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Lithium Reserves and Resources in Mongolia and their Exploitation

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Statutory Declaration

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Abstract

In recent years, lithium demand is drastically increasing and it is said to be becoming a new oil due to increasing number of electrical vehicles. This light-weight, highly reactive metal is able to store relatively high electrical energy in its chemical bonds and it is widely used in electrical and electronics industry as a rechargeable battery. Studies show that increasing number of electrical vehicles might set demand of lithium to 1'000'000t by 2025.

Lithium is spread all over the world, but in trace concentration. However, several types of deposits hold economical value. These types of deposits are brines, pegmatites and clays. Brines are salt lakes where lithium is dissolved within the water. Its lithium extraction is relatively simple and inexpensive. Pegmatite deposits require energy intensive, complex processes. Operating cost of hard rock mines of lithium can be twice the operating cost of brine mines due to beneficiation and extraction processes. But, brines possess greater environmental risks like leakage.

Mongolia has currently 4 economically feasible hard-rock, pegmatite deposits that are under exploration and planning phase. These are Huh Dely deposit, Munkhtyn Tsagaan Durvuljin deposit, Eguzer deposit, and Bear Mountain deposit in Dundgobi and Sukhbaatar province. Unfortunately, Mongolia does not have brine deposits. Since, lithium mine is considered to be the least harmful mine, and deposits' locations are ideally located to the infrastructure; engineering, economical, political, societal, psychological, and ecological aspects of feasibility have great expectations. Due to increasing demand for lithium-ion batteries for electrical vehicles, lithium price is expected to exceed \$10000/t lithium carbonate within next five years.

1 Introduction

Our planet is facing formidable sustainability challenges with on the one side global warming from combustion of fossil fuels and on the other side the world's electricity demand is about to double by 2050 while fossil fuels are limited. Great hopes are placed on the renewable energies but only fraction of harnessed energy is being used due to energy storage issues. Lithium-ion batteries, by having comparatively a higher energy density among other batteries, show great promise for storing renewable energy and providing it to consumers.

Before Electric Vehicles (EV) and lithium-ion batteries (LIB), lithium market was dominated by ceramics and glass industries to increase mechanical strength and thermal shock resistivity. Together these industries accounted about 40% of the lithium demand with other applications including air treatments, greases, polymer production and metallurgical casting powders making up the rest of the demand.

In the beginning of 1990s, lithium gained recognition in battery-related energy sector as its lightweight and higher energy density compared to other types of batteries and its growth started as small rechargeable lithium-ion batteries which quickly became consumer preferred power source in fast growing consumer electronics and cordless power tool markets. Since then, lithium demand for LIB increased to nearly 60000t which is 12 times higher than before and during the same period demand of lithium for other application merely doubled to 56000t [1].

Global Green House Gas (GHG) emission from transportation sector takes around 27%. The well-to-wheel (WTW) GHG emission from the EVs are determined by combining the energy used by EVs and carbon intensity of electricity generation. Based on the global average carbon intensity of power generation and WTW emissions from a global average EV are lower than from a global average Internal Combustion Engine (ICE) vehicle powered by liquid and gaseous fuel blends. For instance, WTW GHG emission of 2018 EV stock was about 38 million tons of carbon-dioxide equivalent. This compares to 78 million tons of carbon-dioxide equivalent that an equivalent ICE fleet would have emitted, leading to net saving from EV deployment of 40 Mt CO₂ -eq [2].

The **EV 30@30** Campaign was launched at the 8th Clean Energy Ministerial (CEM) meeting in 2017 with the goal of accelerating the deployment of electric vehicles. This campaign redefines the ambition of CEM's Electric Vehicles Initiative (EVI), setting the objective to reach a 30% sales share for EVs by 2030 with following goals [2]:

- To enhance energy security

Wide-scale production of EVs will significantly reduce dependence on petroleum and other primary energy source, and will promote development in both electric vehicles and renewable energy sector by further reducing emissions from EVs.

- To lower GHG emission

Holding global temperature increase below 2 degrees Celsius is essential and to hold it changes in current transportation is required. If an integrated EV ecosystem is developed, greenhouse gas emission can be reduced as much as 77% by 2050.

- To support the uptake of clean electricity

EV's high storage capacity batteries could enable greater use of variable renewables in electricity production.

- To boost economic and industrial competitiveness

One of the most innovative sectors is the automotive sector and electric mobility will increase economic and industrial competitiveness by attracting investment.

- To establish policy that fosters a robust market, opening opportunities for vehicle manufacturers.

Substantial policy support about the complex interplay between different support mechanisms, the vehicle market, and infrastructure investments are needed to ensure electrification occur quickly and cost effectively.

- To improve citizens' quality of life, especially in major cities

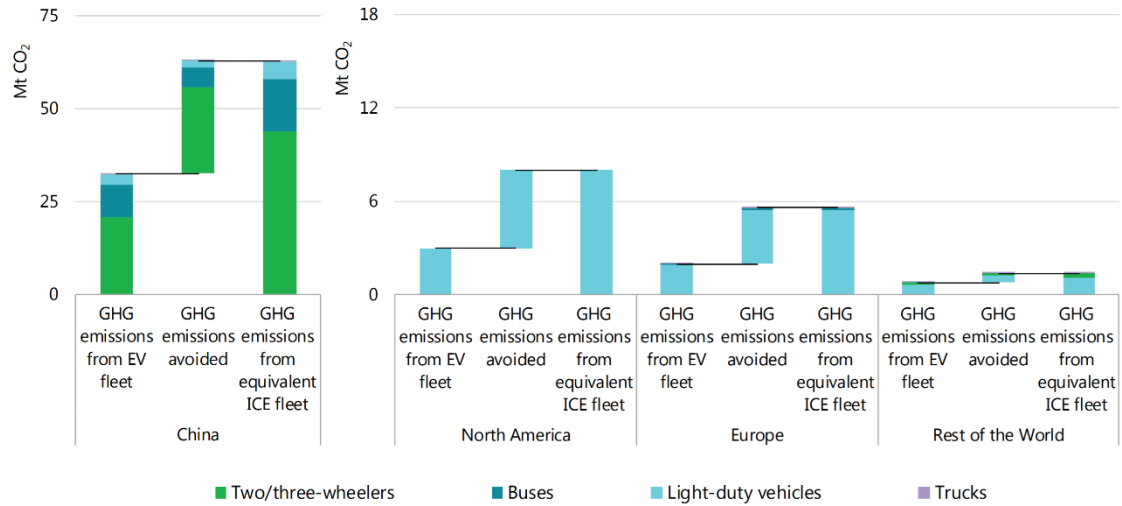
EVs reduce local air pollutants, improve air quality, and lessen noise pollution.

Eleven countries endorsed the campaign: Canada; China; Finland; France; India; Japan; Mexico; Netherlands; Norway; Sweden; and United Kingdom. In addition, 29 companies and organizations support the campaign: C40; FIA Foundation; Global Fuel Economy Initiative; Hewlett Foundation; Natural Resource Defence Council; REN21; SLoCaT; The Climate Group; UN Environment; UN Habitat; World Resources Institute; ZEV Alliance; ChargePoint; Energias de Portugal (EDP); Enel X; E.ON; Fortum; Iberdrola; Renault-Nissan-Mitsubishi Alliance; Schneider Electric; TEPCO and Vattenfall [2, 3].

This environmentally friendly way of transportation has promising room for development and in 2018 alone, global EV number exceeded 5.1 million units, up by 2 million units since 2017. Here China accounted world's largest electric car market with nearly 1.1 million units sold in 2018 [5]. Europe followed with 1.2 million EVs taking almost half of the global electric car stock.

Lithium prices have halved since 4th quarter of 2017, driven by perceptions of oversupply in the market and, as a result, major producers are pulling back and re-assessing expansion plans. Recently, some companies claim that a slowdown in EV sales in China due to a subsidy cut have resulted in slower growth than anticipated [5].

Despite the fact, many researchers forecast battery demand for lithium is set to triple by 2025 to 700,000 metric tons LCE (Lithium Carbonate Equivalent). Adding around 300,000 metric tons LCE of non-battery lithium demand means global lithium resource demand could reach the famed “1 million metric tons LCE by 2025” [6, 7]. However, we emphasize that battery demand alone will not reach this target.



Notes: GHG emissions from an equivalent ICE fleet indicate the WTW CO₂-eq emissions that would have been emitted if the EVs would have been ICE vehicles of equivalent size. The carbon intensity of the national power systems account for transmission and distribution losses. Light-duty vehicles include cars and light-commercial vehicles. Buses include buses and minibuses. Trucks include medium- and heavy-freight trucks.

Sources: IEA analysis based on country submissions; carbon intensity of the national/regional power systems from (IEA, 2018c); accounting for transmission and distribution losses from (IEA, 2018c).

Figure 1. Green House Gas Emission Avoided by EVs by Region [2]

2 Lithium Fundamentals

2.1 What is Lithium?

Lithium is the third element of the Mendeleev's periodic table (IA Group, monovalent element). Its nucleus contains three protons and three to four neutrons. Lithium belongs to alkali metals group, but due to its small ionic radius it differs from sodium, potassium, rubidium, and cesium. Lithium has gained its popularity due to its numerous remarkable properties. Lithium is the softest and lightest solid element in the world. This silvery-white alkali metal is a highly reactive and flammable element and due to these properties, it has to be stored in mineral oils. Lithium is a good conductor of heat and electricity because like other alkali metals lithium has a single valence electron that is easily given up to form a cation [8]. It occurs in the nature only in compounds like pegmatitic minerals. Because of its solubility, it is also commonly occurred in salty water. With ionic radius of 0.76Å, lithium cannot substitute the larger alkali ions sodium and potassium in rock-forming minerals, but it can partly substitute Fe, Al and especially Mg in some minerals during the late phases of magmatic crystallization, but this replacement occurs only under certain conditions. [9]

2.2 Discovery & Occurrence

Lithium bearing Petalite ore ($\text{LiAlSi}_4\text{O}_{10}$) was firstly discovered by the Brazilian chemist José Bonifácio de Andrada e Silva in 1800 [10]. But the presence of the Lithium in the ore was discovered in 1817 by Swedish chemist Johan August Arfvedson in a laboratory. Soon after, he also discovered that same element was present in minerals like spodumene ($\text{LiAlSi}_2\text{O}_6$) and lepidolite ($\text{K}(\text{Li},\text{Al},\text{Rb})_2(\text{Al},\text{Si})_4\text{O}_{10}(\text{F},\text{OH})_2$). In 1821, William Thomas Brande isolated Lithium from lithium oxide through electrolysis process which is a broadly applied method to separate alkali metals. In 1855, lithium production in a larger scale through electrolysis started. This procedure became foundation to produce lithium commercially and in 1923 German company Metallegesellschaft AG started performing an electrolysis on a liquid mixture of lithium chloride and potassium chloride [11].

2.3 Lithium Geology

Lithium is a comparatively rare element, although it is found in many rocks and some brines, but always in very low concentrations. The average amount in the earth's crust is estimated to be about 20 ppm. Even with this low concentration, there are a fairly large number of both lithium mineral and brine deposits, but finding deposits that has potential economic value is challenging [10]. Many of the deposits are either small or low in concentration and some are located in remote areas. Some of the well-known deposits that could be economically beneficial are shown in Figure 1.2.

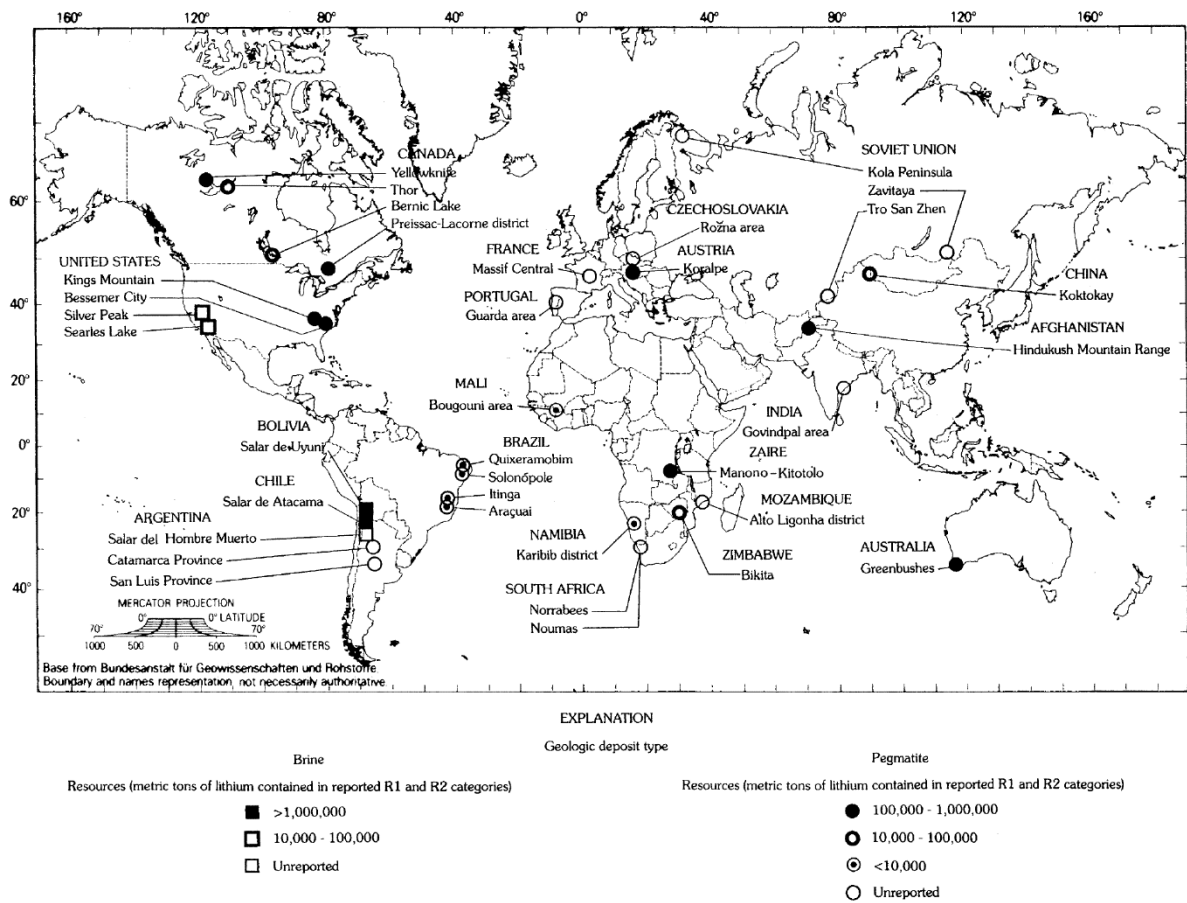


Figure 2. Location and reserve estimate of some of the world's lithium deposits [9]

The deposits have been formed because of lithium's higher solubility than most other cations, so it sometimes has concentrated in flowing and cooling magma or its accompanying aqueous fluids, as well as evaporating brines. Thus, its minerals are generally found in the latter stages of alkaline magma flow, intrusion and crystallization, as occurs in pegmatite formations. There are about 145 minerals containing lithium as a major component (>200 with >0.002% Li_2O), and about 25 contain over 2% Li_2O . Forty-three of the better known of these minerals are listed in Table 1.1. Mineral sources may contain valuable elements like Be, Cs, F, P, Sn, Ta and Rb. Similarly, brines contain B, K, Na and Mg with tendency of higher concentration.

