

TECHNOLOGY & COSTS

Technoeconomics - Energy & Chemicals (TECH) TECH 2018S11 Lithium Extraction Technologies

Table of Contents

A Report by **Nexant, Inc.**

Published Date: November 2018

www.nexantsubscriptions.com

Contents

1	Executive Summary	1
1.1	Introduction.....	1
1.2	Occurrence.....	3
1.2.1	Lithium Minerals.....	3
1.2.2	Lithium Resources	4
1.3	Mining Methods	8
1.3.1	Brine Deposits.....	8
1.3.2	Hard Rock Deposits	9
1.4	Commercial Technologies.....	10
1.4.1	Brine Deposits.....	10
1.4.2	Hard Rock Deposits	11
1.5	Emerging Technologies	12
1.5.1	Brine Deposits.....	13
1.5.2	Hard Rock Deposits	14
1.6	Process Economics	15
1.6.1	Lithium Carbonate.....	15
1.6.2	Lithium Hydroxide Monohydrate	16
1.6.3	Lithium Chloride	17
1.7	Effect of Brine Composition on Processing Costs.....	18
1.8	Integration of Downstream Processing with Upstream Mineral Resources.....	20
1.9	Market Analysis	22
1.9.1	Total Lithium Demand	22
1.9.2	Lithium Carbonate Demand.....	23
1.9.3	Lithium Hydroxide Monohydrate Demand	24
1.9.4	Lithium Chloride Demand	25
2	Introduction	26
2.1	Industry	26
2.1.1	History	28
2.1.2	Business Developments.....	28

2.1.3	Strategic Considerations	31
2.2	Technology and Licensing	32
2.2.1	Key Developers.....	32
2.2.2	Commercial Technologies	34
2.2.3	Developments in Technology	37
2.3	Lithium Compounds.....	38
2.3.1	Lithium Carbonate.....	38
2.3.2	Lithium Hydroxide Monohydrate	39
2.3.3	Lithium Chloride	40
3	Occurrence	42
3.1	Lithium Minerals	42
3.1.1	Lithium Aluminum Silicates.....	42
3.1.2	Micas	43
3.1.3	Lithium Phosphates.....	43
3.1.4	Other Lithium Ores.....	43
3.2	Lithium Resources	44
3.2.1	Hard Rock Deposits	45
3.2.2	Brines	46
4	Mining Methods and Beneficiation	48
4.1	Hard Rock Deposits.....	48
4.1.1	Mining Methods.....	48
4.1.2	Beneficiation Process Description	49
4.1.3	Process Features	53
4.2	Brine Deposits	54
4.2.1	Mining Methods.....	54
4.2.2	Beneficiation Process Description	54
4.2.3	Process Features	56
5	Commercial Process Technologies.....	59
5.1	Brine Processing	59
5.1.1	Introduction	59
5.1.2	Lithium Carbonate Production by Soda Ash Precipitation.....	60
5.1.3	Lithium Hydroxide Production via Reaction with Calcium Hydroxide.....	66
5.1.4	Lithium Chloride Production.....	69
5.2	Pegmatite Processing	73
5.2.1	Introduction	73
5.2.2	Lithium Carbonate Production by Sulfuric Acid Roasting and Carbonation	74
5.2.3	Lithium Hydroxide Monohydrate Production by Sulfuric Acid Roasting and Reaction with Calcium Hydroxide.....	79
5.2.4	Lithium Hydroxide Monohydrate Production by Sulfuric Acid Roasting and Reaction with Caustic Soda	79
5.2.5	Lithium Hydroxide Monohydrate Production by Lime Roasting and Crystallization.....	81

