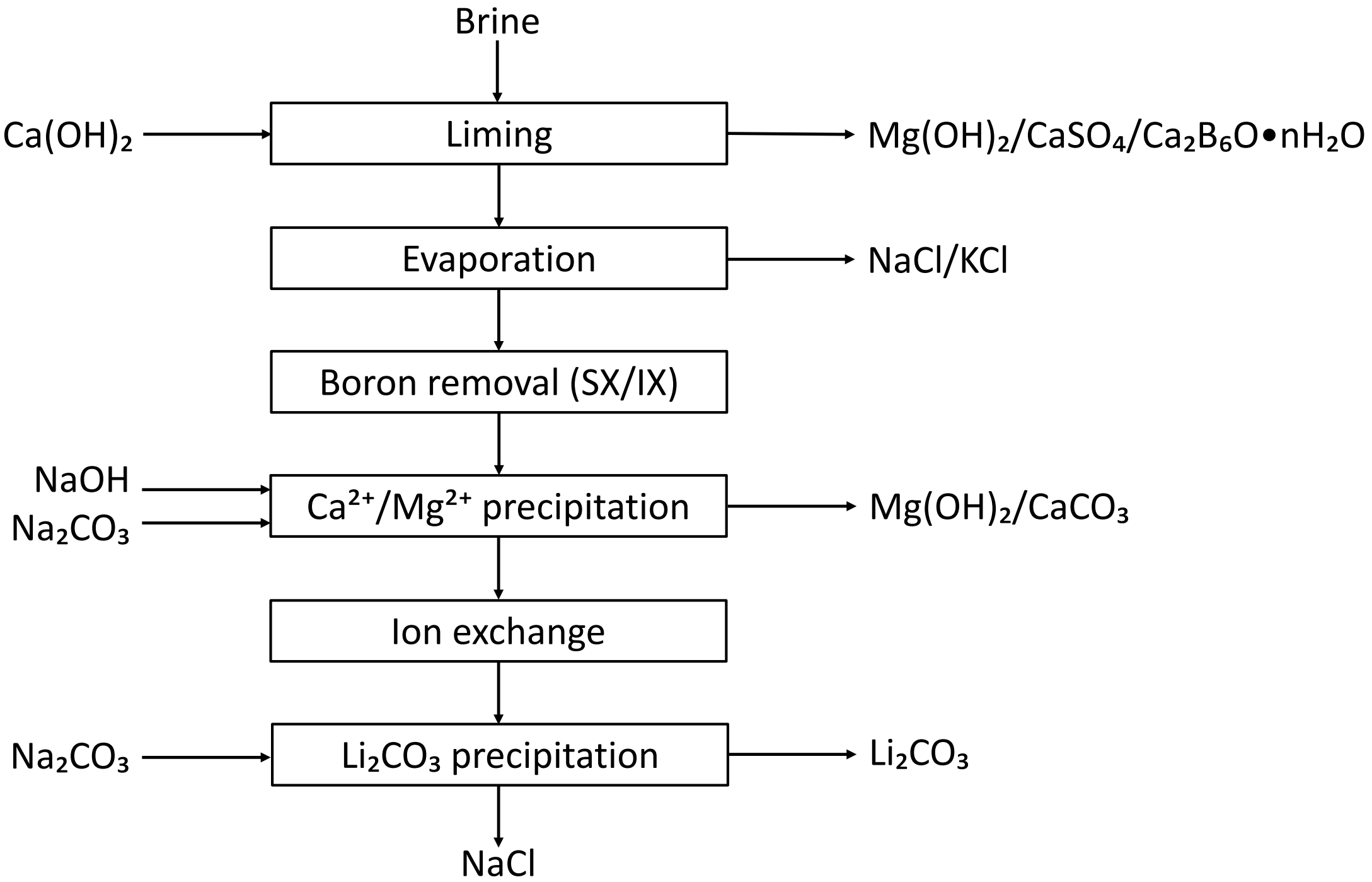
$$2Li^+ + Na_2CO_3 \rightarrow Li_2CO_3 + 2Na^+$$

$$K_2Li_2Al_4Si_7O_{21} + 8H_2SO_4 \rightarrow 2K^+ + 2Li^+ + 4Al^{3+} + 8SO_4^{2-} + 8H_2O + 7SiO_2$$

Li_2CO_3 recovery from minerals

Reagent	Price	$/kg LCE	
		$LiAl(SiO_3)_2$	$K_2Li_2Al_4Si_7O_{21}$
Energy	$15/GJ	0.2	0.2
H_2SO_4	$250/t	1.3	2.7
CaO	$150/t	0.3	0.7
Na_2CO_3	$370/t	0.5	0.5
	Sub-total	2.4	4.1


17 500
15 000
12 500
10 000
7 500
5 000
2 500
0
Price in U.S. dollars per metric ton
5 180
5 180
6 060
6 800
6 690
6 500
7 400
13 900
2010
2011
2012
2013
2014
2015
2016
2017**
Data visualized by
tableau
© Statista 2018


Brine
Ca(OH)2
Liming
Mg(OH)2/CaSO4/Ca2B6O•nH2O
Evaporation
NaCl/KCl
Boron removal (SX/IX)
NaOH
Na2CO3
Ca2+/Mg2+ precipitation
Mg(OH)2/CaCO3
Ion exchange
Na2CO3
Li2CO3 precipitation
Li2CO3
NaCl