Table 1. Lithium Minerals [9]

Formula and Group of Some of the Lithium Minerals (Vine, 1980)

Name and formula	Mineral group or series
Amblygonite (Li,Na)AlPO ₄ (F,OH)	Amblygonite
Bertossaite (Li,Na) ₂ (Ca,Fe,Mn)Al ₄ (PO ₄) ₄ (OH,F) ₄	—
Bikitaite LiAlSi ₂ O ₆ ·H ₂ O	Zeolite (?)
Bityite Ca(Al,Li) ₂ [(Al,Be) ₂ Si ₂ (O,OH) ₁₀]·H ₂ O	Margarite
Brannockite KLi ₃ Sn ₂ Si ₁₂ O ₃₀	—
Cookeite (Li,Al ₄)Si ₃ AlO ₁₀ (OH) ₈	Chlorite
Cryolithionite Li ₃ Na ₃ Al ₂ F ₁₂	—
Eckermannite Na ₃ (Mg,Li) ₄ (Al,Fe)Si ₈ O ₂₂ (OH,F) ₂	Amphibole (asbestos)
Elbaite Na(Li,Al) ₃ Al ₆ B ₃ Si ₆ O ₂₇ (OH,F) ₄	Tourmaline
Ephesite Na(LiAl ₂)(Al ₂ Si ₂)O ₁₀ (OH) ₂	Margarite
Eucryptite LiAlSiO ₄	—
Ferghanite LiH(UO ₂ /OH) ₄ (VO ₄) ₂ ·2H ₂ O	—
Ferri-sicklerite (Li, Fe ³⁺ , Mn ²⁺)PO ₄	Sicklerite
Gerstleyite (Na,Li) ₄ As ₂ Sb ₈ S ₁₇ ·6H ₂ O	—
Hectorite Na _{0.33} (Mg,Li) ₃ Si ₄ O ₁₀ (F,OH) ₂	Smectite
Holmquistite Li ₂ (Mg,Fe ²⁺) ₃ (Al,Fe ³⁺) ₂ Si ₈ O ₂₂ (OH) ₂	Amphibole
Hsianghualite Ca ₃ Li ₂ Be ₃ (SiO ₄) ₃ F ₂	—
Lepidolite K(Li,Al) ₃ (Si,Al) ₄ O ₁₀ (F,OH) ₂	Mica
Liberite Li ₂ BeSiO ₄	—
Lithiophilite Li(Mn ²⁺ , Fe ²⁺)PO ₄	Lithiophilite–triphyllite
Lithiophorite (Al, Li)MnO ₂ (OH) ₂	—
Lithiophosphate Li ₃ PO ₄	—
Manandonite ^a LiAl ₄ (AlBSi ₂ O ₁₀)(OH) ₃	Chlorite
Montebrasite (Li, Na)Al(PO ₄)(OH,F)	Amblygonite
Nambulite LiNaMn ₈ Si ₁₀ O ₂₈ (OH) ₂	—
Natromontebrasite (Na, Li)Al(PO ₄)(OH,F)	Amblygonite
Palermoite (Li, Na) ₂ (Sr,Ca)Al ₄ (PO ₄) ₄ (OH) ₄	—
Petalite LiAlSi ₄ O ₁₀	—
Polyolithionite KLi ₂ Al(Si ₄ O ₁₀)(F,OH) ₂	Mica
Rankamite (Na,K,Pb,Li) ₃ (Ta,Nb,Al) ₁₁ (O,OH) ₃₀	—
Regularly interstratified montmorillonite-chlorite	—
Sicklerite Li(Mn ²⁺ , Fe ³⁺)PO ₄	—
Sogdianite (K,Na) ₂ Li ₂ (Li,Fe,Al,Ti) ₂ Zr ₂ (Si ₂ O ₅) ₆	—
Spodumene LiAlSi ₂ O ₆	Pyroxene
Swinefordite	Smectite
Taeniolite KLiMg ₂ Si ₄ O ₁₀ F ₂	Mica
Tavorite LiFe ³⁺ PO ₄ OH	—
Tosudite	—
Triphyllite Li(Fe ²⁺ , Mn ²⁺)PO ₄	Triphyllite–lithiophilite
Virgilite	—
Zinnwaldite K(Li,Al,Fe) ₃ (Al,Si) ₄ O ₁₀ (OH,F) ₂	Mica
<i>More recently determined lithium minerals^b</i>	
Diomignite Li ₂ (B ₄ O ₆)O ₇ ?	—
Liddicoatite (end member of the group) CaLi ₂ Al ₇ B ₃ Si ₆ O ₂₇ (OH) ₄	Tourmaline
Chlorite, boron-bearing (end member) Li ₂ Al ₅ BSi ₂ O ₁₄ ·4H ₂ O	Chlorite

^a Manandonite is listed by some as the same formula with 2H₂O.^b Garrett (1998).

The lithium-rich brines usually obtained most of their concentration from geothermal waters, with perhaps some of the lithium coming from surface leaching of volcanic ash, clays or other rocks. However,

lithium is very difficult to leach from the lattice structure of all rocks and minerals, so little is dissolved unless water is very hot. Experimental studies have shown that at ambient temperatures, only 55 – 170 ppb dissolves from extended contact with granitic rocks, but at 275 – 600°C 0.25 – 2.4 ppm Li can be extracted in the same agitated, long contact-period. Analyses of cores into deep-ocean rift or subduction zones have shown that lithium is adsorbed on, rather than leached from near-surface rocks (up to 1.8km in depth), and only significantly leached from deeper rocks at temperatures greater than 300 – 350°C. Based upon the isotopic analyses of lithium in the upper rocks there is some exchange by adsorption and simultaneous leaching in the temperature range of 50 – 350°C, but little net change. Other rocks or higher temperature leaching conditions must allow a greater amount of lithium to be removed, since some geothermal springs have lithium values of 6 – 50 ppm, but lithium concentration is still low. When these dilute geothermal waters are concentrated by the evaporation occurring in arid climate, closed, reasonably impervious basins, comparatively strong lithium brines have resulted in a few large playa deposits. Many large medium-concentration lithium brines have also been formed in various oil or gas field waters, potash deposit end-liquors (seawater only contains about 0.17 ppm Li), and a number of miscellaneous sources such as the Salton Sea geothermal brine and end-liquors from various commercial solar pond operations.

2.4 Types of Lithium Deposits

Today 59% of world's lithium resources is estimated to be found in brines and 25% in hard rock minerals, the remainder is in clays, oil brines, and geothermal waters.

Economically beneficial deposits belong to several types:

- **Lithium brines**
- **Sediment-hosted deposits**
- **Pegmatites and highly differential granites**

Geological key controlling factors of the formation of Li deposits are the lithium content of magmatic rocks, the history of magmatic events and of magmatic differentiation, the tectonic history, fluid-rock interactions related to hydrothermalism and/or weathering, and ultimately the climate.

Brine Deposits

Commercially recoverable deposits of lithium exist in a high concentration salt solution called brine. Interior saline desert basins where evaporation rate exceeded the rate of recharge, are the main type of brine deposits where lithium is mined from. There are many terminologies used to describe such dry lake beds. They are referred to as, most commonly, Salars, salt pans, salt flats, salt marsh or alkali flats Playas [12]. Geothermal waters become easily enriched in lithium from lithium bearing rocks than cold water. So,

hot geothermal waters contain rather high concentration of lithium, between 0.1 and 500 mg/L. Their lithium can come from weathering of silicates, volcanic activities, and leaching from lake sediments.

Lithium is commonly found in many brines, but the concentration tends to be low and non-feasible. There are a few deposits where brine sources had become actually commercial. These are Salar de Atacama, Chile; Salar de Hombre Muerto, Argentina, and Clayton Valley, USA. Their brines were formed from the porous strata as their principal source of the lithium. By-product lithium has also been recovered from Searles Lake, but its concentration in the lake brine is only 50 – 80 ppm Li. Because of the very dilute lithium concentration in even the best of brine deposits, they all owe their value to the availability of solar evaporation ponds to inexpensively further concentrate the lithium.

In some oil deposits, lithium is produced as a waste product of certain oil extraction process. This lithium bearing oil reserves are called mineral-rich brines or oilfield brines. Smackover oilfield brine in southern Arkansas, USA, has been investigated for their potential economic source of lithium as it contained between 100 and 500 mg/L of lithium concentration. Lithium produced from oilfield brines does not require evaporation ponds, but lithium extraction process can be expensive process because such brines can occur at depth of more than 2km and pumping from such depths could be economically challenging. Even though, current lithium production from other sources are meeting the demand, geothermal waters and oilfields could be economic source of lithium in the future depending on demand.

The most abundant source of lithium-rich brine are the high-altitude continental brine aquifers of the Andean mountain region in South America. The Andes is a major subduction zone, which has resulted in a series of endorheic basins. The brine deposits of South America occur at high altitude, which promotes the evaporation process due to the inverse relationship between atmospheric pressure and altitude. Salars exist in three countries, Argentina, Bolivia, and Chile, collectively known as the Lithium Triangle, where 50% of global lithium reserves are found. Argentina has several salars, including the Salar de Hombre Muerto, the Salar de Olaroz, and the Salar de Marianna, all of which contain substantial amounts of lithium. The Salar de Atacama in Chile is currently the largest producer of lithium from a brine source. By far, the largest reserve base of lithium in the world is in the Salar de Uyuni in the southwest of Bolivia. Bolivia alone may hold up to 25% of world lithium reserves [12].

Hard Rock Deposit

In the world, there is 145 lithium containing minerals. Lithium minerals can be divided into three different categories: complex aluminum silicate, micas and phosphates. However, most of them are not of commercial value. Economically beneficial reserves contain spodumene, lepidolite, and petalite. Spodumene color is white when iron content is low, and dark green when iron content is high. The two main types of pegmatites are niobium, yttrium, fluorine (NYF) and lithium, caesium, tantalum (LCT) [21]. Pegmatites are essentially igneous rock that is coarse grained due to late crystallization of post-magmatic fluids. Pegmatite rocks are the last to solidify, and because of it, it tends to become enriched by diffuse

elements like lithium. During this cooling process some volatile elements like fluorine and boron remain in the solution until the pegmatite forming stage, so they become concentrated with lithium and form fewer but larger crystals. One factor that influence lithium distribution within the mineral is MgO and FeO to Li₂O ratio. Since, magnesium and lithium have similar chemical properties, lithium is shown to substitute for magnesium [20]. Similarly, lithium in magmatic solution substitutes for Mg, Al, Ti, and Fe. When MgO+FeO to LiO ratio is high, crystals that firstly precipitate will contain little lithium [19, 20]. So, physical separation processes are efficiently applied. Pegmatites are commonly distributed throughout earth's crust and LCT pegmatites contain 12– 30% spodumene along with feldspar, mica and quartz. Three main global lithium suppliers from hard rock deposits are Australia, Canada, and Zimbabwe [19].



Figure 3. Spodumene and Pegmatite [8]

2.5 Global Lithium Reserves and Resources

Minerals in a deposit is identified by two major groups, resource and reserves. Resources refer to the amount of a mineral that are known to be in the deposit that might be economically feasible. Resources are reasonably well defined in terms of grade and concentration and it is further subdivided into 3 more categories. An inferred resource is based on early information to give reasonable estimates on the amounts of minerals present in the deposit. When more information about the deposit like grade, concentration and size are known, it becomes indicated resources. Measured resources can be referred when all the characteristics of a deposit are known. Reserve is part of the resource that can be feasibly / economically extracted from resource. Key factors that decide reserve's amount are current mining technology, environmental factors and available infrastructure [12]. Reserves may be divided into two categories, probable reserves where the deposit might be potential to economic, and proven reserves where the reserve is economic.

Back in 1980s, all the lithium was mined from hard rock mineral reserves. As the exploration of lithium proceeded, mineral-rich brines were found to be able to produce lithium cheaply. Such brines resulted closure of several lithium mineral mines.

Global annual lithium production has been increasing continuously since mid-1900s and in 2012 it was about 37000 metric tons. The present-day lithium supply is coming from pegmatite deposits and closed-basin brines. The main lithium producers from brines are Argentina, Chile, China, and the United States. The main lithium producers from pegmatite are Australia, Brazil, China, Portugal, and Zimbabwe.

Global identified lithium resources total more than 39 million metric tons, which is nearly three thousand times the current annual production of around 10000 metric tons. From this resource, the United States Geological Survey (USGS) estimated that approximately 13 million metric tons of reserves are to be economically recoverable. Due to recent studies and continuing exploration, identified lithium resources have increased substantially to total about 80 million tons [13]. An important additional aspect of global lithium reserves is recycling of lithium. Lithium-ion battery recycling is expected to contribute major role in the supply of lithium in the long term. Even though lithium is not renewable resource, it can be recycled indefinitely, whereas oil and coal can be used only once. Resources of lithium are expected to satisfy demand into the next century [14].

Table 2. World Resources in thousand metric tons

Bolivia	21000
Argentina	17000
Chile	9000
USA	6800
Australia	6300
China	4500
Congo	3000
Germany	2500
Canada	1700
Mexico	1700
Czechia	1300
Mali	1000
Russia	1000
Serbia	1000
Zimbabwe	540
Brazil	400
Spain	300
Portugal	250
Peru	130
Austria	50
Finland	50
Kazakhstan	50
Namibia	9
World total (rounded)	80000

Now that a very large potential market exists for hybrid and electric mobile devices, more exploration of lithium is being done and it is getting more intense than it has been for other metals, like gold and copper. It is very likely that economically viable, large lithium deposits remain to be found around the world or some deposits may become feasible as the metal price increases due to high demand.

It is difficult to estimate world's total lithium reserves and resources. Some countries are known to contain lithium deposits, but the data is insufficient or publicly not available because explorations are done by investors and venture capitalists rather than researchers in the field. For example, US does not provide their mine production data of lithium to USGS to avoid disclosing company proprietary data. Also, in Mongolia, lithium data was not available for public.

Table 3. Resources and Reserves by deposit types

	Resources in thousand metric tons	Resources in %	Reserves in thousand metric tons	Reserves in %
Global Total	45202	100%	12199	100%
• Salt lakes (Brines)	23572	52.15%	10003	82%
• Oil fields (Brines)	1497	3.31%	n/a	n/a
• Geothermal (Brines)	1000	2.21%	n/a	n/a
• Pegmatites	16574	36.67%	2089	17%
• Greisen/ aplite	161	0.36%	n/a	n/a
• Black shales	6	0.01%	n/a	n/a
• Clay	1344	2.97%	107	1%
• Lacustrine sediment hosted	1047	2.32%	n/a	n/a

Based on 88 deposits of 22 countries, this table came. Though resource increased amount of brines that take is still high.

2.6 Application

Lithium has become versatile metal with wide range of applications. Due to its great chemical and physical properties, lithium's applications vary from its use as a medication to treat bi-polar disorder to its use in aircraft engines and aeronautics industry.

2.6.1 Glass and Ceramics

Throughout its usage in industries for past few decades, the principle use of lithium was in glass and ceramics industries. But it is still major consumer of lithium after lithium-ion batteries. In glass and ceramics industries, either lithium ore or lithium carbonate (or any other lithium compounds) may be used. They work as fluxing (chemical cleaning or purifying) agent to reduce production cost by lowering production temperature and reducing viscosity. Due to lithium's small ionic radius, it has a low coefficient of thermal expansion ($46 \text{ } \mu\text{m}/(\text{m}^*\text{k})$). When added to molten glass, it reduces the thermal expansion and fluidities (elasticity) of the mix. Adding 0.17% Li_2O to glass lowers the melting temperature by 25°C and reduces energy consumption by 5 to 10%. When used in ceramic production, it lowers the firing temperatures and increases the strength of ceramic bodies. The addition of lithium provides additional durability, particularly in heatproof ceramic and glass cookware. The addition of lithium produces pyro-ceramic products with prolonged furnace refractory lifespans, greater surface tension, resistance to thermal shock, and increased mechanical strength. Lithium also improves the color fastness of glazes and decreases shrinkage during production and increases resistance to corrosion. [12, 22, 23, 24]

One of the important requirements for the lithium in glass industry is its iron content. Most of the lithium ore concentrates have low enough harmful impurities and iron that can be directly used in some glass formulations, while there are other glass types that require high purity of lithium. Some types of ores can even be directly, if lithium content is high enough and iron content is low enough, without being formed into high-purity concentrate. Such lithium concentrate should contain Li_2O higher than 4.8% and lower than 0.2% of Fe_2O_3 .