5.2.6	Lithium Carbonate Production by Lime Roasting and Carbonation with Soda Ash	84
6	Emerging Process Technologies	85
6.1	Introduction.....	85
6.2	Overview of Emerging Brine Technologies.....	86
6.3	Salar de Uyuni Processing (K-UTEC AG).....	87
6.4	Electrodialysis of Brine (Tenova Bateman).....	89
6.5	Extraction of Lithium from Brine Using Adsorption Media (Eramet)	92
6.6	Production of Lithium Hydroxide Monohydrate via Phosphate Precipitation (POSCO).....	94
6.7	Direct Extraction of Lithium from Brine (Rincon)	97
6.8	Petroleum Brine Processing (MGX Minerals)	100
6.9	Lithium Extraction from Waste Brine Using Adsorption Media (Standard Lithium)	103
6.10	Overview of Emerging Mineral Technologies.....	104
6.11	L-Max® Process (Lepidico).....	106
6.12	SiLeach® Process (Lithium Australia)	109
6.13	Electrolysis of Lithium Sulfate Solution from Pegmatite (Nemaska Lithium)	112
6.14	ELi™ Process (Neometals).....	115
6.15	Lithium Clay Processing (Bacanora Minerals)	119
6.16	Jadarite Processing (Rio Tinto)	121
7	Process Economics.....	123
7.1	Costing Basis	123
7.1.1	Investment Basis.....	123
7.1.2	Pricing Basis	123
7.1.3	Cost of Production Basis	125
7.2	Cost of Production Estimates	125
7.2.1	Overview.....	125
7.2.2	Brine Processing Models.....	127
7.2.3	Mineral Processing Models.....	140
7.2.4	Summary	155
8	Sensitivity Analysis.....	158
8.1	Overview	158
8.2	Brine Deposits	159
8.2.1	Brine Composition	159
8.2.2	Climate	160
8.3	Hard Rock Deposits	163
8.3.1	Integration of Downstream Processing with Upstream Mineral Resources.....	163
8.3.2	Sulfuric Acid Consumption	166
9	Market Analysis.....	167
9.1	Global Supply	167
9.1.1	Upstream	167

9.2	9.1.2 Downstream.....	168
	Global Demand.....	171
	9.2.1 Total Lithium Demand	171
	9.2.2 Lithium Carbonate Demand.....	172
	9.2.3 Lithium Hydroxide Monohydrate Demand	174
	9.2.4 Lithium Chloride Demand.....	176

Appendices

A	Lithium Conversion Tables	179
B	Definitions of Capital Cost Terms Used in Process Economics	181
C	Definitions of Operating Cost Terms Used in Process Economics.....	186
D	TECH Program Title Index (2008-2018).....	189
E	References	194

Figures

Figure 1	Lithium Value Chain.....	1
Figure 2	Lithium Mine Capacity, 2013–2023	2
Figure 3	Battery Value Chain.....	3
Figure 4	Lithium Resources by Type, 2017	4
Figure 5	Lithium Resources by Country, 2017	5
Figure 6	Major Global Brine Deposits.....	5
Figure 7	Major Global Hard Rock Deposits	7
Figure 8	SQM's Salar de Atacama Brine Beneficiation Block Flow Diagram	8
Figure 9	Hard Rock Beneficiation Block Flow Diagram.....	9
Figure 10	Overview of Commercial Brine Extraction Technologies	10
Figure 11	Overview of Commercial Mineral Extraction Technologies.....	11
Figure 12	Overview of Emerging Brine Technologies	13
Figure 13	Overview of Emerging Mineral Technologies.....	14
Figure 14	Summary of Lithium Carbonate Cost of Production Estimates	16
Figure 15	Summary of Lithium Hydroxide Monohydrate Cost of Production Estimates	17
Figure 16	Summary of Lithium Chloride Cost of Production Estimates	17
Figure 17	Cash Cost Sensitivity to Brine Magnesium Content	18
Figure 18	Cash Cost Sensitivity to Concentrated Brine Magnesium Content	19
Figure 19	Lithium Carbonate (COP 5) Cost of Production in Australia and China	20
Figure 20	Lithium Hydroxide Monohydrate (COP 8) Cost of Production in Australia and China.....	21
Figure 21	Lithium Carbonate Cost of Production in Australia and China	21
Figure 22	Primary Lithium Consumption by Compound.....	22
Figure 23	Global Upstream Lithium Supply and Demand	23
Figure 24	Global Lithium Carbonate Consumption by End Use	24
Figure 25	Global Lithium Hydroxide Monohydrate Consumption by End Use.....	25
Figure 26	Global Lithium Chloride Consumption by End Use	25
Figure 27	Lithium Value Chain.....	26