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

$$2NaOH + Mg^{2+} \rightarrow 2Na^{+} + Mg(OH)_2$$

$$Na_2CO_3 + Ca^{2+} \rightarrow 2Na^{+} + CaCO_3$$

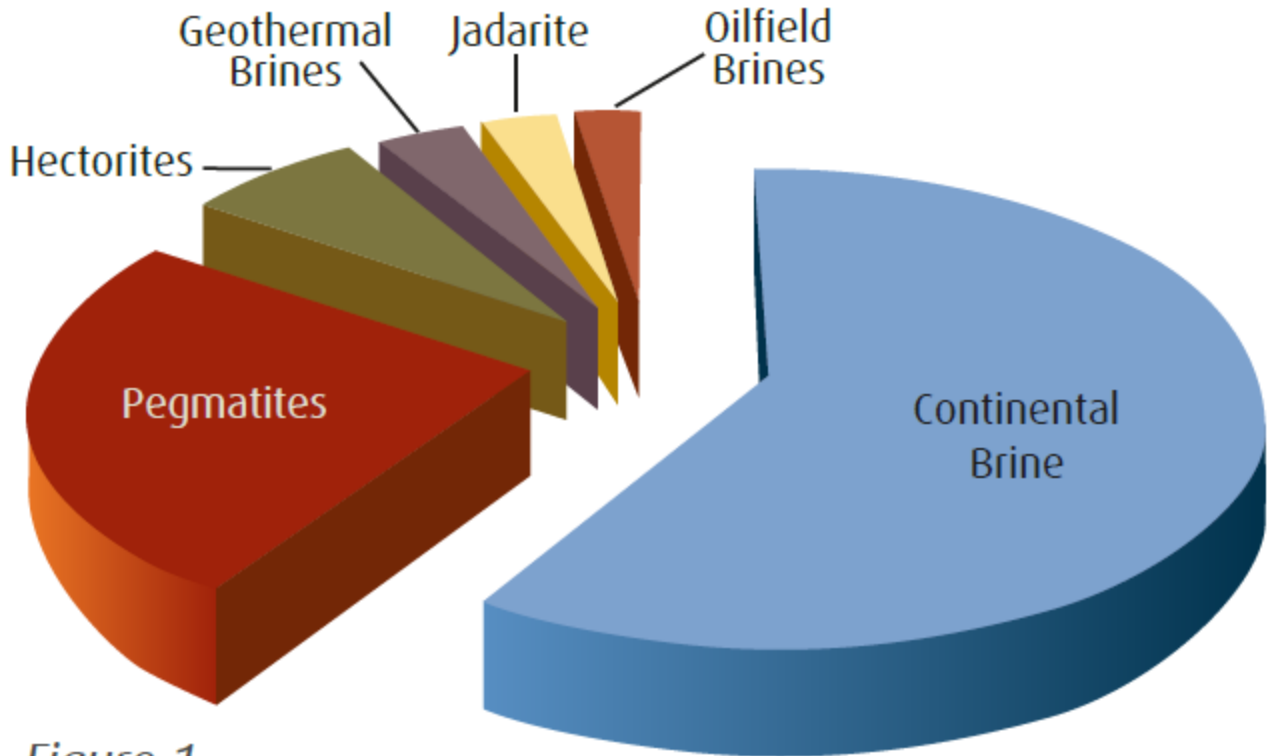
$$Na_2CO_3 + 2Li^{+} \rightarrow 2Na^{+} + Li_3CO_3$$

Element	Geothermal brine	Continental brine	Oilfield brine
Fe	1200 - 3700	-	35 - 41
Mn	1000 - 2000	-	25 - 30
Zn	800 - 700	-	-
Mg	700 - 5700	2 - 9650	2900 - 3500
Ca	22600 - 39000	300 - 530	29100 - 34500
Na	50000 - 70000	65000 - 910000	54900 - 67000
K	13000 - 34200	18500 - 31300	2400 - 5900
Li	100 - 400	1500 - 2420	146 - 386
Cl	142000 - 209000	159000 - 189500	144500 - 171700
SO_4	42 - 50	8000 - 19000	375 - 450
B	400 - 500	400 - 685	123 - 366
Si	40	-	90

Garrett, D.E. Handbook of lithium and natural calcium chloride

Li_2CO_3 recovery via solar evaporation

Reagent		Requirement, kg/kg LCE			Cost, $/kg LCE		
Reagent	US$/t	Geo.	Cont.	Oilfield	Geo.	Cont.	Oilfield
CaO	150	9.0	1.1	5.3	1.4	0.2	0.8
NaOH	560	0.1	0.02	0.1	0.1	0.0	0.2
Na_2CO_3	370	69.5	1.8	61.2	25.7	0.7	22.6
		Sub-total of reagent costs			**27.1**	**0.8**	**23.5**