Lithium fluoride crystals are used in specialized optics. Lithium fluoride forms a simple ionic crystal lattice structure, which is useful in the ultraviolet (UV) and infrared (IR) optics. The lithium fluoride crystals are transparent to short wavelength ultraviolet radiation, more so than any other material. The lithium fluoride crystal has one of the lowest refractive indexes and the farthest transmission range in the deep UV of most common materials. [12, 22, 24] Due to these properties, lithium fluoride is widely used in production of prism, monochromator lens and telescope lenses. Other lithium applications in glass are double-glazed window with thin layer of metallic chemicals, for production of monochromatic television tubes and computer monitors.

2.6.2 Lubricants

Before lithium grease entered the market in 1940s, sodium-based greases were dominant. Lithium greases basically replaced sodium-based greases as soon as it entered the market because it was waterproof, capable of maintaining its viscosity for a long time, has an extremely low melting point, high mechanical strength, and high thermal resistance. Lithium grease is an oil mixed with an emulsifying agent like soap. Lithium stearate and lithium 12-hydroxystearate are often used in the saponification of triglycerides (lipids) to manufacture high-temperature resistant greases [25]. These greases are commonly used as a lubricant in metal-on-metal mechanisms, both indoor and outdoor, and are commonly used in automotive applications. Mixtures containing 5–10% of the lithium soap are an excellent lubricant for bearing surfaces, since they are almost totally water insoluble, and stable in consistency over a range of shear and temperatures from -55 to +200^o C [9].

2.6.3 Warfare

On 16th of July 1945 in the desert of New Mexico, United States successfully tested their first nuclear weapon. Soon after, on 6 and 8 August, United States dropped nuclear weapons on Japanese cities of Hiroshima and Nagasaki, ending the Second World War in the Pacific. In January 1946, elimination of nuclear weapons was called by United Nations, but in August 1949, The USSR (United Soviet Socialist Republic) tested its first nuclear weapon, which further intensified ongoing Cold War between two superpowers, United States and USSR.

Lithium demand significantly increased during the Cold War along with increasing nuclear weapons because both stable isotopes of ⁶Li and ⁷Li were used in production of nuclear weapon. ⁶Li was used as a neutron absorber and ⁷Li was used as an enriched lithium fluoride coolant in the nuclear power industry. Both isotopes, when exposed to a stream of neutrons in an exothermic ⁶Li and endothermic ⁷Li reaction, produce the radioactive hydrogen isotope tritium, an important component in nuclear weapons. In the 1950s, the USA military required vast amounts of lithium as lithium hydroxide, from which they harvested ⁶Li to produce staged thermonuclear weapons [26, 27]. Tritium is also important for the future production of thermonuclear fusion reactors, a technology which has the potential to cleanly meet the future energy needs of the world [19, 22]. The estimated future requirement of lithium to meet the demand of a mass production of thermonuclear the fusion reactors is 200 to 1000 ton per 1 GW electric power [28].

2.6.4 Lithium in Medicine

Lithium has been used in medical industry since Roman Empire. The Roman physician Soranus of Ephesus first discovered that patients suffering from mania showed improved results after drinking lithium containing alkaline water. But he did not know it was lithium at that time. Lithium was used to treat gout because lithium solution was dissolving uric acid crystals in urine but it was only effective for manic gout patients [34,147]. Also, in 20s, lithium was added into soft drinks and water to boost mental health because

its neuroprotective property. Lithium chloride was also used in table salts for people on sodium diets. However, due to lack of research, some goods were overly charged by lithium and resulted some lithium toxicity. So, it is banned in soft drinks and in medicines now.

Despite its cases of toxicity, lithium is used to treat bi-polar disorder as lithium interacts neurotransmitters and receptors of the brain. It can increase serotonin levels and control production of norepinephrine and some hormones. Some studies show that people live in region where drinking water is lithium-rich, showed lower suicide rate. However, lithium's interaction with human body is still not fully understood and it is early to make conclusive decision. Further researches are much needed [34,15].

2.6.5 Lithium in Batteries

Early lithium batteries were not rechargeable and lithium was used as the cathode. Commonly faced problem by this battery was accumulation of dendrites (microscopic fibers of lithium) on the lithium electrodes caused by lithium-ion addition and removal. If the dendrites accumulated long enough on electrodes, they fill the gap between electrodes and cause fire due to short circuit. In 1972, Michael Stanley Whittingham developed first rechargeable lithium battery. Technology was based on a lithium disulphide cathode, lithium perchlorate in dioxolane as the electrolyte and a lithium metal anode. But, formation of dendrites was still happening due to thermal runaway. From this, John Bannister Goodenough developed modern LIBs by using lithium in its ionic form rather than lithium metal, which directly solved dendrite formation. In 1991, LIBs commercialized by Sony and Asahi Kasei and Sony Corporation released very first portable phone and, since then, the demand of lithium for batteries has consistently grown.

Modern LIB consists of a graphite anode, a lithium metal oxide cathode, and an electrolyte solution doped with a lithium solution, such as lithium hexafluorophosphate in a mixed organic solvent (often ethylene carbonate or dimethyl carbonate). The design of EV LIBs consists of a number of battery cells arranged in sequence in a module, a group of modules becomes a battery pack, and a group of packs is referred to as the battery system. The terms battery and battery cell are often used interchangeably in the literature, and a battery is made from a number of cells (e.g., a 12 V lead-acid battery contains 6 cells). According to Tahil (2007), a 30 kWh LIB system for an EV cost €7500 in 2007. The price of Li/kWh has steadily decreased since then, from €800/kWh in 2010 to just over €200/kWh in 2018 and is expected to fall to €100/kWh by 2025.

LIB has highest energy density compared to other batteries because lithium is the most electropositive of all elements. Also, it has low self-discharge rate, high rechargeable number (1000 cycles), no memory effect, fast charging, less maintenance and, it is lightweight. However, disadvantages are need for a protection circuit and travel restrictions, in order to stop thermal runaway. Typical LIB's operating range is between 20⁰ C to 60⁰ C.

Other battery types are still in use for hybrid EV despite not being as powerful as LIB. These are nickel metal hydride and nickel-cadmium based batteries. LIBs are gradually taking over other types of batteries as there is no development for those types of batteries and LIBs are getting as efficient as possible.

To manufacture 1 billion EVs with 5-kWh LIB, 20% of the total reserve of lithium will be used. But 5-kWh battery is a conservative estimate for a standard EV, and as battery technology advances, LIBs capacity will undoubtedly increase and it is expected to reach value of 60-kWh. This would require 50% of total reserve as an EV battery needs 0.165 kg of lithium carbonate for each kWh, a plug-in hybrid electric vehicle (PHEV) battery requires 0.176 kg per kWh, and a hybrid electric vehicle (HEV) would require 0.375 kg. Depending on their application and required power, LIBs should contain different amount of lithium carbonate (e.g., smartphones- at least 3g, a laptop- 10 to 30g, tools- 40 to 60g, EVs- 8-100kg). High performance EV Tesla Model S Performance contains 85-kWh battery that has 50.8 kg lithium carbonate to travel 539 km.

2.6.6 Air treatment

Lithium is used in several different air treatment-related applications:

- Cooling;
- Drying;
- CO₂ capture.

Lithium bromide solutions are used as coolant in industrial air-cooling systems working by absorption, not by air compression like the more widespread compressor-based air-cooling systems. In these absorption systems water from moist warm air under low pressure is absorbed by a concentrated solution of lithium bromide, which becomes diluted in the process. The diluted solution is then concentrated again in a heat exchanger, where the water will be vaporized, moving to a condenser where it will cool down and be collected. The concentrated lithium bromide solution is regenerated, ready for a new cycle. The heat is being provided by a gas burner or from waste industrial heat, as this kind of cooling process is widely used in industrial plants. Lithium serves also in air drying systems, based on lithium bromide or chloride (LiBr or LiCl). Lithium hydroxide is used in CO₂ scrubbers aboard the space vessels and submarines. [15]

2.6.7 Primary Aluminum Production

Aluminum production is very energy intensive process due to high melting point of alumina (2072⁰ C). Metallic aluminum production is carried by Hall-Héroult process where molten alumina is electrolyzed. To reduce melting point, alumina is bathed in cryolite (NaF₂) with additional additives that will reduce viscosity and melting point. In this bath, lithium is added as a lithium carbonate or chloride to

form lithium fluoride by reacting with aluminum fluoride. 2%- 3% of lithium fluoride will reduce process temperature by 12-18^o C, enhance electrical conductivity, reduce electricity consumption by 2%- 4%, reduce cathode carbon consumption by 1%- 2%, and reduce Fluor emissions by 40%- 50%. Li use per ton aluminum produced would be 0.32 kg Li, if 2% LiF is added to 60 kg cryolite.

2.6.8 Other uses of Lithium

- In electronics: lithium niobate and tantalate are used for their electro-optical, acoustic, piezoelectric, and pyroelectric properties in the production of surface wave filters in the mobile telecommunications sector and in consumer electronics;
- For the production of some cements, where Li is used as an additive to accelerate hardening;
- Water treatment: Li hypochlorite (LiClO) is used for swimming pool water cleaning;
- Lithium acetate (LiC₂H₃O₂) and hydroxide (LiOH) are used as additives in some textile and polymer dyeing processes;

Lithium nitrate (LiNO₃) is used in fireworks, to generate the red color.

2.7 Lithium's Global Demand & Production

Driven by power storage demand lithium's price increased as EV and batteries manufactured more. In 2018 alone, EV purchase have dramatically increased to over 2 million units and following this demand lithium supply is to triple by 2025. Researchers predict that there will be 3.8 to 4.5 million EVs in use by 2025. Following this, lithium demand is expected to increase by 8%- 11% every year, and by 2025 battery market is estimated to grow to €180 billion. Additionally, European Union is encouraging to purchase EVs and developing its infrastructure by setting directives like the Clean Vehicle Directive 2009/33/EC and the Energy Efficiency Directive 2006/32/EC [41]. Many major vehicle manufacturing companies like Tesla, Nissan, General Motors, Ford and Toyota are following the directives and actively pursuing the development of EV. Plus, individual countries are contributing to this clean transportation technology by reducing tax and putting more charging points to increase purchase of EVs.

Expected huge demand for lithium seems unreliable since EV market is just about to start the large-scale commercialization. The reasons behind this doubt is there is not well-developed infrastructure like petrol stations and this makes the technology feel less reliable to costumers. Traditional internal combustion engine petrol stations have easy to get infrastructure development and when it is compared to electric car charging points there is not many stations also, when costumer is in hurry refilling the fuel takes only a few minutes and for the charging stations, it could take 20-40 minutes. Though there are innovative ideas for fast charging, it is yet to be commercialized.

Despite its unreliability, lithium carbonate demand is still expected to grow into 1 million tons by 2025. Though there is global pandemic of COVID-19 that is threatening global economy, researchers believe that this pandemic will delay inevitability by just a few years.

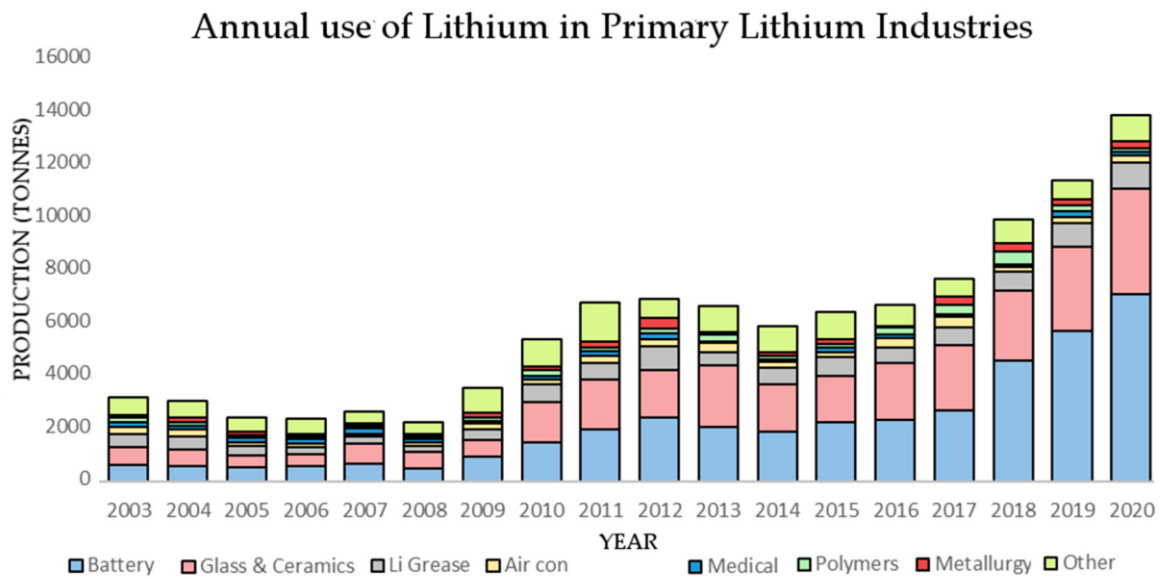


Figure 4. Annual use of lithium in tons in each industry [7]

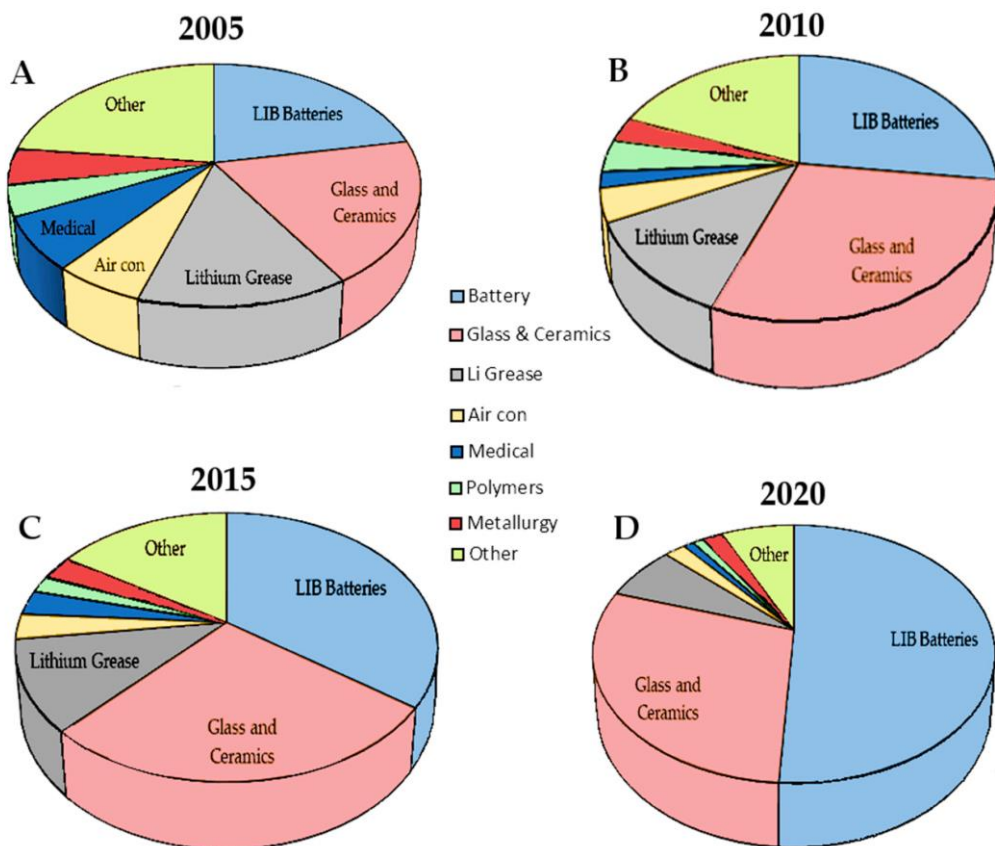


Figure 5. Percentage lithium use in each industry and its projection [7]