Figure 28	Lithium Mine Capacity, 2013–2023	27
Figure 29	Battery Value Chain	28
Figure 30	History of SQM	29
Figure 31	History of Albemarle Lithium	30
Figure 32	History of Livent Corporation (FMC Lithium)	30
Figure 33	Key Considerations for New Entrants	31
Figure 34	Barriers to Entry	32
Figure 35	Simplified Diagram of Lithium Extraction	34
Figure 36	Commercial Brine Process Routes	35
Figure 37	Commercial Mineral Ore Process Routes	36
Figure 38	Lithium Resources by Type, 2017	44
Figure 39	Lithium Resources by Country, 2017	44
Figure 40	Major Global Hard Rock Deposits	45
Figure 41	Major Global Brine Deposits	46
Figure 42	Jaw Crusher	50
Figure 43	Spiral Concentrators	51
Figure 44	Flotation Cell Diagram	52
Figure 45	Hard Rock Beneficiation Block Flow Diagram	54
Figure 46	Janecke Diagram for Brines	55
Figure 47	Byproduct and Impurity Content of Major Brine Deposits	57
Figure 48	SQM's Salar de Atacama Brine Beneficiation Block Flow Diagram	58
Figure 49	Overview of Commercial Brine Extraction Technologies	59
Figure 50	Conventional Mixer-Settler Design	63
Figure 51	Low Purity Lithium Carbonate Production from Brine Resources	61
Figure 52	High Purity Lithium Carbonate from Brine Resources	62
Figure 53	Lithium Hydroxide Production from Lithium Carbonate	67
Figure 54	Typical Counter-Current Decantation Unit	68
Figure 55	Typical Evaporative Crystallizer Unit	69
Figure 56	Simplified Flow Diagram for Livent's Selective Recovery Technology	70
Figure 57	Lithium Chloride Production from Brine	71
Figure 58	Lithium Chloride Production from Lithium Carbonate	72
Figure 59	Overview of Commercial Mineral Extraction Technologies	73
Figure 60	Lithium Carbonate Production via Sulfuric Acid Roasting	75
Figure 61	High Purity Lithium Carbonate via Bicarbonate Circuit	76
Figure 62	Lithium Hydroxide Production via Sulfuric Acid Roasting	80
Figure 63	Lithium Hydroxide Production via Lime Roasting	82
Figure 64	Overview of Emerging Brine Technologies	86
Figure 65	Nexant's Potion for K-UTEC AG Lithium Extraction Technology	87
Figure 66	Block Flow Diagram of Tenova Bateman's Lithium Extraction	90
Figure 67	Nexant's Supposition for Tenova's LiP™ Technology	90
Figure 68	Overview of LiEL™ Technology	91
Figure 69	Block Flow Diagram of ERAMET's Lithium Extraction Technology	93
Figure 70	Block Flow Diagram of POSCO's Lithium Extraction Technology	95