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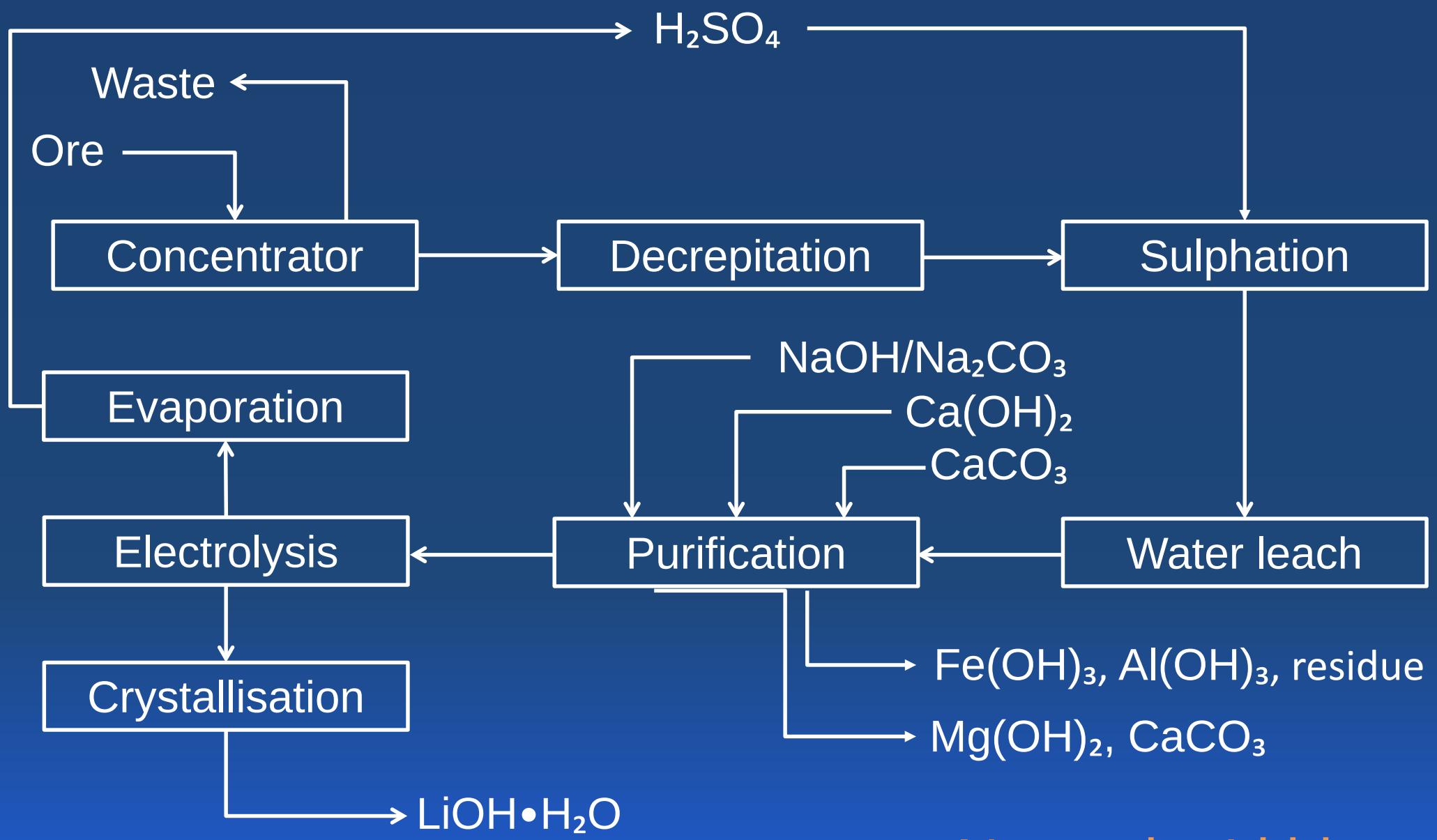
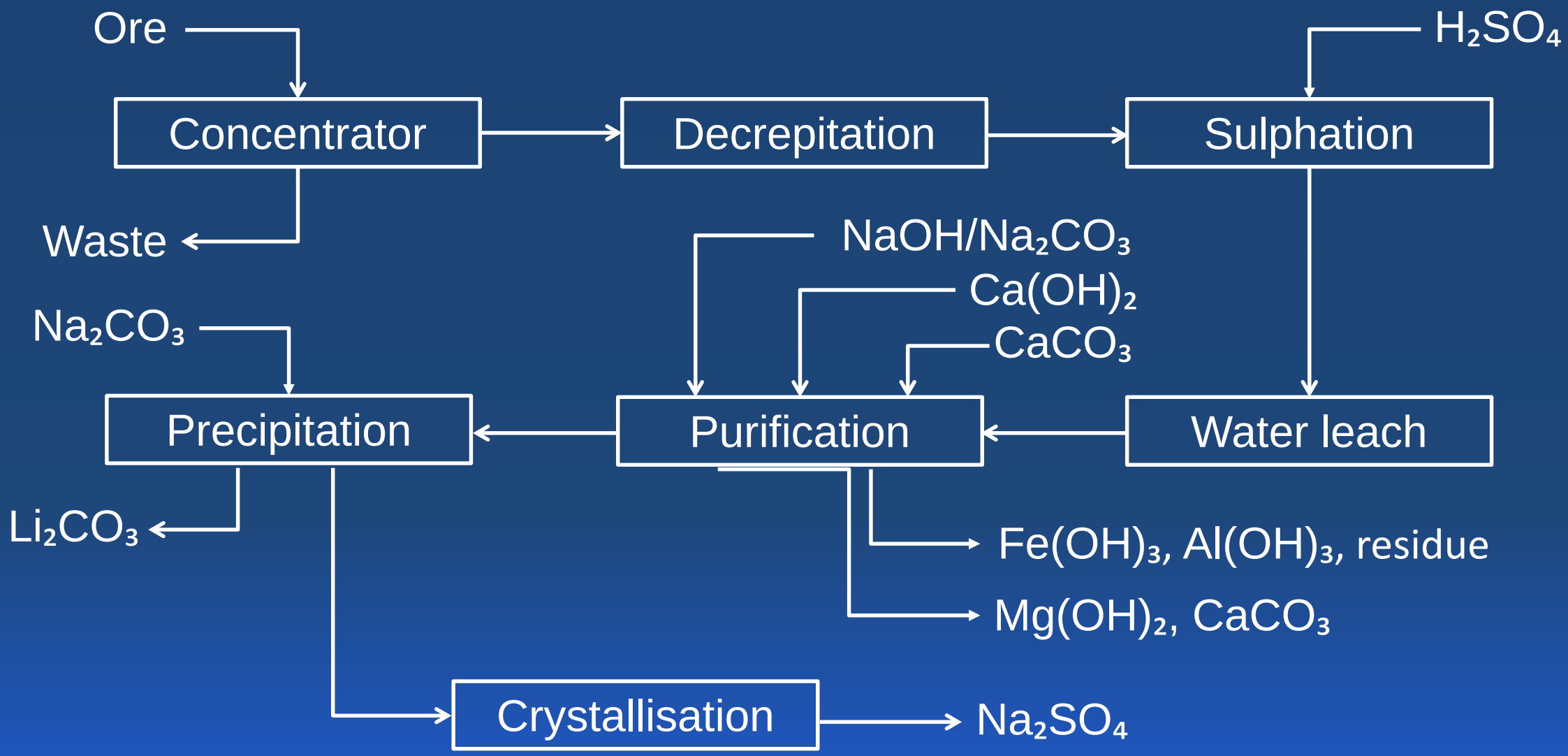
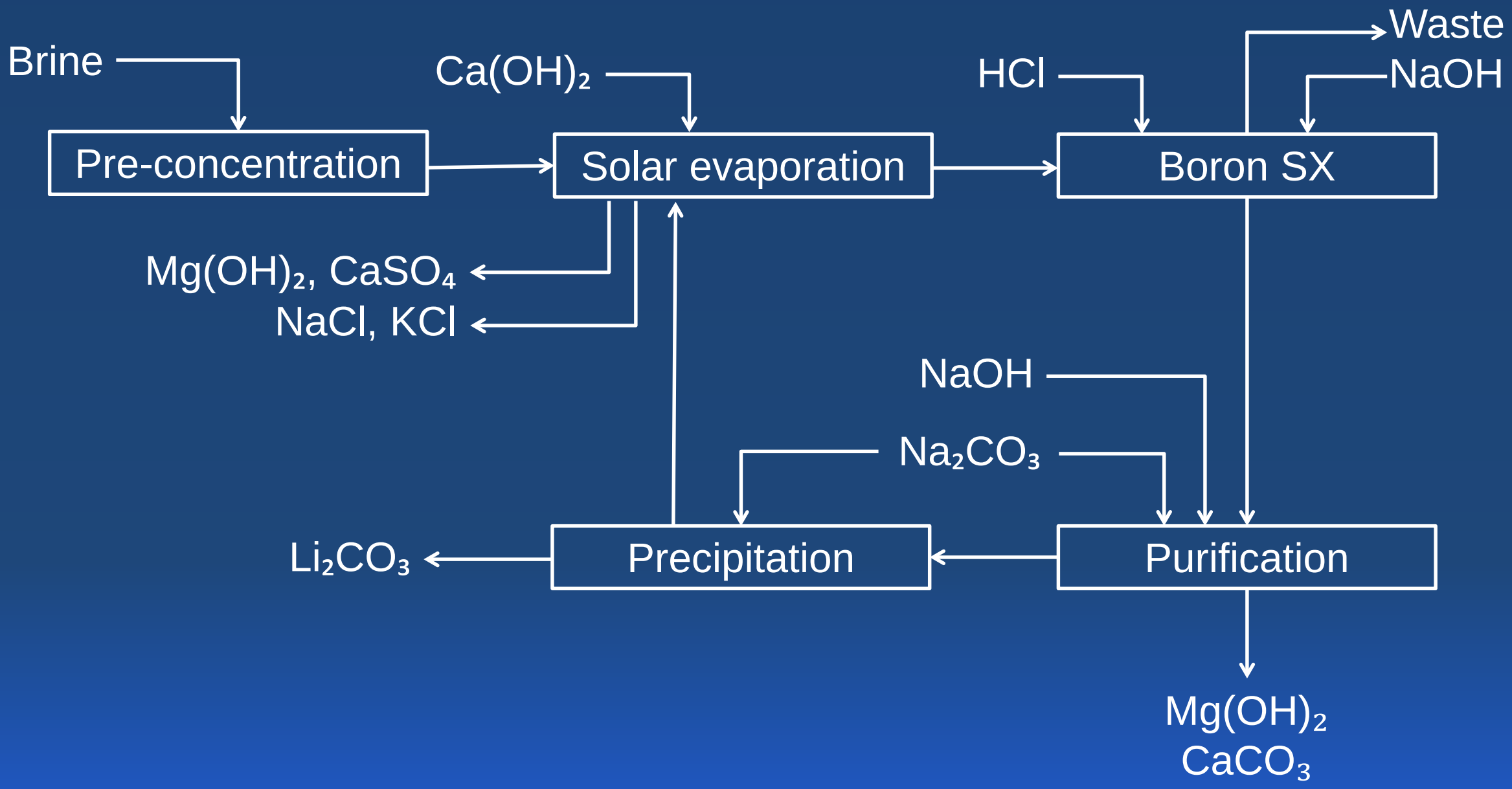