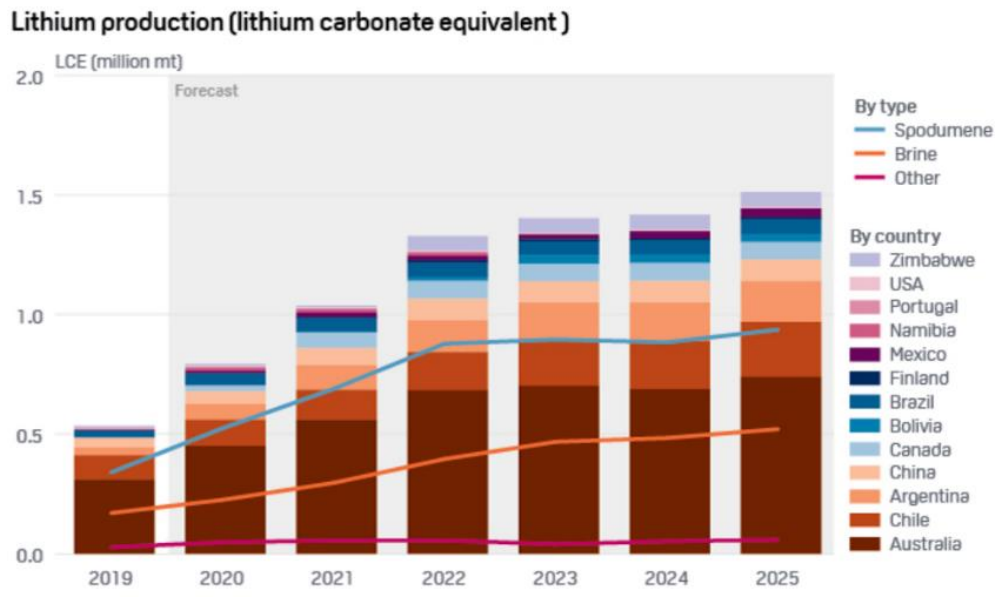


Figure 6. Lithium Production Prediction [32]

2.8 Lithium Recycling

Lithium recycling is not economically feasible yet to recycle on large-scale because most of the lithium is still in use in our society, for example, LIBs in our smartphones and EVs. Less than 1% of lithium is being recycled today. However, if demand of lithium increases, which it will, recycling will be prioritized from the waste streams. One of the waste streams is smartphones and its batteries. Millions and millions of new smartphones are being produced every year because mobile phone manufacturers update their specifications every year to keep customers excited and interested in their phones resulting millions of phones to go wastelands. These phones contain 30 to 40 g lithium inside the battery along with other precious metals. For example, amount of gold in single smartphone could be 9 mg, palladium 24 mg, and silver at 250 mg. Precious metals of phones are being recycled today. In the future, when there is enough waste reserve of phone, recycling of lithium from phones will become feasible.

Unlike other hard recycle materials, lithium recycling is relatively easy because lithium's melting point is 180⁰ C and low solubility of its salts makes it easy to recycle. LIBs contain copper, aluminum, cobalt. These can be recovered during recycling. After several years of use of LIBs and EV, large scale recycling plant will be strong investment.

In Mongolia, EV's LIB recycling could become economically feasible in the coming years. Automobile import has been increasing over the past years and in 2019, total number of imported automobiles was 94065. Out of this, 69472 was passenger vehicles, and most of it is hybrid cars. Unfortunately, most of the imported cars are used cars that are over two - ten years old. Currently, 80% of the total vehicles are over 10 years old and that is 757157 vehicles in Mongolia [16]. 16% of it is hybrid-

vehicles with LIBs. Since, the imported cars are old, soon there will be huge amount of waste LIBs that can be reserve for recycling plant.

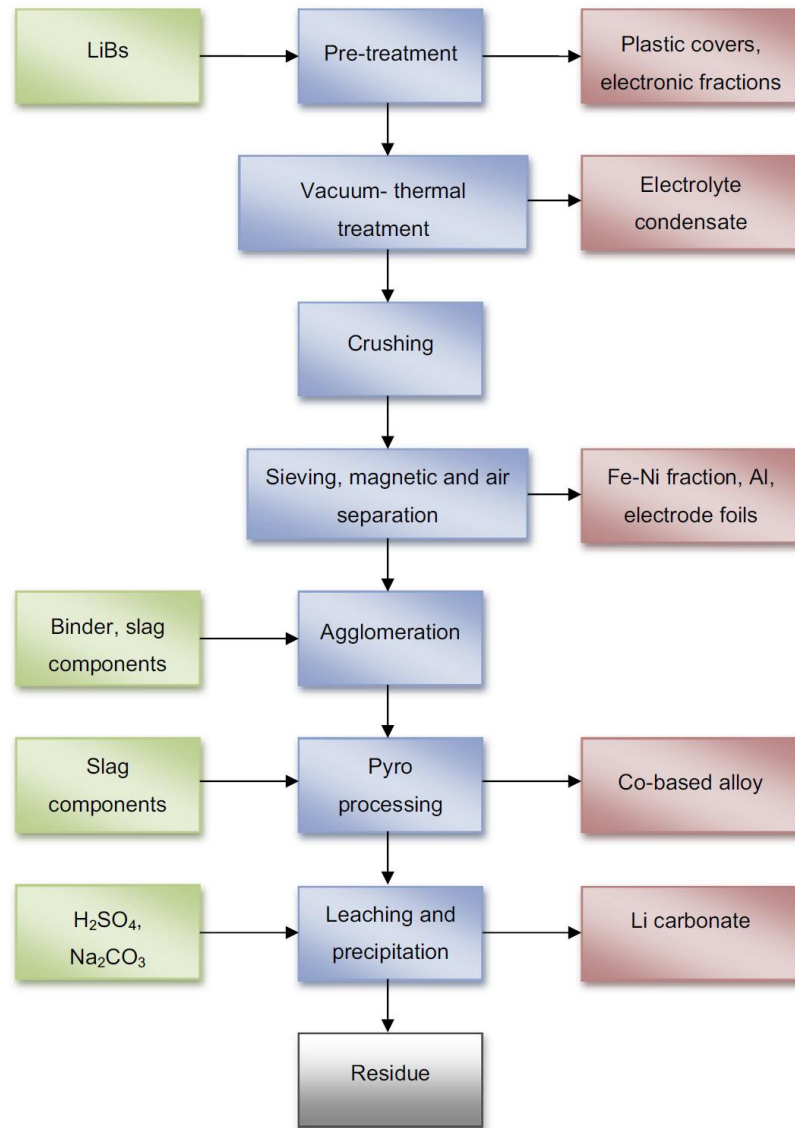


Figure 7. Lithium-ion Battery Recycling [49, 50]

3 Lithium Production Method

3.1 Brine Processing

Lithium can be easily recovered from brines by solar evaporation. This is an inexpensive process, but some requirements must be fulfilled. Evaporating ponds should be a flat and large as possible to effectively evaporate the water, and since it relies on solar radiation to evaporate, number of sunny days should be as high as possible. These are usually fulfilled for dry lakes, but not for the oilfield and geothermal. Sizing of the ponds are usually based on solar radiation, humidity, wind and climate of the

area. To make the most cost-effective pond, dividing it to segments will maximize evaporation rate. So that crystallized salt from each pond can be harvested periodically without disrupting the whole system. Also, using as much gravity flow between the pond as possible will reduce operating costs.



Figure 8. Brine segments [17]

Then, the crucial part of pond design is managing leakage. If the pond is constructed by soil, the soil should be impermeable clay, and the whole pond area should be backfilled with impermeable layer of clay at proper depth. However, ponds constructed in such way may leak excessively. Another option for constructing pond is with an impermeable membrane. One of the largely used membrane is 25 Mil Reinforced Hypalon. It is highly puncture-resistant, has a very long service life (.25 years) with low-to-moderate concentrations of magnesium chloride in the brine, and it is quite resistant to ultra-violet oxidation. Also, PVC or polypropylene plastic membranes are applicable.

Theoretically, using membranes can solve leakage, but in practice membranes leak. Producing a single membrane for the pond could solve the problem. However, membranes sheets are produced in limited dimensions and they are joined (sealed) together for the desired size. During this process, membranes may have holes from imperfect seals or punctures from underlying rocks. These are usually found by careful visual inspection and some electric testing.

Because of brine's low concentration, detecting leakage is as important as getting high recovery. Detecting leakage is challenging. Many methods were suggested and used but many of them were not successful. Fortunately, there are several ways. One way to detect is placing porous tubes under the ponds and withdraw leakage by vacuum. Also, pressure sensors between the pond and the moist soil underneath will indicate leakage. For some cases, piezometers (hydrostatic pressure sensors) are applied. After

detecting leakage, finding leakage point and repairing membrane can be far more problematic. But in all cases, membranes are more reliable than clay-lined ponds despite its expenses.

After evaporation, to get a high purity Li solution, other contaminants (Ca, Mg, B, Fe, Al) have to be removed. These contaminants are usually saturated with Na, K, Cl, and sulfate and removing contaminants is crucial. Each contaminant can be separated by different techniques, for example, Mg and sulfate are removed by adding lime, Boron is removed by iso-octyl alcohol-kerosene solvents [18]. Most commonly applied methods of removing such contaminants are precipitation and removal, and use of ion-exchange resins to remove contaminants after precipitation. Ion-exchange resins are used to further purify Li products from 99.5% to 99.9%. To do so, lithium carbonate (99.5% purity) must be dissolved again into lithium bicarbonate (LiHCO_3). Then resins will remove more impurities from the solution and high purity lithium carbonate (>99.9%) will be produced. With similar principle other Li products (e. g., LiCl), can be purified further.

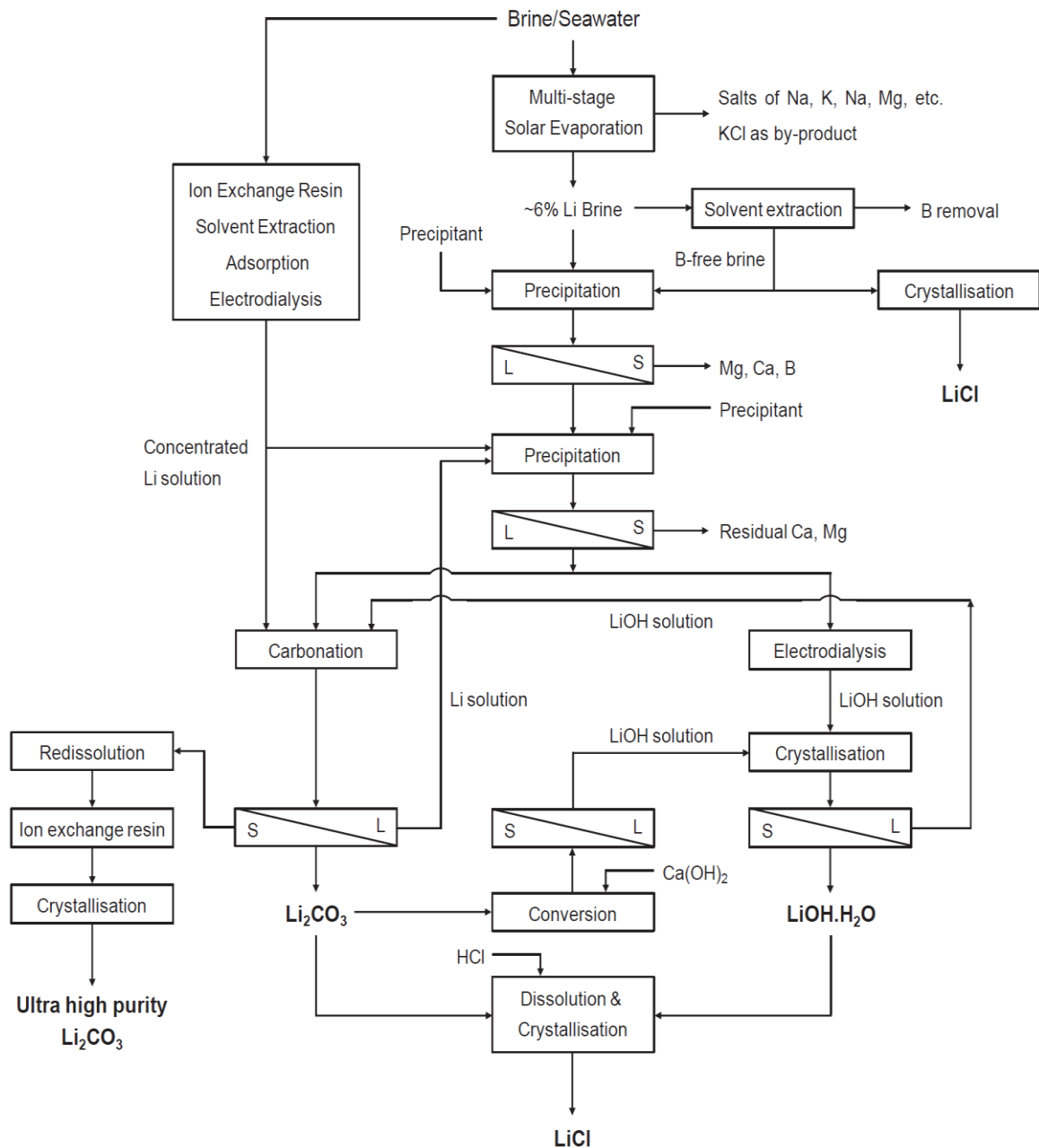


Figure 9. General Flowsheet of Lithium Production From Brine

Magnesium possesses economic threat when its concentration is higher than 5000ppm. If it is not removed, lithium will be lost as lithium carnallite ($\text{LiCl} \cdot \text{MgCl}_2 \cdot 6\text{H}_2\text{O}$) during evaporation process. To recover magnesium before evaporation is treating brines with lime to form magnesium hydroxide. Calcium and Boron are also precipitated to gypsum and borate along with magnesium. These precipitates are marketable products for fire retardant filler. At second precipitation stage, sodium oxalate is added to recover calcium as a calcium oxalate which can be reused for the first stage after calcination.