Figure 71	Block Flow Diagram of Rincon's Lithium Extraction Technology	97
Figure 72	Block Flow Diagram of Petrolithium Extraction Technology.....	101
Figure 73	Block Flow Diagram of Standard Lithium's Lithium Extraction Technology	104
Figure 74	Overview of Emerging Mineral Technologies.....	105
Figure 75	Block Flow Diagram of Lepidico's Lithium Extraction Technology	107
Figure 76	Importance of Byproduct Recovery to L-Max® Technology	108
Figure 77	Block Flow Diagram of Lithium Australia's Lithium Extraction Technology.....	111
Figure 78	Block Flow Diagram of Nemaska's Lithium Extraction Technology.....	113
Figure 79	Comparison of Nemaska Lithium Cost of Production with Conventional Route	115
Figure 80	Block Flow Diagram of ELi™ Technology.....	117
Figure 81	Electrolysis of Lithium Chloride	118
Figure 82	Block Flow Diagram of Bacanora's Lithium Extraction Technology	119
Figure 83	Nexant's Postulation for Jadarite Lithium Extraction Technology	121
Figure 84	Nexant's Approach to Cost of Production Estimation	126
Figure 85	Summary of Lithium Carbonate Cost of Production Estimates	156
Figure 86	Summary of Lithium Hydroxide Monohydrate Cost of Production Estimates	157
Figure 87	Summary of Lithium Chloride Cost of Production Estimates	157
Figure 88	Cash Cost Sensitivity to Brine Magnesium Content	159
Figure 89	Cash Cost Sensitivity to Concentrated Brine Magnesium Content	160
Figure 90	Cash Cost Sensitivity to Average Maximum Daily Temperature.....	161
Figure 91	Cash Cost Sensitivity to Average Minimum Daily Temperature.....	161
Figure 92	Cash Cost Sensitivity to Average Annual Wind Speed	162
Figure 93	Cash Cost Sensitivity to Average Annual Relative Humidity.....	162
Figure 94	Lithium Carbonate (COP 5) Cost of Production in Australia and China, 2018.....	164
Figure 95	Lithium Hydroxide Monohydrate (COP 8) Cost of Production in Australia and China, 2018	164
Figure 96	Lithium Carbonate Cost of Production in Australia and China, 2011	165
Figure 97	Cash Cost Sensitivity to Sulfuric Acid Consumption.....	166
Figure 98	Total Upstream Lithium Capacity by Resource	167
Figure 99	Announced Upstream Lithium Capacity Additions	168
Figure 100	Primary Lithium Consumption by Compound.....	171
Figure 101	Global upstream Lithium Supply and Demand, LCE Basis.....	172
Figure 102	Global Lithium Carbonate Consumption by End Use	173
Figure 103	Global Lithium Carbonate Consumption by End Use	174
Figure 104	Global Lithium Hydroxide Monohydrate Consumption by End Use.....	175
Figure 105	Global Lithium Hydroxide Monohydrate Consumption by End Use.....	175
Figure 106	Global Lithium Chloride Consumption by End Use	176
Figure 107	Global Lithium Chloride Consumption by End Use	177

Tables

Table 1	Lithium Compound Applications	1
Table 2	Common Lithium Minerals.....	3
Table 3	Development Stage for Each Emerging Technology.....	12
Table 4	COP Identification and Description.....	15
Table 5	Lithium Compound Applications	26
Table 6	Overview of Major Producers	33
Table 7	Overview of Mining Services Companies.....	34
Table 8	Overview of Emerging Technologies	38
Table 9	Lithium Carbonate Grades Offered by Producers	39
Table 10	Lithium Hydroxide Monohydrate Grades Offered by Producers.....	40
Table 11	Lithium Chloride Grade Offered by Producers	41
Table 12	Common Lithium Minerals.....	42
Table 13	Simplified Mine Data for Major Lithium Deposits, 2018	49
Table 14	Greenbushes' Feed and Product Composition	53
Table 15	Typical Order of Crystallization in Solar Evaporation Ponds.....	55
Table 16	Composition of Major Brine Deposits.....	56
Table 17	Typical Concentrated Brine Composition.....	58
Table 18	Commercial Brine Extraction Technologies	59
Table 19	Solubility of Inorganic Hydroxides.....	66
Table 20	Commercial Mineral Extraction Technologies	73
Table 21	Comparison of Alpha-Spodumene with Beta-Spodumene	77
Table 22	Development Stage for Each Emerging Technology.....	85
Table 23	Overview of K-UTEC AG Salt Technologies' Patents.....	88
Table 24	K-UTEC AG Experimental Results for Lithium Chloride Production.....	88
Table 25	Selection of POSCO's Lithium-related Patents	94
Table 26	Nano-filtration Experimental Results (Patent WO2016209301)	98
Table 27	Results from MGX Mineral's Lithium Recovery Trials	102
Table 28	Lepidico's Deposit Interests	106
Table 29	Lithium Australia's Deposit Interests, Q2 2018	110
Table 30	2018 Prices Used in Cost of Production Tables	124
Table 31	Fixed Cost Assumptions for Argentina.....	127
Table 32	Table of Common Assumptions for Brine Processing Models	128
Table 33	Inlet (Brine) and Outlet (Concentrated Brine) Composition and Flowrate	129
Table 34	Factors Used in Update of Cost of Production Contributions.....	130
Table 35	Cost of Production Estimate for: Brine Concentrate, 6% Lithium Process: Solar Evaporation, Argentina	131
Table 36	Cost of Production Estimate for: Lithium Carbonate (Average Purity) Process: Carbonation of Lithium Brine with Soda Ash, Argentina	133
Table 37	Cost of Production Estimate for: Lithium Hydroxide Monohydrate (High Purity) Process: Lithium Carbonate conversion to Lithium Hydroxide, Argentina.....	135
Table 38	Cost of Production Estimate for: 40 wt % Lithium Chloride Solution Process: Direct Production of Lithium Chloride from Brine, Argentina	137