Nemaska Lithium



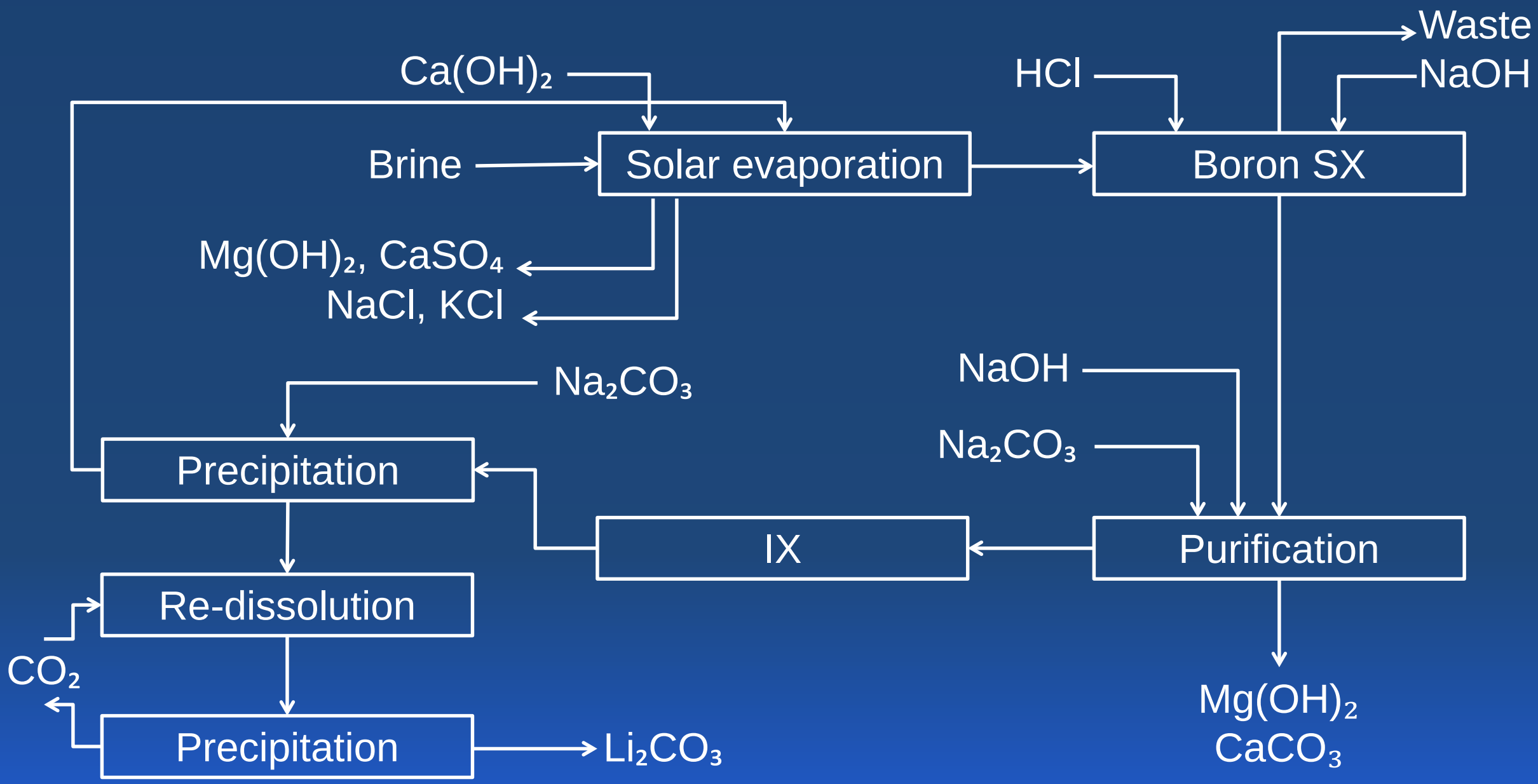
ALTA 2017

Quebec Lithium



ALTA 2017

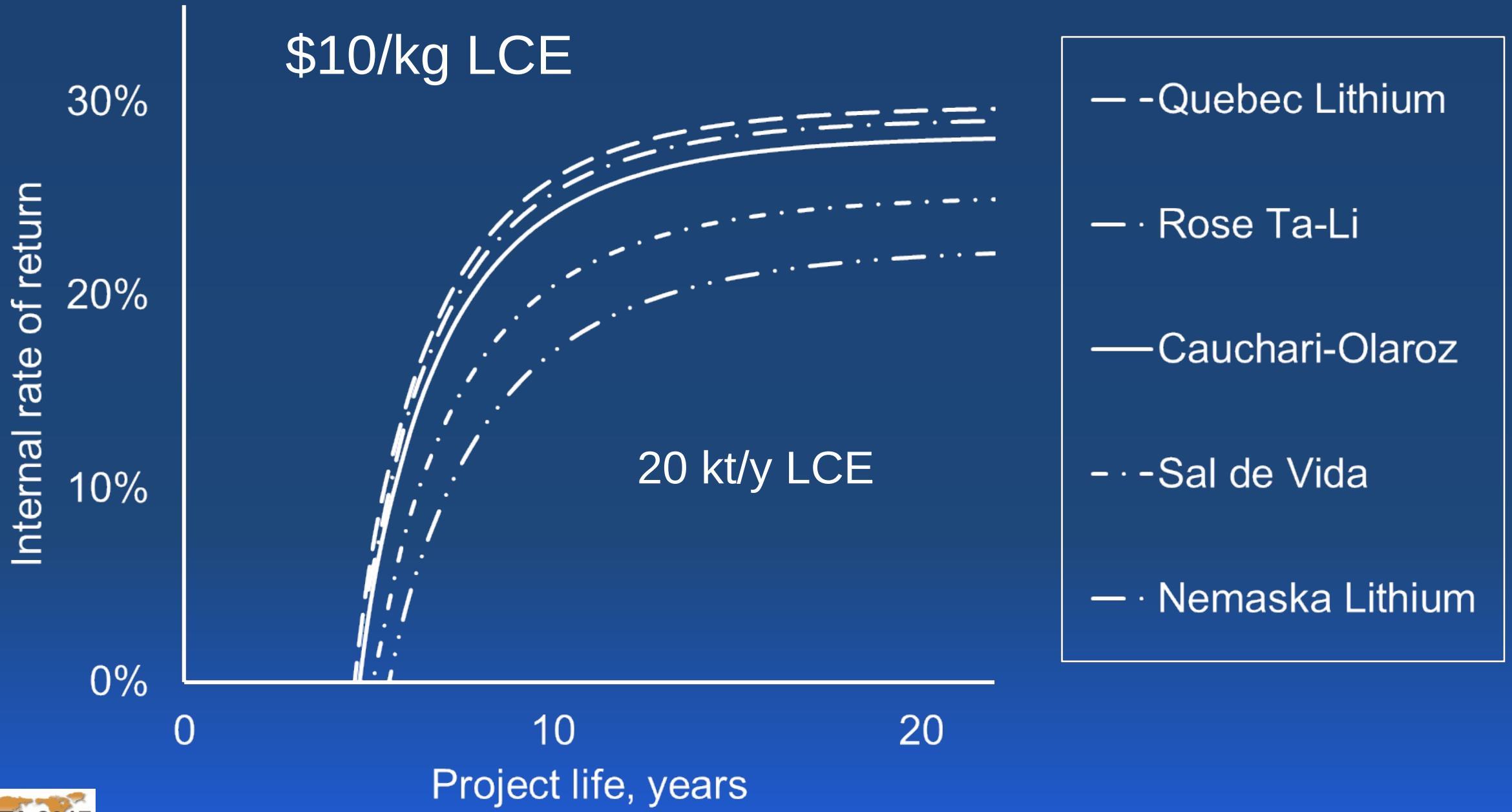
Cauchari-Olaroz

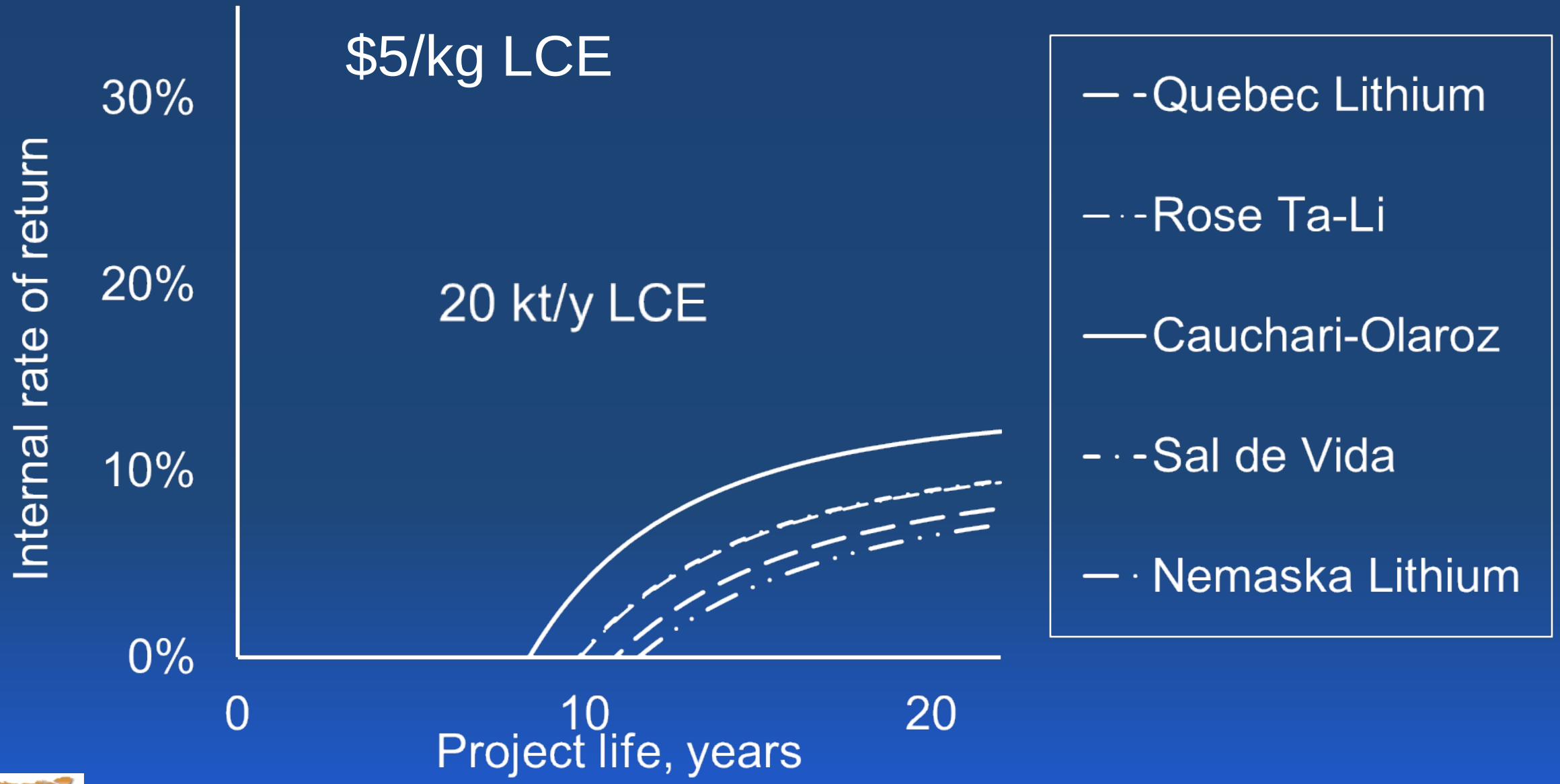

Ca(OH)₂
Brine
Solar evaporation
Mg(OH)₂, CaSO₄
NaCl, KCl
HCl
Waste
NaOH
Boron SX
Na₂CO₃
Precipitation
NaOH
Na₂CO₃
IX
Purification
Re-dissolution
CO₂
Precipitation
Li₂CO₃
Mg(OH)₂
CaCO₃