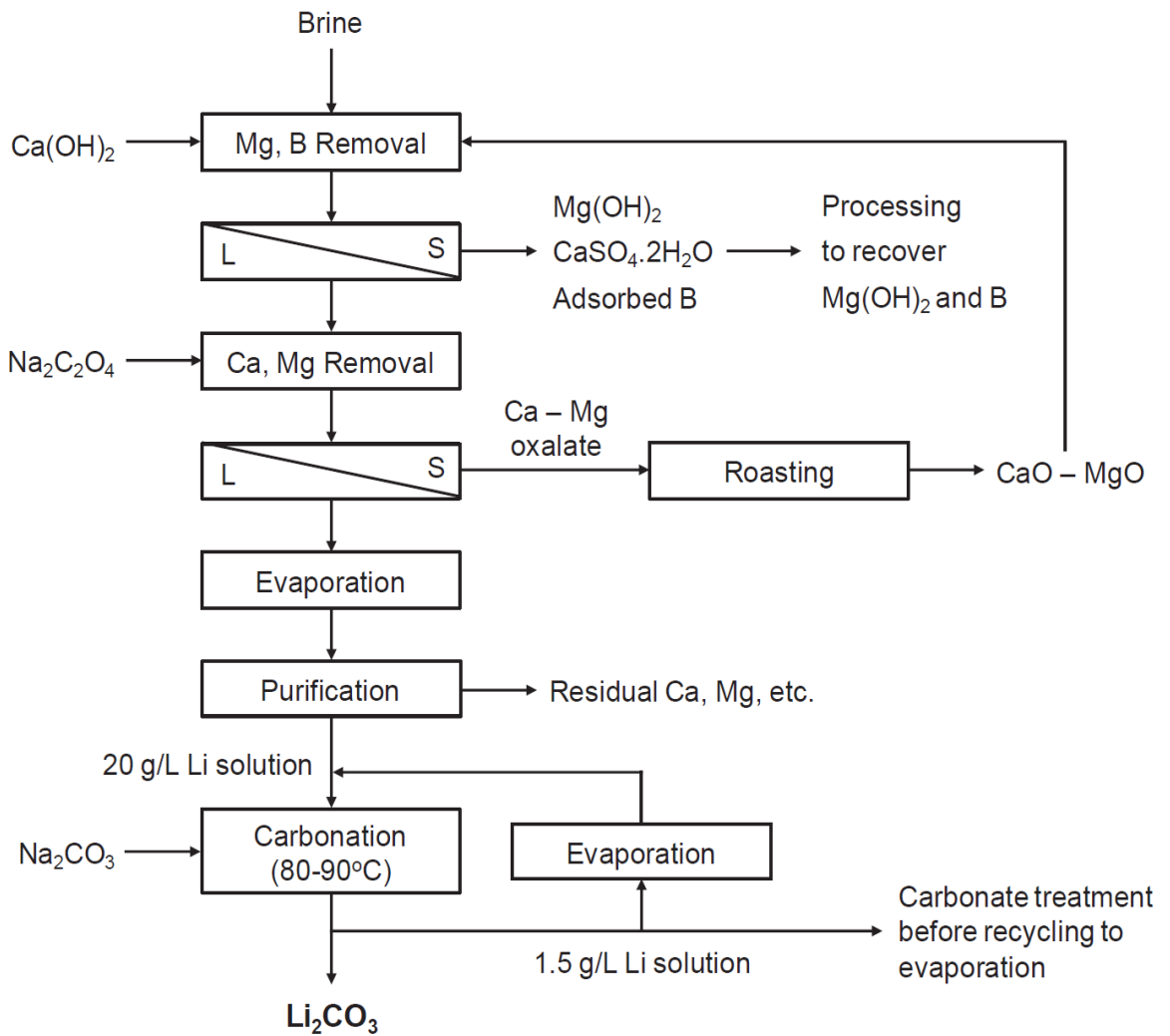


Figure 10. Simplified Lithium Production From Brine

3.2 Selective Lithium Extraction

3.2.1 Electrolysis

Conventional solar evaporation process takes several months to give concentrate. Since this process is not reliable for some regions and due to its time consumption, developers extensively worked on alternative methods. One developed technology is electrolysis that is based on reverse electro dialysis of water desalination where concentrated electrolyte is the product.

Electrolysis of lithium is based on indirect transfer of Li ion from $\text{LiFe}^{\text{II}}\text{PO}_4$ electrodes to $\text{Fe}^{\text{III}}\text{PO}_4$ through anionic selective membrane as shown in Figure 10.

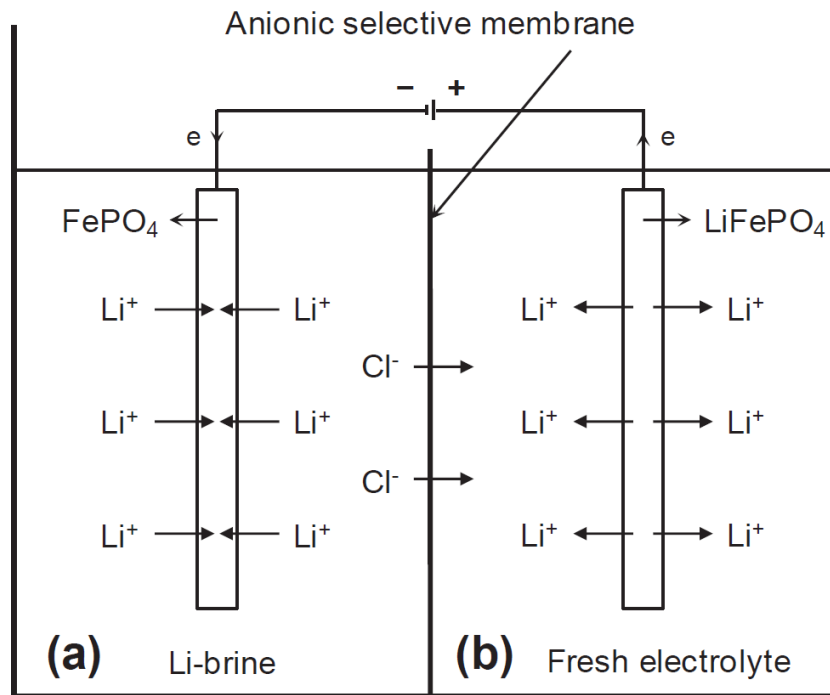
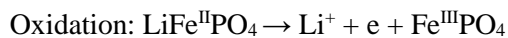
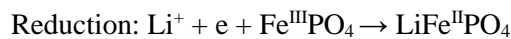


Figure 11. Lithium Electrolysis [10]



When a current is applied to the cell, Li ions in brine will be started collecting on the negative electrode $\text{Fe}^{\text{III}}\text{PO}_4$ (reduction process) while Li ion on positive electrode $\text{LiFe}^{\text{II}}\text{PO}_4$ will be extracted (oxidation process). As lithium continuously extracted from brine, Li will be gradually concentrated in the electrolyte. The whole process can be operated continuously as electrodes replaced. Careful voltage control can minimize sodium and magnesium.

3.2.2 Adsorption

Another extensively studied method is adsorption of lithium by MnO_2 , TiO_2 , and aluminum hydroxide based synthetic adsorbents. The up-taking efficiency Li from the solution depends on Li intercalation into the nonstoichiometric lattice of these oxides. Depending on the solution's concentration, and composition, loading capacity of the adsorbents varies from 3 – 35 mg Li/g adsorbents. Higher the concentration of the lithium, higher the loading capacity will be. However, due to impurities of the brine (Ca, Mg, Na, ...), overall lithium loading capacity reduces as the impurities intercalate too.

The desorption of lithium from these adsorbents is done by HCl eluent that will produce lithium chloride. To produce lithium carbonate, lithium chloride undergoes soda ash carbonation at 100°C . Impurities are suggested to be separated before adsorption because eluent also elute Ca, Mg, etc.

3.3 Lithium Ore Processing

Lithium concentration in igneous rocks is very low. High concentration of lithium containing minerals can be found in granitic pegmatites. The most important minerals are spodumene and petalite. Spodumene theoretically should contain 8% of Li_2O , but in practice it is less. Still, it is considered the most important lithium ore due to its relative high concentration. A typical run of mine ore contains 1 – 2% Li_2O , while required spodumene concentrate for producing lithium carbonate should have 6 – 7% Li_2O (75% – 85% spodumene). Commonly processed ores are shown in Table 4.

Table 4. Commonly Processed Ores

Lithium ore		Formula	Li (%)
Spodumene		$\text{LiAlSi}_2\text{O}_6$	3.73
Lepidolite		$\text{K}(\text{Li},\text{Al})_3(\text{Si},\text{Al})_4\text{O}_{10}(\text{F},\text{OH})_2$	3.58
Zinnwaldite		$\text{KLiFeAl}(\text{AlSi}_3)\text{O}_{10}(\text{F},\text{OH})_2$	1.59
Amblygonite		$(\text{Li},\text{Na})\text{Al}(\text{PO}_4)(\text{F},\text{OH})$	3.44
Petalite		$\text{LiAlSi}_4\text{O}_{10}$	2.09
Clays	Hectorite	$\text{Na}_{0.3}(\text{Mg},\text{Li})_3\text{Si}_4\text{O}_{10}(\text{OH})_2$	0.54
	Montmorillonite	$(\text{Na},\text{Ca})_{0.3}(\text{Al},\text{Mg})_2\text{Si}_4\text{O}_{10}(\text{OH})_{2n}(\text{H}_2\text{O})$	n/a



Figure 12. Largest lithium mine, Greenbushes, Australia [7]

Processing of lithium bearing ore is shown in Figure 12. It involves, firstly, comminution, and beneficiation (flotation, magnetic separation, or heavy media separation) to produce 4 – 6% Li_2O concentrate. Then, concentrate is fed into roasting and leaching tanks to transfer lithium into solution. During thermal treatment, metal hydroxide, acids, or salts are added to get leachable compounds of lithium sulfate, carbonate, or chloride. Preliminary removal of contaminant is usually carried out by precipitation and proceeded to evaporation or ion exchangers.