Table 39	Cost of Production Estimate for: 40 wt % Lithium Chloride Solution Process: Lithium Carbonate conversion to Lithium Chloride, Argentina.....	139
Table 40	Fixed Cost Assumptions for Australia.....	140
Table 41	Table of Common Assumptions for Mineral Processing Models.....	141
Table 42	ROM Ore and Concentrated Ore Composition and Flowrate	142
Table 43	Other Upstream Mining Operation Assumptions.....	142
Table 44	Factors Used in Update of Cost of Production Contributions.....	143
Table 45	Cost of Production Estimate for: 7% Lithium Oxide Concentrate Process: Truck & Shovel and Beneficiation Plant, Australia.....	144
Table 46	Cost of Production Estimate for: Lithium Carbonate (High Purity) Process: Sulfuric Acid Roasting followed by Carbonation, Australia.....	147
Table 47	Cost of Production Estimate for: Lithium Hydroxide Monohydrate (Low Purity) Process: Lime Roasting, Australia.....	149
Table 48	Cost of Production Estimate for: Lithium Hydroxide Monohydrate (High Purity) Process: Lithium Carbonate Conversion to Lithium Hydroxide, Australia	151
Table 49	Cost of Production Estimate for: Lithium Hydroxide Monohydrate (High Purity) Process: Sulfuric Acid Roasting and Reaction with Caustic Soda, Australia.....	154
Table 50	COP Identification and Description.....	155
Table 51	Global Commodity Lithium Salts Capacity, 2018	169
Table 52	Global Lithium Salts Capacity Additions	170
Table 53	Lithium Content by Compound	179
Table 54	Lithium Mass Conversion Tables.....	180

Nexant Inc.

TECHNOLOGY & COSTS

Techneconomics - Energy & Chemicals (TECH) Lithium Extraction Technologies

The Nexant Subscriptions' Techneconomics - Energy & Chemicals (TECH) program is recognized globally as the industry standard source for information relevant to the chemical process and refining industries. Techneconomics - Energy & Chemicals (TECH) reports are available as a subscription program or on a single report basis.

Contact Details:

Americas:

Marcos Nogueira Cesar, Vice President, Global Products, E&CA: Nexant Subscriptions
Phone: + 1-914-609-0324, e-mail: mcesar@nexant.com

Erica Hill, Client Services Coordinator, E&CA-Products
Phone: + 1-914-609-0386, e-mail: ehill@nexant.com

EMEA:

Anna Ibbotson, Director, Nexant Subscriptions
Phone: +44-207-950-1528, aibbotson@nexant.com

Asia:

Chommanad Thammanayakatip, Managing Consultant, Energy & Chemicals Advisory
Phone: +66-2793-4606, email: chommanadt@nexant.com

Nexant, Inc. (www.nexant.com) is a leading management consultancy to the global energy, chemical, and related industries. For over 38 years, Nexant has helped clients increase business value through assistance in all aspects of business strategy, including business intelligence, project feasibility and implementation, operational improvement, portfolio planning, and growth through M&A activities. Nexant has its main offices in San Francisco (California), White Plains (New York), and London (UK), and satellite offices worldwide.

Copyright © by Nexant Inc. 2018. All Rights Reserved.