Sal de Vida

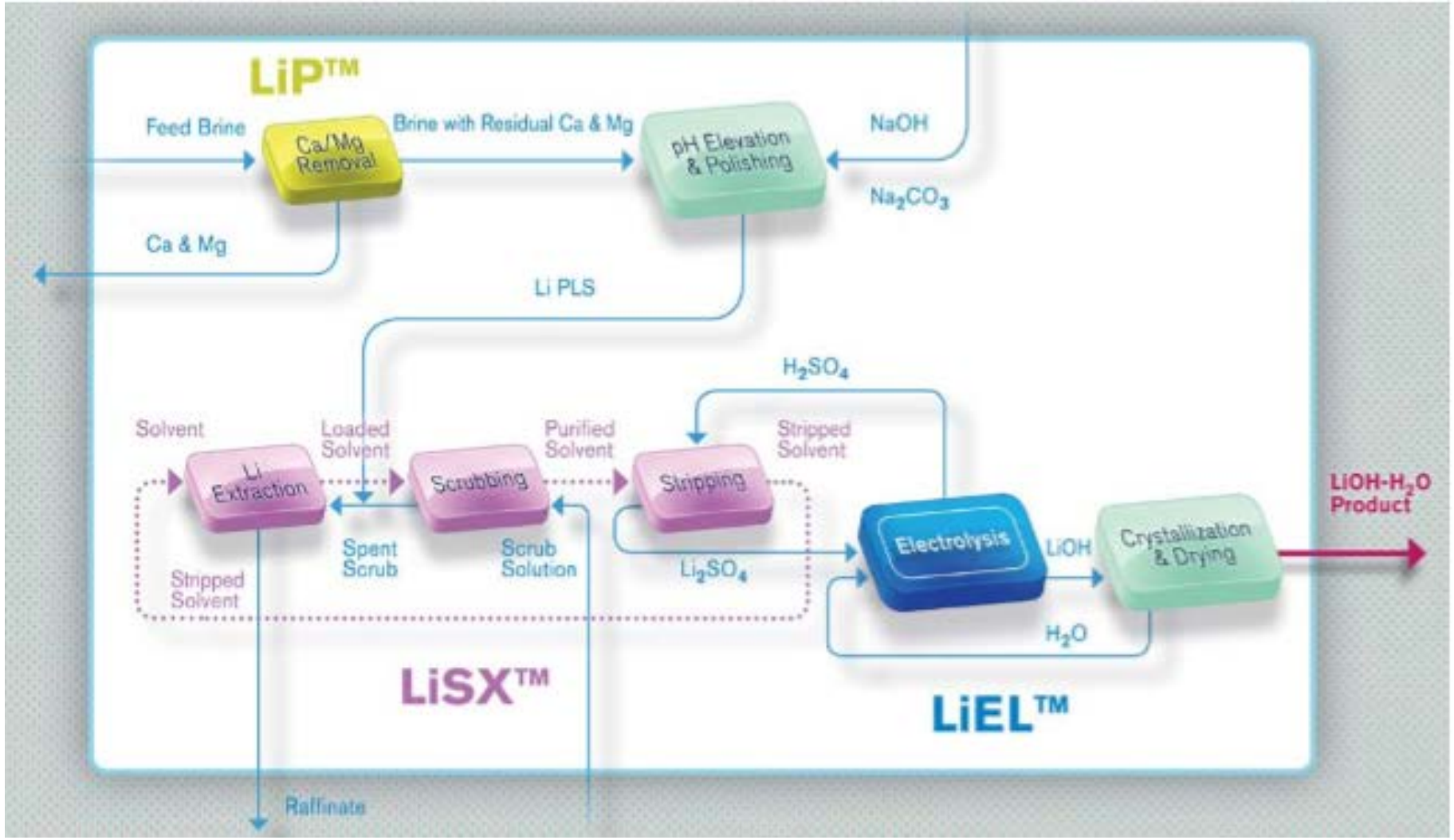
Project	Source	Main Li product	Capex $/(t/y) LCE	Opex $/t LCE
Nemaska Lithium	Spodumene ore	Hydroxide	15924	2482
Quebec Lithium	Spodumene ore	Carbonate	9577	3366
Cauchari-Olaroz	Salar brine	Carbonate	12459	1978
Sal de Vida	Salar brine	Carbonate	14102	2249

NI 43-101	Reagents	Opex	Δ
Nemaska	1.3	2.5	1.2
Quebec	2.4	3.4	1.0
Cauchari-Olaroz	0.8	2.0	1.2
Sal de Vida	0.8	2.2	1.4


$10/kg LCE
20 kt/y LCE
Internal rate of return
30%
20%
10%
0%
0
10
20
Project life, years
Quebec Lithium
Rose Ta-Li
Cauchari-Olaroz
Sal de Vida
Nemaska Lithium


$5/kg LCE
20 kt/y LCE
Internal rate of return
30%
20%
10%
0%
0
10
20
Project life, years
Quebec Lithium
Rose Ta-Li
Cauchari-Olaroz
Sal de Vida
Nemaska Lithium

Pure Energy Minerals, Clayton Valley project



Pure Energy Minerals. Ni 43-101 Technical Report

Li SX chemistry

$$xLi^+ + xNaOH \textbf{ +nHDBM + mTOPO} \rightarrow xNa^+ \textbf{ + xLiDBM + (n-x)HDBM•mTOPO +} xH_2O$$

$$\textbf{xLiDBM} + \textbf{(n-x)HDBM•mTOPO +} xH_3O^+ \rightarrow xLi^+ \textbf{ + nHDBM + mTOPO +} xH_2O$$

Lee *et al*. Solvent Extraction of Lithium. Journal of Inorganic Nuclear Chemistry, 1968

Li Extraction via SX – Reagent costs

Reagent	Cost, $/t	Solar	Li SX
CaO	150	0.1	0
NaOH	560	0	0.6
Na_2CO_3	370	1.3	0
Electricity		-	0.4
	Sub-total	**1.5**	**1.1**