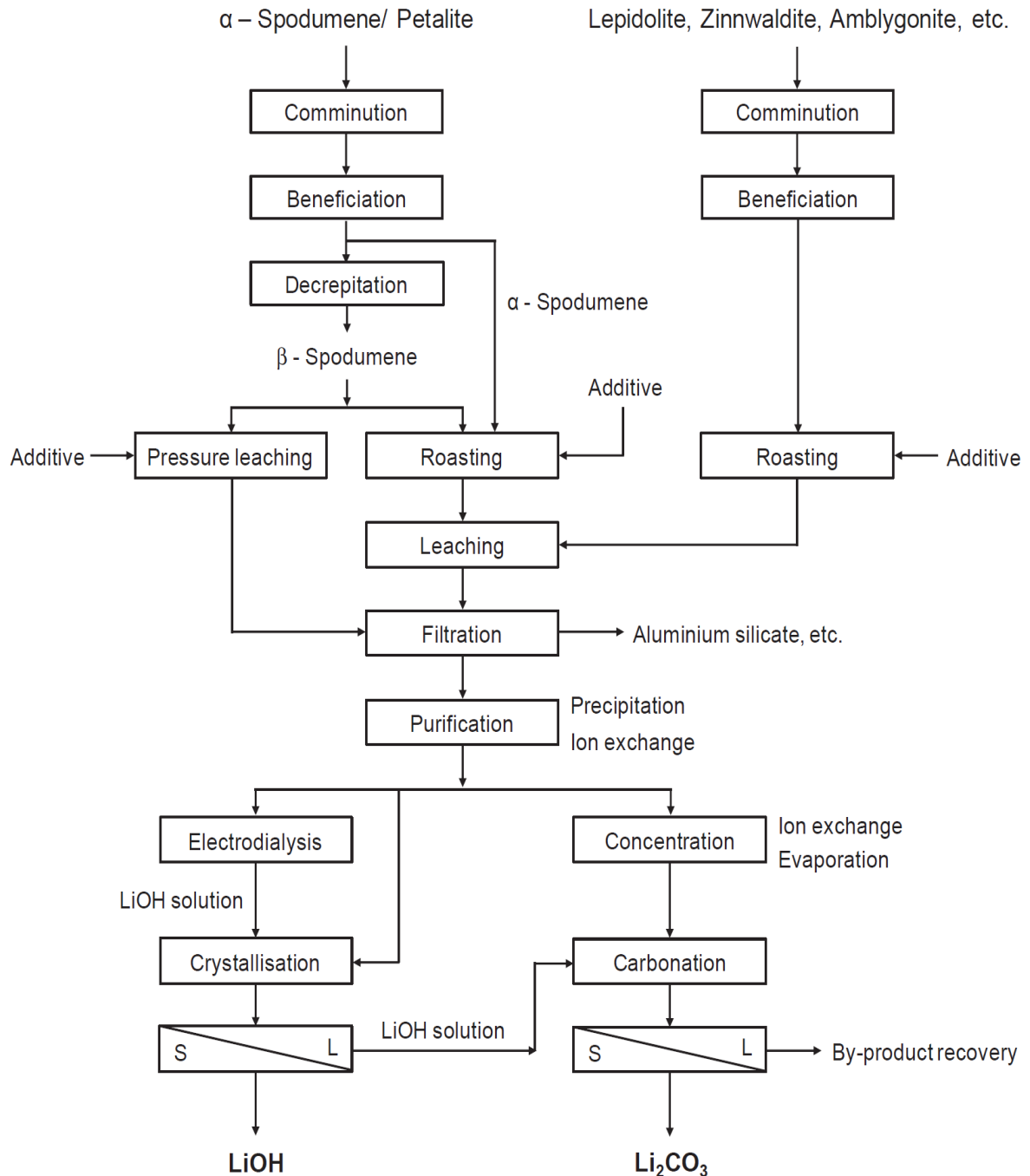


Figure 13. General Flowsheet for Ore Processing

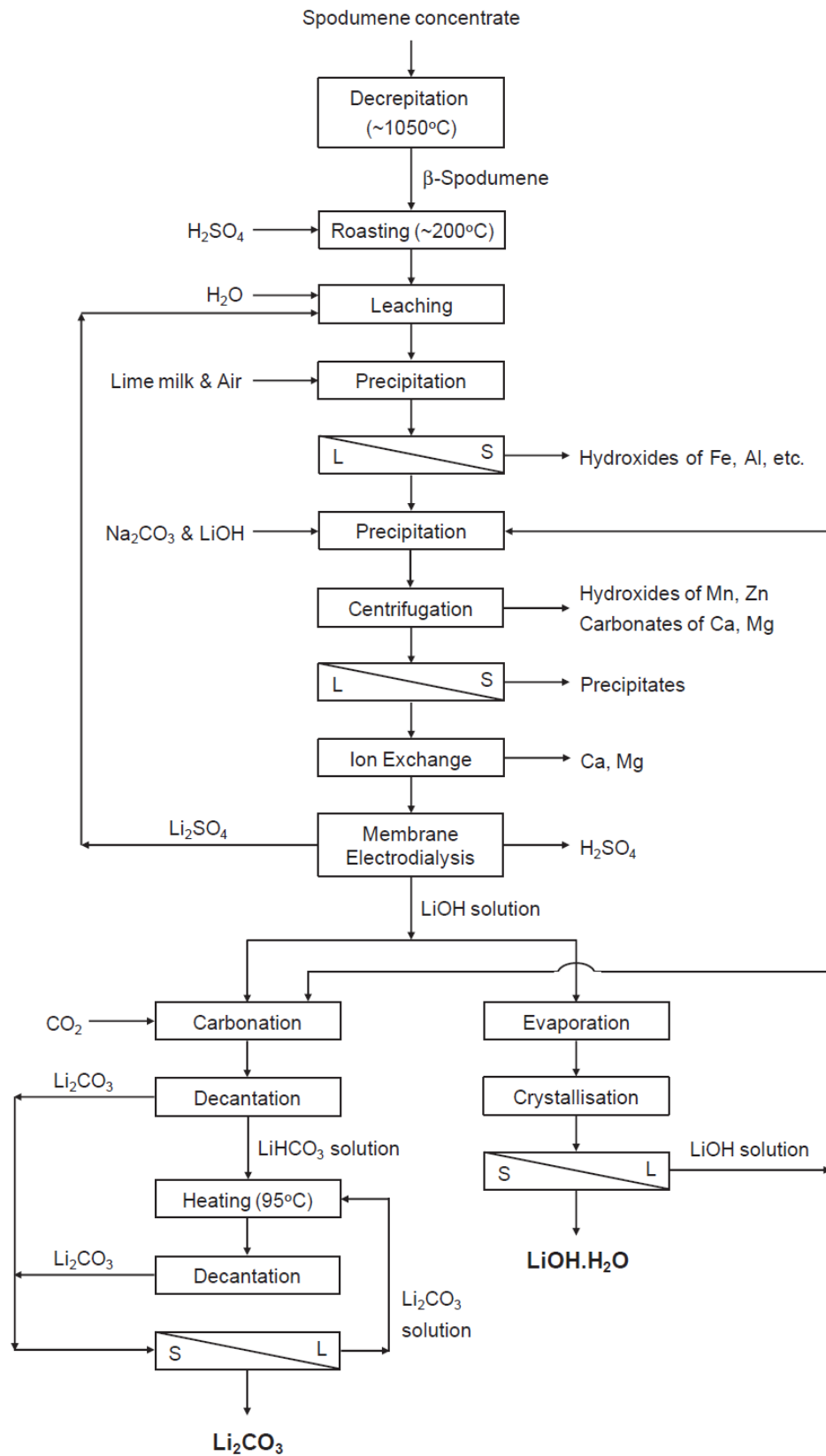


Figure 14. Simplified Flowsheet

Separation of lithium from the orebody can be efficiently achieved by considering their electric, magnetic, and physical properties. Preliminary physical separations are performed by dry & wet screening, magnetic, electromagnetic and heavy media separation. Gravity separation is efficient for coarsely grained spodumene. Flotation and other beneficiation process will produce high grade spodumene concentrate ready for lithium extraction. Lithium can be extracted from concentrate through roasting and acid roasting operations. Roasting is also referred as calcination. It is a thermal processing technique that makes physical deformation to the material. In lithium compound production from concentrate, calcination is utilized by two separate processes: decrepitation and acid roasting.

Spodumene's crystal structure in nature is monoclinic alpha form called α -spodumene. Such form of spodumene is refractory for hot acids. To extract lithium from the ore through leaching, ore's crystal structure must be changed to β -spodumene which has tetragonal beta form (30% larger crystal structure). This is done by decrepitation process that operates between 900 – 1100^o C. Suitable lithium concentrate for the presses is at least 6% Li₂O.

Now that β -spodumene is digestible in acid, lithium can be extracted into water soluble lithium sulfate by mixing it with sulfuric acid. This acid roasting operates at about 200^o C. At 170^o C, an exothermic reaction starts and lithium is extracted from β -spodumene. Then water leaching at 90^o C will extract lithium into solution. Purification of lithium from impurities such Al, Fe, Mg, etc., is done by adding NaOH. Sodium hydroxide will react with impurities and form its hydroxides and removed at pH 12. Then, through electrodialysis, or ion exchanger, purified lithium will be further concentrated.



Figure 15. Decrepitation equipment [31]



Figure 16. Processes steps in Laboratory [30]

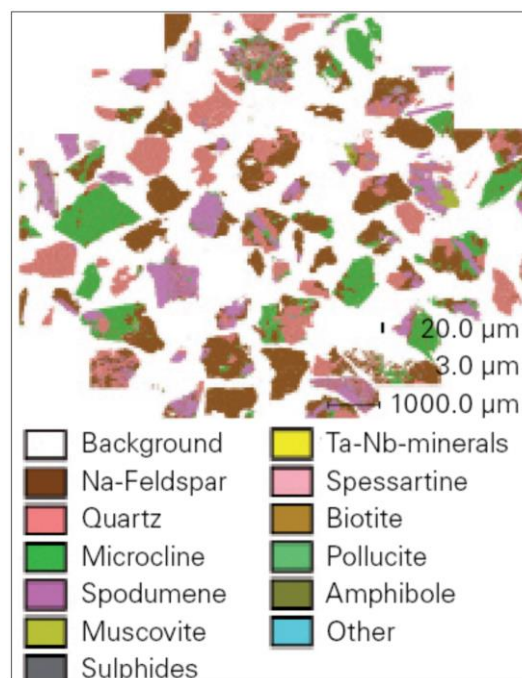


Figure 17. Spodumene Mineralization [30]

4 Results & Discussion

4.1 Mongolian Reserves and Resources

4.1.1 Huh Dely Lithium Mine

Huh Dely mine is located in Dundgobi province, Ulziit Soum. It is 550 km southwest from Ulaanbaatar and 98 km from Mandalgobi city. “Alkali Metal Mongolia” LLC is currently owning the mine with mining license. But mining operation has not started yet [43].



Figure 18. Dundgobi Province [45]



Figure 19. A) Huh Dely Deposit, B) Munkhtyn Tsagaan Durvuljin Deposit [45]

Huh Del sedimentary lithium deposit is located in the Tugrug Valley Southwest of Tsagaan Nuur valley. The identified ore body deposit is 6000 m long, 5000.0m wide and 51.11 m thick. In addition to core mineral elements, the deposit also has supplementary minerals such as potassium, lithium and supplementary elements such as cesium, rubidium and light rare earth minerals. Lithium content varies from 793ppm to 3480 ppm with average content of 1656 ppm, n=5.

The deposit's reserve (A), proven (B), probable (C) grade is 443.6 thousand tons of lithium in 283.9 million tons of ore with an average content of 0.156%, respectively. The measured ore reserve (A) is 23.5 million tons proven, the B grade ore reserve is 98,7 million tons. In another words, measured reserve amount is 37.7 thousand tons of metal lithium and proven reserve amount is 151,3 thousand tons. In addition, measured and proven reserve has 173.3 thousand tons of strontium with average content of 0.145%, 4970.5 thousand tons of potassium with average content of 3.7 %. Identified inferred mineral is 992.2 thousand tons of lithium metal in 644.3 million tons of ore with 0.153 % average content of lithium.

According to this data from MRPAM, this proven reserve contains enough lithium to produce 800 thousand tons of lithium carbonate. With increasing demand and to be skyrocketed lithium prices, this deposit's worth is estimated to be more than \$5 billion¹.

4.1.2 Munkhtyn Tsagaan Durvuljin Lithium Deposit

Munkhtyn Tsagaan Durvuljin Lithium Deposit is located in Bayanjargalan Soum in Dundgobi province. This deposit's mining license is owned by "Lithium Mining" LLC and mining operation has not started yet.

The amount of proven reserve is 2,276,989 tons of ore with average content of 0.65% Li₂O, which is able to produce 14,575 tons of pure lithium. There is 4286.1 tons of rubidium with average content of 0.15 % and 0.622 tons of cesium reserve with average content of 0.03% [43]

Similarly, but since the deposit is smaller, this deposit is able to produce 75 thousand tons of lithium carbonate which will be valued more than \$500 million¹.

These two deposits are relatively close to the infrastructure, but not too close to local society. For feasibility aspects like ecological, economical, and societal, they are ideally located. However, they are quite far from Mongolian border, meaning transportation and exportation could be challenging. Well-developed transportation infrastructure is highly needed.

4.1.3 Eguzer's Lithium Deposit

Eguzer's deposit is located in Sukhbaatar province, Erdenetsagaan Soum. It is 900 km east from Ulaanbaatar and 220 km from Baruun-Urt. In 1940s, Russian geologist discovered this deposit while he was doing hydrogeological survey for the Mongolian army. Then, till 1955, the deposit was used to produce tungsten and molybdenum concentrate [48].

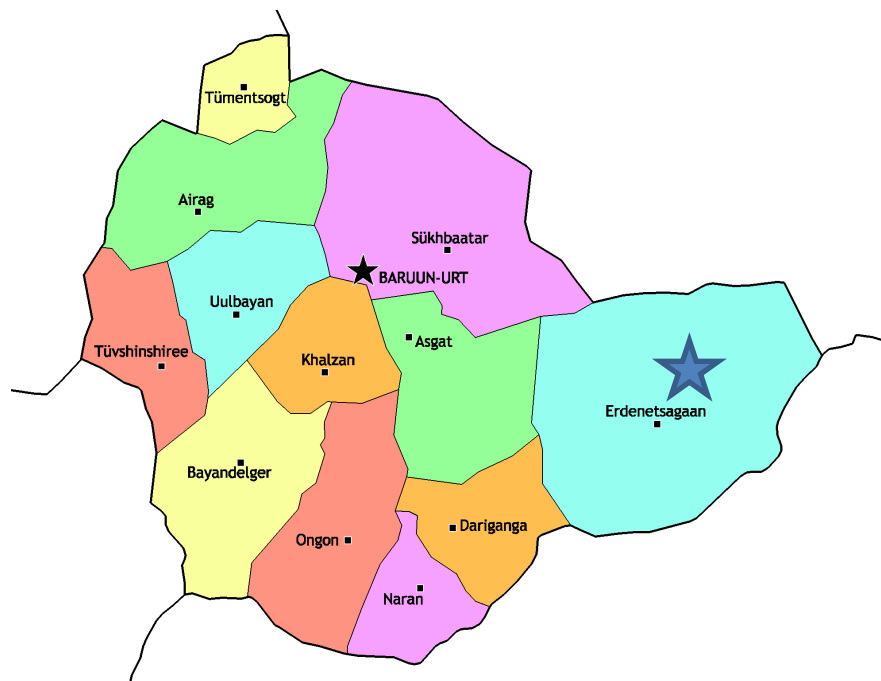


Figure 20. Sukhbaatar province and Erdenetsagaan soum [45]

From 1940 to 1977, several explorations were conducted to find molybdenum and tungsten reserve, and its probable reserve for molybdenum dioxide found to be 12000 tons with grade of 0.12% and for tungsten trioxide it was around 42500 tons with grade of 0.25%.

In 2012 and 2015, further studies were conducted by “Biluut Mining” LLC to produce detailed information about lithium concentration and reserve. The total estimated reserve was 18.7 million tons ore with average grade of 0.044%. Total amount of lithium metal was 8663.2 tons. Further details are included in appendix. Detailed geological study is attached in appendix.

Eguzer’s deposit is not only about lithium, but it is also tungsten and molybdenum deposit. Tungsten and molybdenum will be the main product of the mine and lithium can be recovered as

a by-product. Recovered lithium will be able to produce 40 thousand tons of lithium carbonate, which will be valued more than \$300 thousand¹.

4.1.4 Bear Mountain Project

“Ion Energy” LLC owns exploration license in Sukhbaatar province’s 81758 hectares area. French and Indian joint company “Spirit Banner Capital Corp” is registered in Toronto Stock Exchange, made contract with “Ion Energy” LLC to do lithium exploration. This joint project is expected as a great opportunity as lithium price goes up. However, further details have not been provided yet [49].

Eguzer’s deposit and Bear Mountain deposit are also relatively close to the infrastructure, and can be considered to have similar good feasibility aspects as previous two deposits. However, one advantage is it is close to the Mongolian-Chinese border. This will greatly reduce operating expenditure.



Figure 21. Bear Mountain Deposit (Baavhai Uul) [49]

4.2 Production Cost

Production cost, also known as operation expenditures (OPEX), of lithium carbonate from pegmatite deposits was ranged between \$2900 to \$4500 per ton. Operation expenditures of brine deposits to produce lithium carbonate was between 1591 to 2280 US\$/t. This huge difference between expenditures is because of pegmatite processing plants require huge amount of energy compared to brine processing plant. Brine processing plants leave all the hard work to sun whereas, pegmatite processing plants have

¹ This estimation is not final and decided estimate. It is only preliminary estimate.

more energy intensive, complex processes like liberation of lithium from the orebody. It should be noted that these estimations were made public in 2014, and it only represent preliminary estimate, not the current operation expenditure. Also, depending on the capacities and transportation, cost may vary by 10 – 25%.

However, actual OPEX of lithium carbonate can be reduced for both processes. Lithium deposits usually contain valuable by-products. Brines contain potash and boron, and pegmatite deposits contain feldspar and tantalum. For example, United States’ Cauchari-Olaroz Salars project reduced its OPEX from \$2375 to \$1332 per ton lithium carbonate by generating revenue from its potash production. This will be also applied to Mongolian deposits as they contain cesium, strontium, rubidium, etc.

Unfortunately, lithium carbonate price reduced in May to 42500 CNY which is around \$6000 per ton of lithium carbonate. The reason behind this sudden decrease was due to mismatch between highly expected demand and supply. Lithium producers expected huge growth in EV industry and prepared the supply accordingly. But, China, biggest EV market, reduced subsidies and resulted oversupply of lithium. China is not intended to remove subsidies of EV in near future, but huge initiatives in European Union and other EV manufacturing companies have been already started. This is estimated to make lithium carbonate price reach \$13000/t by 2025 [29]. Development and investment in lithium mines will be profitable.

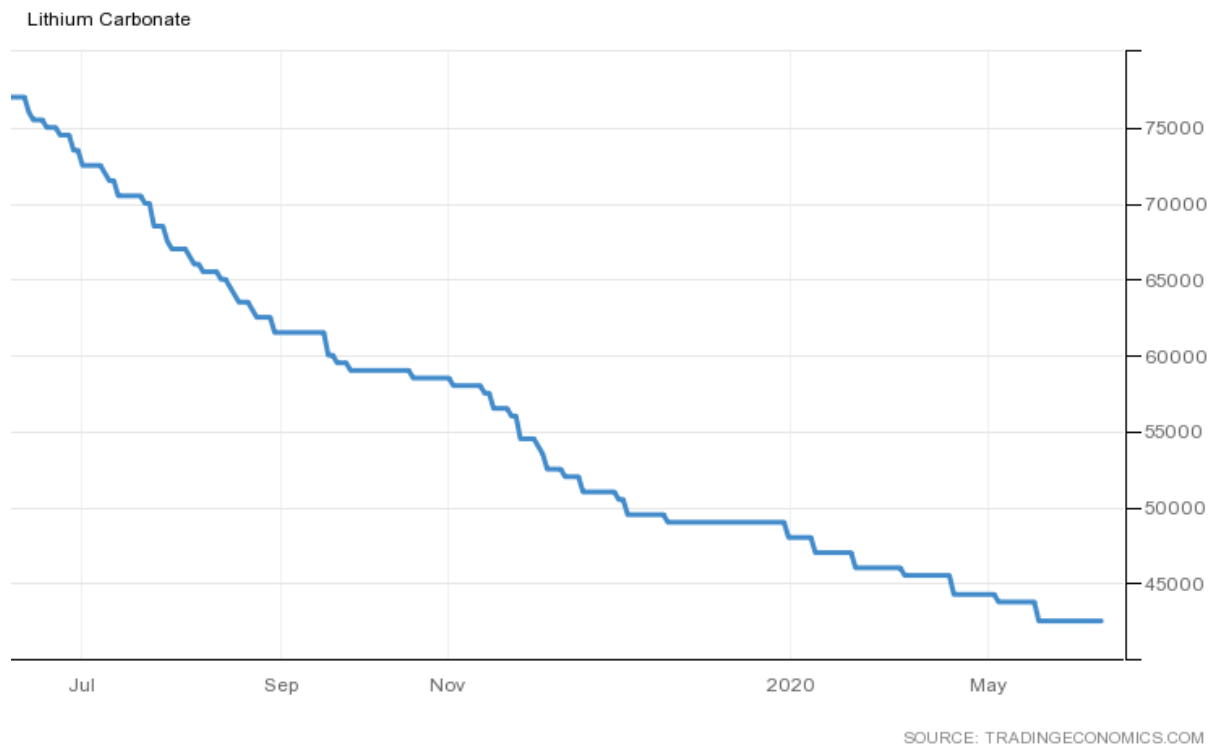


Figure 22. Lithium Carbonate Price in CNY [28]

4.3 Environmental Risk

Like any other mining operations, lithium mining has certain impact on the environment. So, companies must seek out sustainable approach and consider environmental managements very seriously.

The environmental concerns of lithium production are related to air, water, soil pollution, and depletion of water resources. Mongolia is arid country and water consumption of mines is serious concern.

For example, world's second largest lithium mine, Salar de Atacama in Chile, polluted nearby grasslands and rivers by lithium and hydrochloric acid, causing damage to farmers. Hydrochloric acid was lost during the process and lithium was leaked through ponds. Also, 2200 m³ water was used per ton lithium carbonate and most of it was lost permanently through evaporation. This water consumption of the mine was 65% of region's water consumption. Similar environmental damage was also seen in northern Tibet's brine mine. But, compared to other types of mines, lithium mining is less hazardous and least contaminating process to the environment. [27].

Since Mongolia does not have brines, water usage can be minimized for lithium mines as they reuse waste waters and up to 85% of water can be reused. Challenging environmental risks could be acid mine drainage from tailings and rehabilitation of used land. Effective counter measures will greatly reduce environmental risks. However, due to irresponsible mining operations like leaving the mine area without re-cultivation and rehabilitation, many regions of Mongolia are being destroyed and contaminated. This led society against mines. So, societal and ecological aspects of feasibility study might be challenging.

Hybrid vehicle import is increasing year by year, but most imported vehicles are being over 10 years old. When all old vehicles go out of usage, huge amounts of LIBs will go to wasteland and they are very toxic when it is not disposed properly. LIB recycling will greatly reduce environmental risks too.

5 Conclusion

Lithium has gained popularity in energy and battery industry thanks to its great chemical and physical properties. LIB can contain large amount of energy in small volume, compared to other batteries. Which makes it more attractive for electric vehicles. Many countries are joining their force to transfer from internal combustion engine to EVs as the world is facing serious climate changes and transportation sector takes one fifth of GHG emission. It is crucial step for better world.

To give 60kWh battery for 1 billion EVs, 50% of total reserve is estimated to be used and Mongolia can become one of the suppliers for this high demand of lithium. Lithium deposits are divided into 2 types: brines and hard rock deposits (pegmatites). Brines are basically lithium rich salt lakes trapped in underground. Through evaporation process, lithium carbonate is recovered along with by-products. Hard-rock deposits are usually pegmatites. Most important orebody for lithium production is spodumene. Spodumene processing consists of energy intensive processes. Even though, brines are inexpensive to recover lithium but environmental risks are high because ponds may leak lithium and other toxic elements to the soil and contaminate the water. Also, 95% of the water is permanently removed through vaporization which is not suitable for arid countries. On the other hand, waste management for spodumene processing can be easily controlled.

According to Mineral Resources and Petroleum Authority of Mongolia, total probable reserve of lithium is estimated to be around 203,000tons. In this, 4 main hard rock deposits seem to be economically beneficial. These deposits are Huh Dely deposit, Munkhtyn Tsagaan Durvuljin deposit, Eguzer deposit, and Bear Mountain deposit. Out of these deposits, Huh Dely deposit contained largest pegmatite lithium deposit that is highly valuable. Munkhtyn Tsagaan Durvuljin deposit was the second largest deposit with little bit higher than 14 thousand tons of pure lithium. However, it is yet to be decided because Bear Mountain deposit is currently under exploration. Eguzer deposit had relatively low lithium deposit. Since the main product is not lithium from Eguzer deposit, lithium can be economically recovered as a by-product. Unfortunately, Mongolia does not have brine deposits.

Despite the fact that brines are cheaper to operate than hard rock mines, increasing lithium price seem to diminish this difference. Also, lithium mines are considered as least contaminating mine. So, with effective re-habilitation of the land will greatly reduce environmental risks.

Data retrieval part of the thesis was the most challenging part because Mongolia did not have integrated the data of lithium deposits. Detailed study of the deposits was expected, however, due to increasing interest of people in lithium industry, companies that own the deposits avoided to disclose their data to public. This is the case for all around the world. Also, due to COVID-19 pandemic, Mongolian University of Science and Technology's (MUST) library and many other sources were closed.

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7 Appendices

Eguzer's Deposit Geological Survey and lithium concentration:

- Drill Cores and it Lithium concentration

##	Цооногийн дугаар	Интервал, м	Зузаан, м	Li, %	Шугамын дугаар
1	Ts-15	15-18	3	0.069	3
		32.9-39	6.1	0.057	
		44-47	3	0.062	
		53-62	9	0.045	
		70.5-74.5	4	0.030	
		92.5-98	5.5	0.030	
		120.5-122.7	2.2	0.047	
2	Ts-485	94-128	34	0.032	3
3	Ts-486	16.5-22.5	6	0.027	3
		26.9-69.7	42.8	0.041	
4	Ts-509	149-174.5	25.5	0.028	3
		46-52.1	6.1	0.039	
5	Ts-41	97-101	4	0.061	4
		110-150	40	0.055	
		61.8-64.5	2.7	0.037	
		75-80.8	5.8	0.039	
6	Ts-483	84-87	3	0.038	4
		105-114.1	9.1	0.035	
		2.5-4.8	2.3	0.046	
		18.5-21	2.5	0.053	
		24.5-34	9.5	0.047	
		36.8-51.4	14.6	0.045	
		54.5-82.5	28	0.035	
89.8-97	7.2	0.033			
7	Ts-484	103-110.5	7.5	0.030	4
		158-164.15	6.15	0.035	
		0-46	46	0.044	
		65.6-73.2	7.6	0.035	
		82.8-87.6	4.8	0.025	
8	Ts-487	98.5-103.2	4.7	0.038	4
		134.5-137.8	3.3	0.027	
		0-27.4	27.4	0.041	
		42-58	16	0.043	
		67.4-76	8.6	0.069	
9	Ts-488	82.4-91.5	9.1	0.043	4
		128.8-140.95	12.15	0.034	
		25-28	3	0.048	
		40-69.2	29.2	0.049	
10	Ts-489	77-91.6	14.6	0.035	4
		122-140	18	0.059	
		15-87.3	72.3	0.035	
		101.9-132	30.1	0.057	4
		8.1-28.7	20.6	0.047	

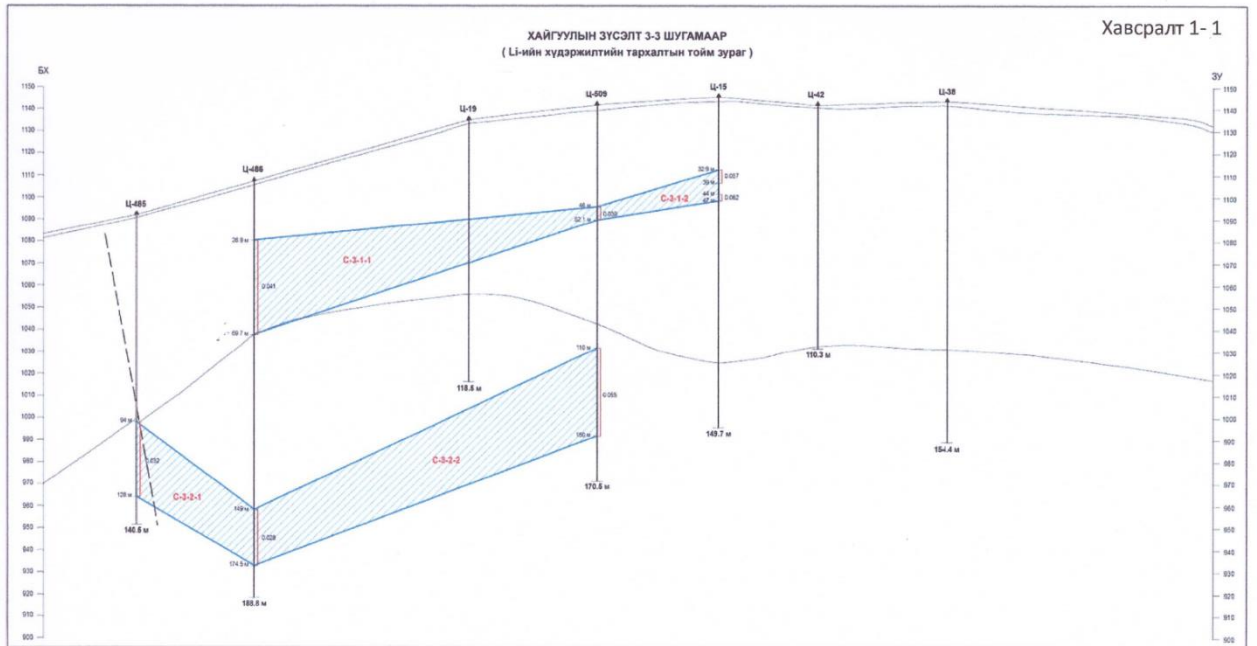
11	Ts-2	37-100	63	0.072	5
		118-127	9	0.037	
12	Ts-7	70-86.1	16.1	0.025	5
		89-90.5	1.5	0.030	
		139.5-141.5	2	0.026	
13	Ts-13	66-79.5	13.5	0.037	5
		83-111	28	0.056	
		114-115.9	1.9	0.052	
		129-132.2	3.2	0.068	
14	Ts-499	26-29.3	3.3	0.043	5
		36-54.1	18.1	0.050	
		58-80.9	22.9	0.050	
		84.1-90.5	6.4	0.024	
15	Ts-500	2-8	6	0.031	5
		26.4-61	34.6	0.042	
		79.1-83.7	4.6	0.032	
		89-94	5	0.043	
		126-146	20	0.090	
16	Ts-506	0	0	0	5
17	Ts-25	6-8	2	0.027	6
		18-120.5	102.5	0.063	
18	Ts-55	57.3-62.2	4.9	0.031	6
		82-100	18	0.037	
		104.5-106.8	2.3	0.092	
19	Ts-65	72-76	4	0.035	6
20	Ts-492	55.5-67	11.5	0.051	6
		74-77.2	3.2	0.039	
		81.7-91	9.3	0.029	
		94.3-96.2	1.9	0.037	
		124-126.5	2.5	0.028	
		161-165	4	0.036	
21	Ts-493	174-178.5	2.5	0.028	6
		58.6-66.1	7.5	0.033	
		79-87.2	8.2	0.057	
22	Ts-494	99.7-156	56.3	0.044	6
		28-67	39	0.049	
		73-103	30	0.045	
		125-133.7	8.7	0.034	
23	Ts-21	140-154.9	14.9	0.043	7
		48.8-56.4	7.6	0.034	
24	Ts-479	65.2-151	85.8	0.084	7
25	Ts-24	50.5-80.5	30	0.043	8
		42-46	4	0.045	
		64.2-68.75	4.55	0.049	
26	Ts-49	98.5-102.5	4	0.043	8
		67.2-88.5	21.3	0.032	
27	Ts-57	113-121.5	8.5	0.027	8
		99.5-152.5	53	0.070	

28	Ts-466	53.5-68.5	15	0.049	8
29	Ts-467	40-80.5	40.5	0.060	8
30	Ts-468	0	0	0	8
31	Ts-516	120.8-180	59.2	0.081	8
32	Ts-517	84.6-121.7	37.1	0.040	8
33	Ts-518	121-131	10	0.050	8
34	Ts-470	26.4-29.25	2.85	0.047	9
		43-80	37	0.067	
35	Ts-471	60.5-85.3	24.8	0.038	9
36	Ts-472	36.5-37.3	1.5	0.031	9
37	Ts-473	26-35.5	9.5	0.044	9
38	Ts-474	0	0	0	9
39	Ts-33	97.1-109	11.9	0.044	10
		117-120.5	3.5	0.048	
40	Ts-62	62-63.5	1.5	0.043	10
		74.5-86.5	12	0.032	
41	Ts-103a	0	0	0	10
42	Ts-104	33-35.7	2.7	0.051	10
43	Ts-447	61-64	3	0.051	10
44	Ts-448	39.2-51.5	12.3	0.027	10
45	Ts-449	46.4-71.5	25.1	0.044	10
46	Ts-70	77.8-79.5	1.7	0.032	12
		86.6-111.5	24.9	0.040	
47	Ts-72	67.2-70.5	3.3	0.034	12
		73.5-88	14.5	0.030	
48	Ts-75	66-72	6	0.050	12
49	Ts-76	132.3-146.5	14.2	0.051	12
50	Ts-112	0	0	0	12
51	Ts-402	0	0	0	12
52	Ts-519	70.4-72	1.6	0.041	12
		133.3-179	45.7	0.031	
53	Ts-520	111-148	37	0.035	12
54	Ts-521	84-98.5	14.5	0.033	12
		112-120.5	8.5	0.032	
55	Ts-77	74-103.7	29.7	0.042	14
		113.4-129	15.6	0.035	
56	Ts-78	72.5-75.9	3.4	0.070	14
		93.5-98	4.5	0.036	
57	Ts-87	72-90	18	0.036	14
58	Ts-403	35.7-47.5	11.8	0.060	14
59	Ts-404	19-25	6	0.025	14
60	Ts-405	15-24	9	0.032	14
		31.5-42.5	11	0.027	
61	Ts-79	103.5-106.5	3	0.027	16
62	Ts-80	93.4-97.4	4	0.030	16
63	Ts-94	36.5-48.5	12	0.043	16
		62-73	11	0.030	
64	Ts-107	79-88.5	9.5	0.039	16

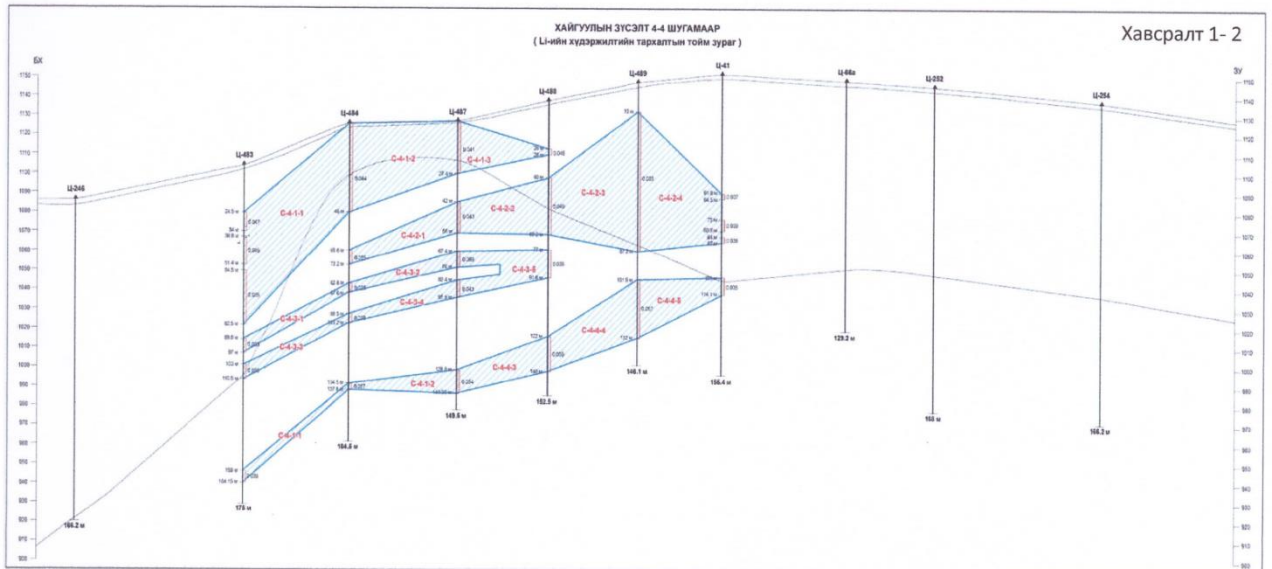
65	Ts-116	117-148.5	31.5	0.063	16
66	Ts-400	73.1-76	2.9	0.044	16
67	Ts-401	0	0	0	16
68	Ts-515	0	0	0	16