Lithium Ion Sieves

$$Li_2TiO_3 + 2H_3O^+ \leftrightarrow H_2TiO_3 + 2Li^+$$

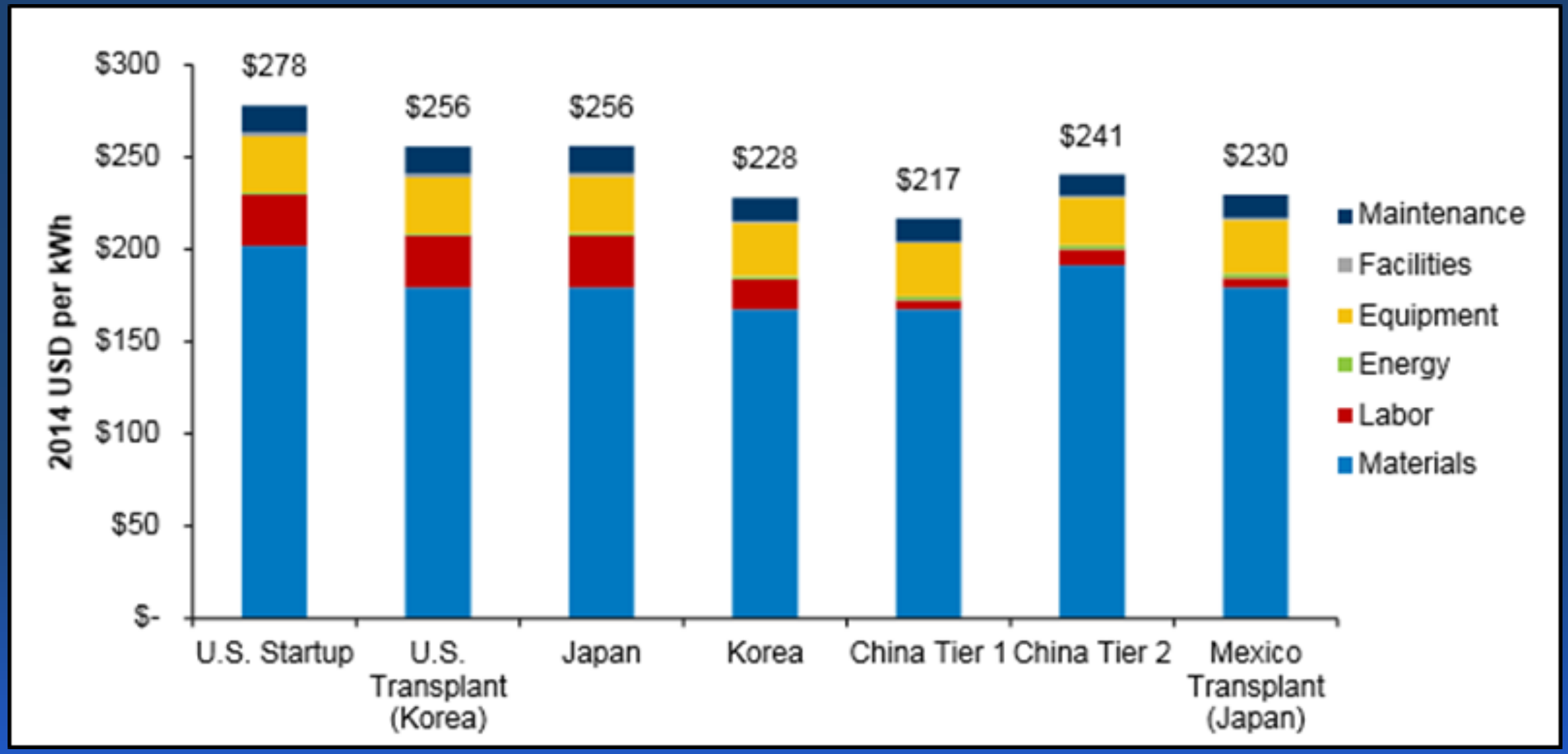
Sea water		mmol/kg		Selectivity Li/Other
Ion	mg/kg	Dissolved	Adsorbed	
Li^+	0.18	0.026	1982	-
Na^+	10561	459	235	149242
K^+	380	9.7	135	5491
Mg^{2+}	1272	52	94	85012
Ca^2	400	10	94	16212

Limjuco et al. Colloids and Surfaces A: Physiochemical and Engineering Aspects, Volume 504, 5 September 2016

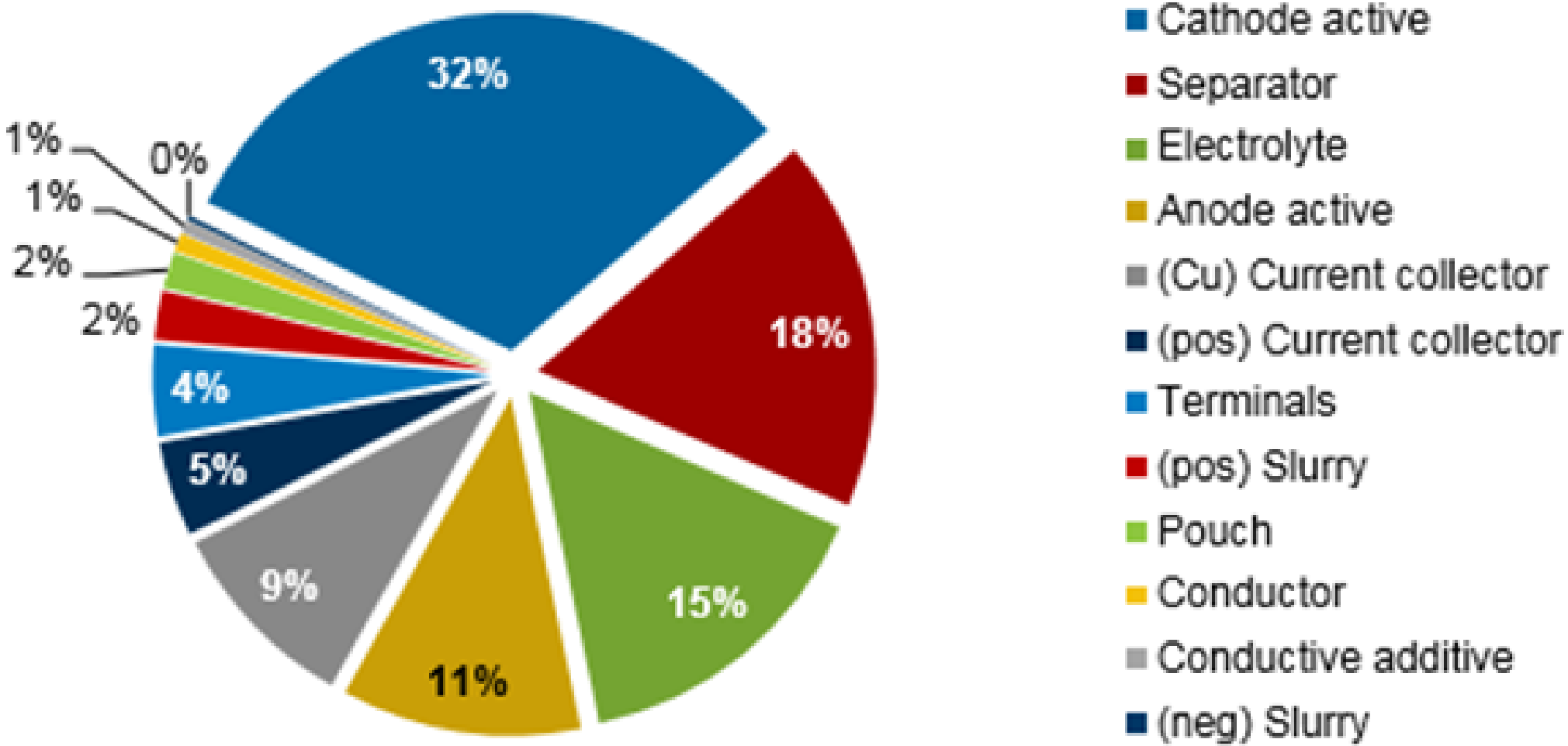
Lithium Ion Sieves – Reagent costs

Reagent		Oilfield brine		Continental brine	
Reagent	Cost, $/t	Li_2CO_3	LiOH	Li_2CO_3	LiOH
HCl	240	0.1	0.1	0.1	0.0
NaOH	560	0.6	0.6	0.6	0.6
Na_2CO_3	370	0.5	0.0	0.5	0.0
Power		-	0.5	-	0.5
	Sub-total	1.3	1.2	1.3	1.1
	Solar technology	23		0.8	

Li-ion battery costs

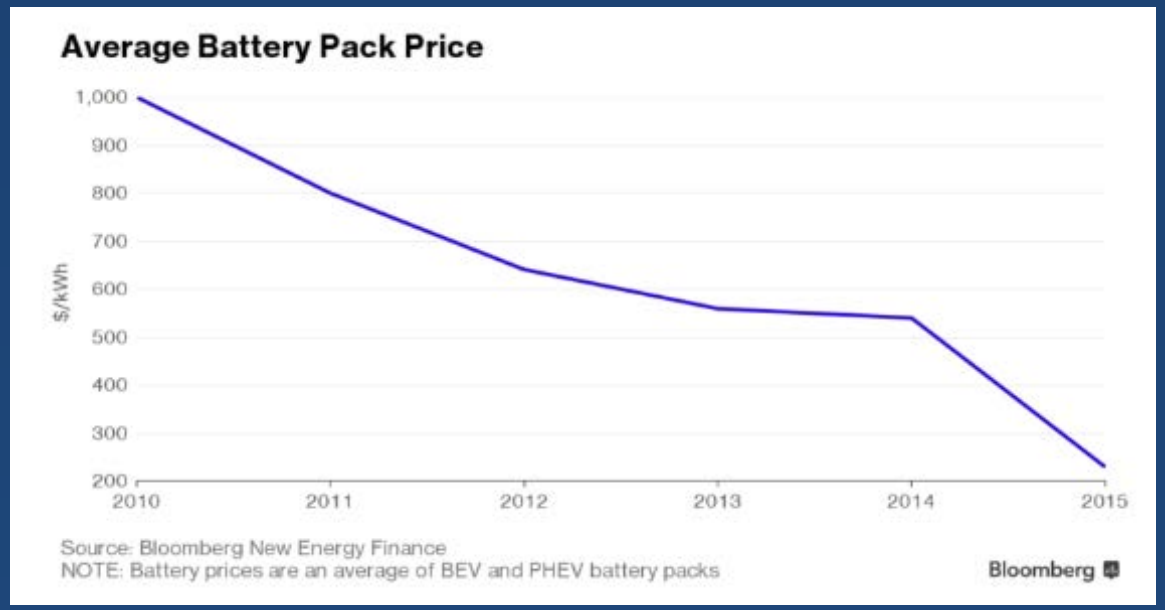


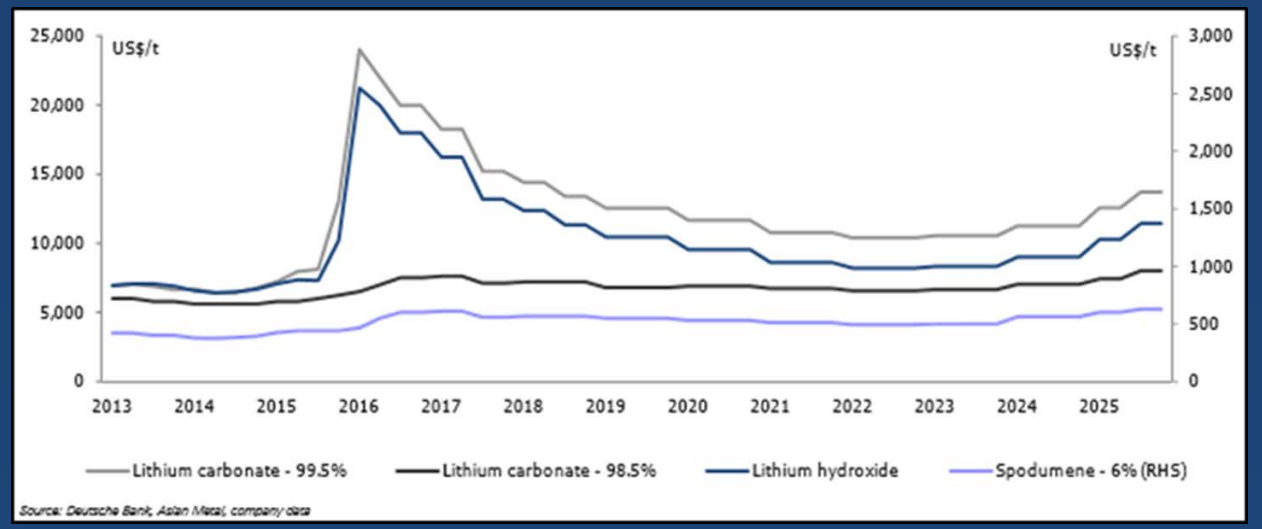
Li-ion battery – material costs



Cathode material cost, $/kWh

Input	$LiCoO_2$	$LiNiO_2$	$LiNi⅓Mn⅓Co⅓O_2$	$LiFePO_4$
Li_2CO_3	51	64	29	28
Co	445	-	83	-
Ni	-	161	24	-
Mn	-	-	1	-
Fe	-	-	-	4
H_3PO_4	-	-	-	7
Total	496	225	137 70	40





The four companies that in 2015 provided 88 percent of the world's lithium can't keep up