- Exploration drill rig sections:

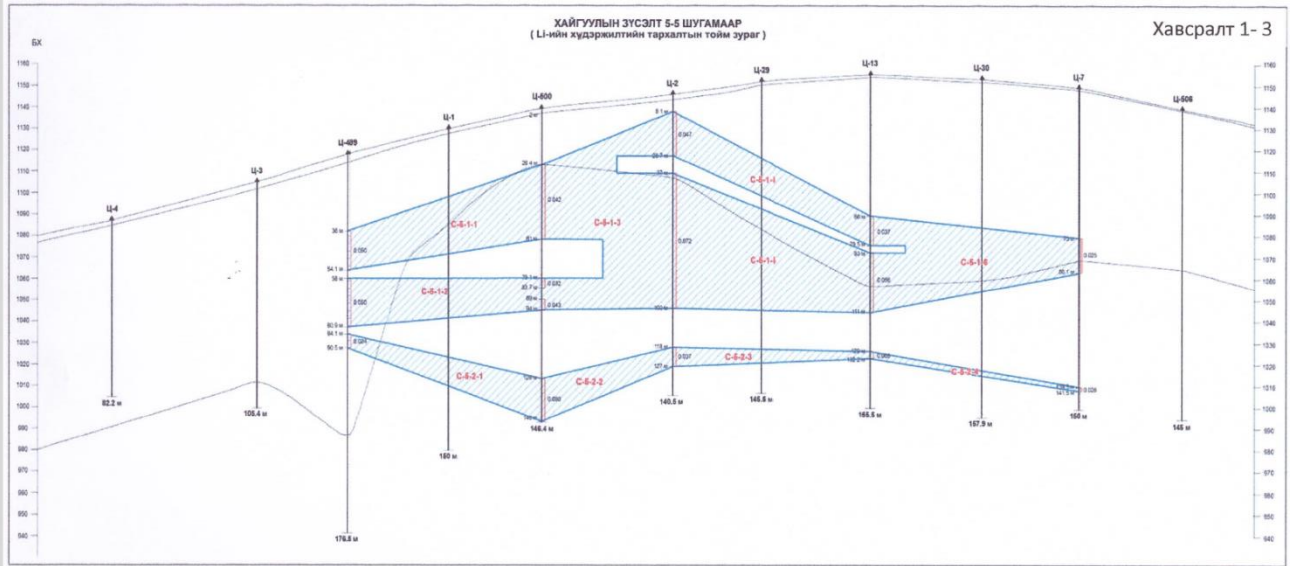
ХАЙГУУЛЫН ШУГАМ 3 - 3



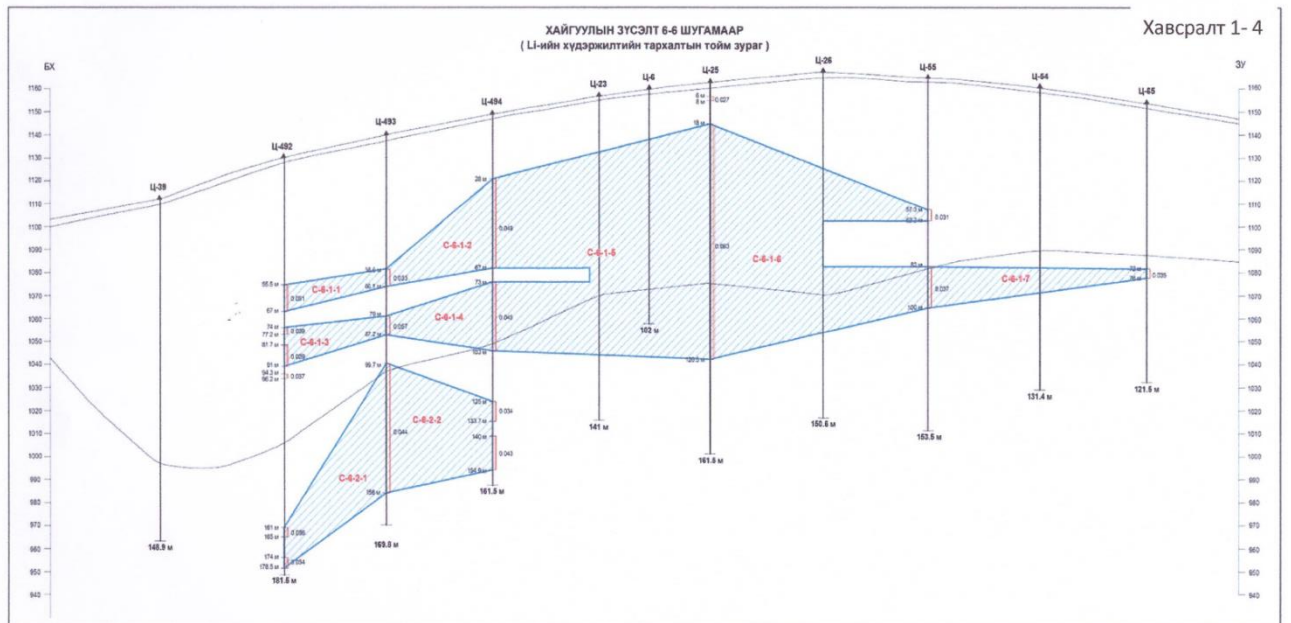
ХАЙГУУЛЫН ШУГАМ 4 - 4



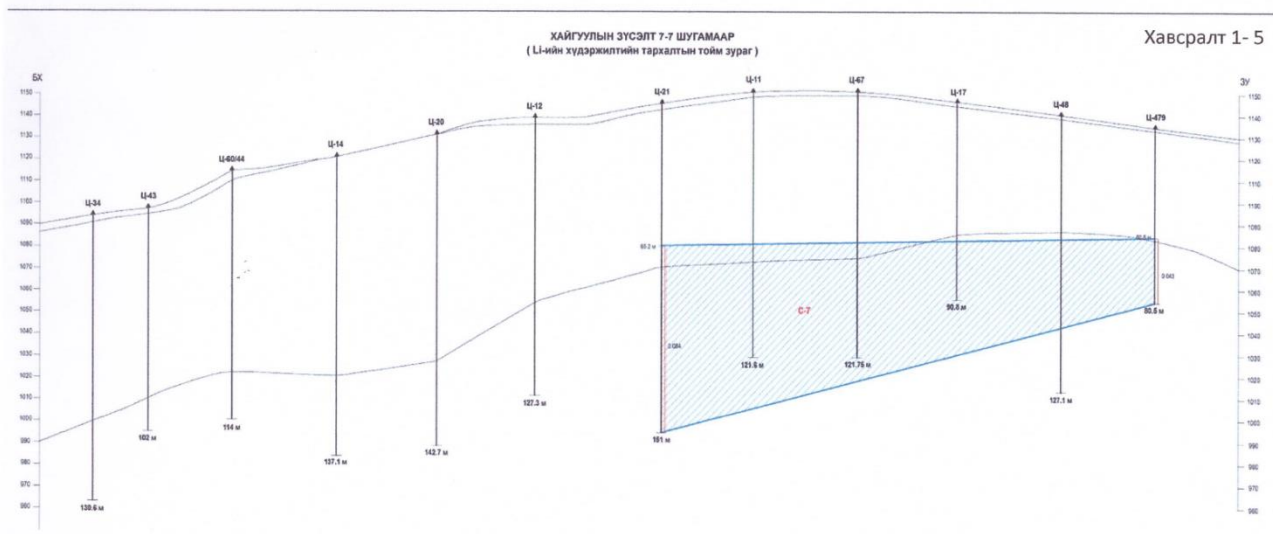
ХАЙГУУЛЫН ШУГАМ 5 - 5



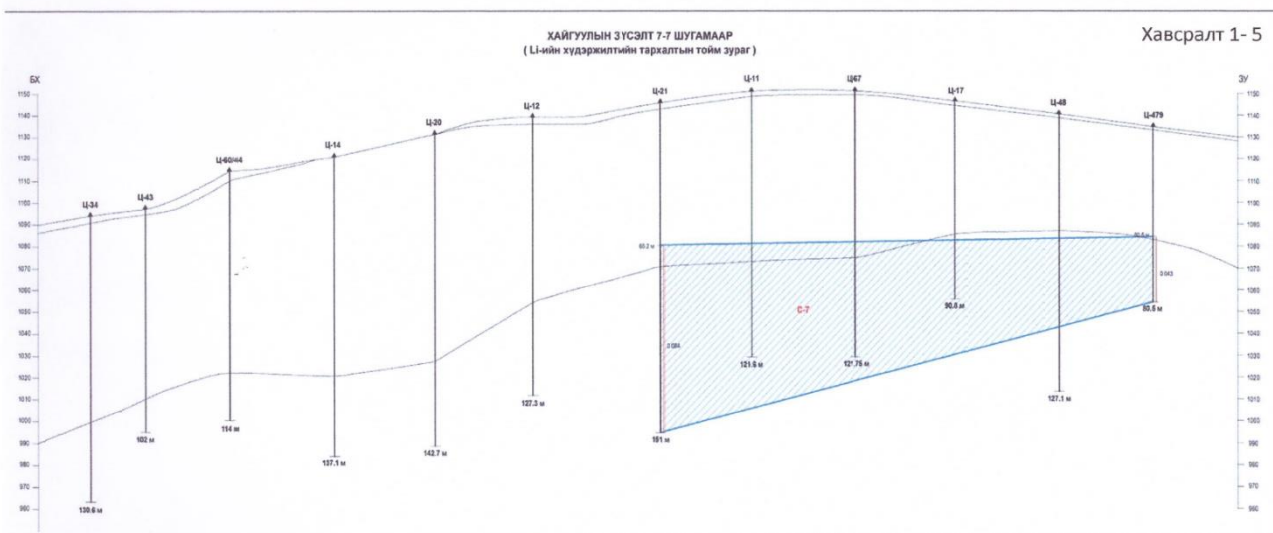
ХАЙГУУЛЫН ШУГАМ 6 - 6



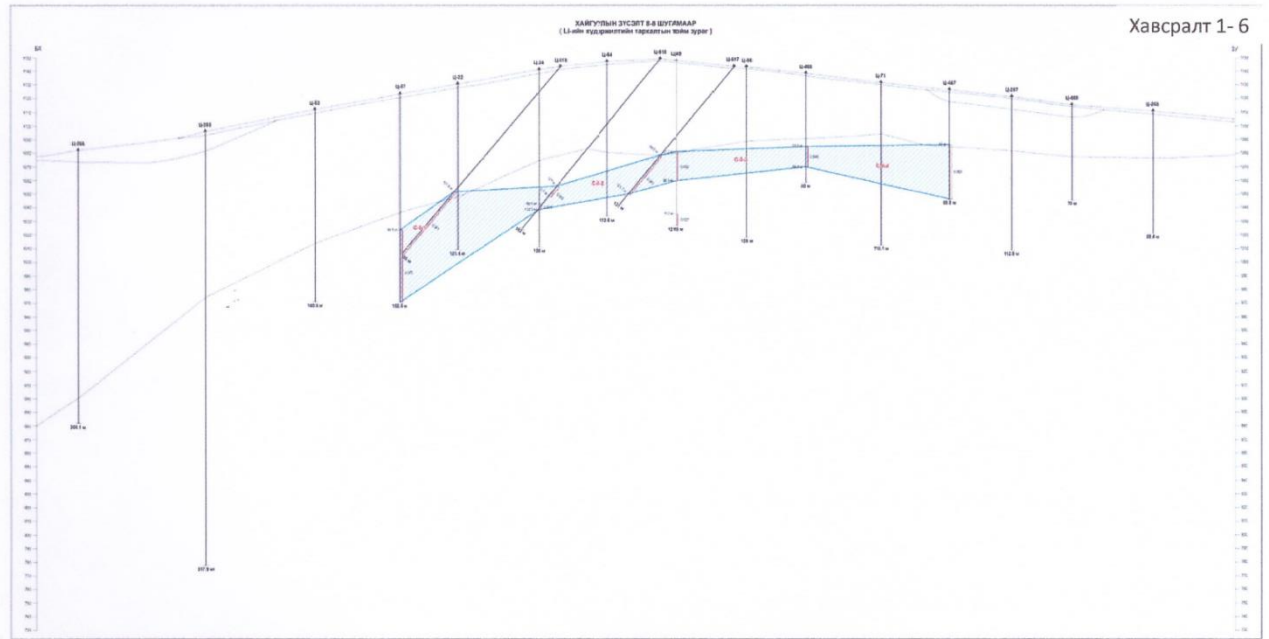
ХАЙГУУЛЫН ШУГАМ 7 - 7



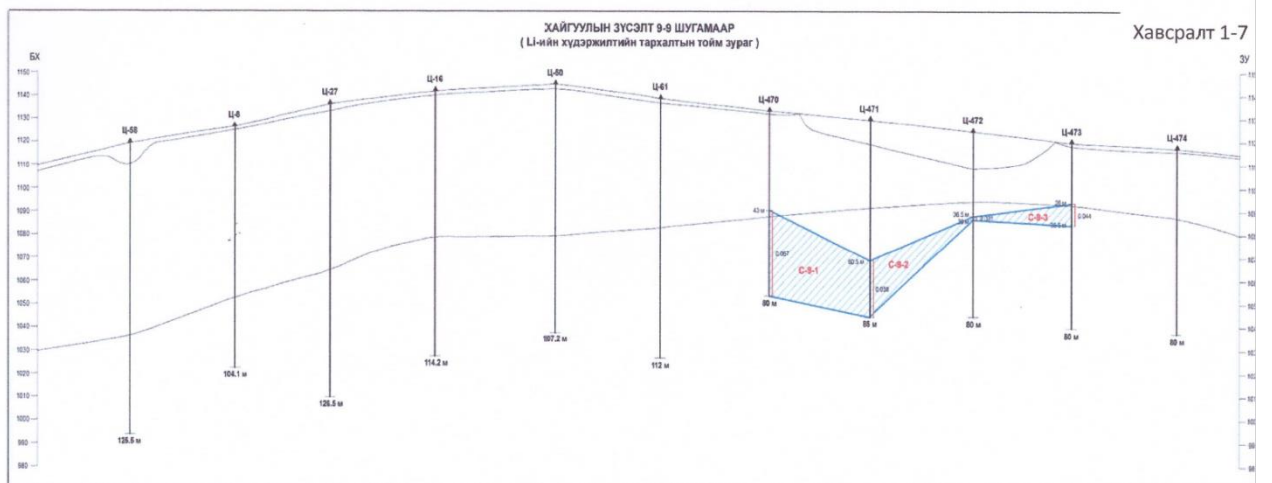
ХАЙГУУЛЫН ШУГАМ 7 - 7



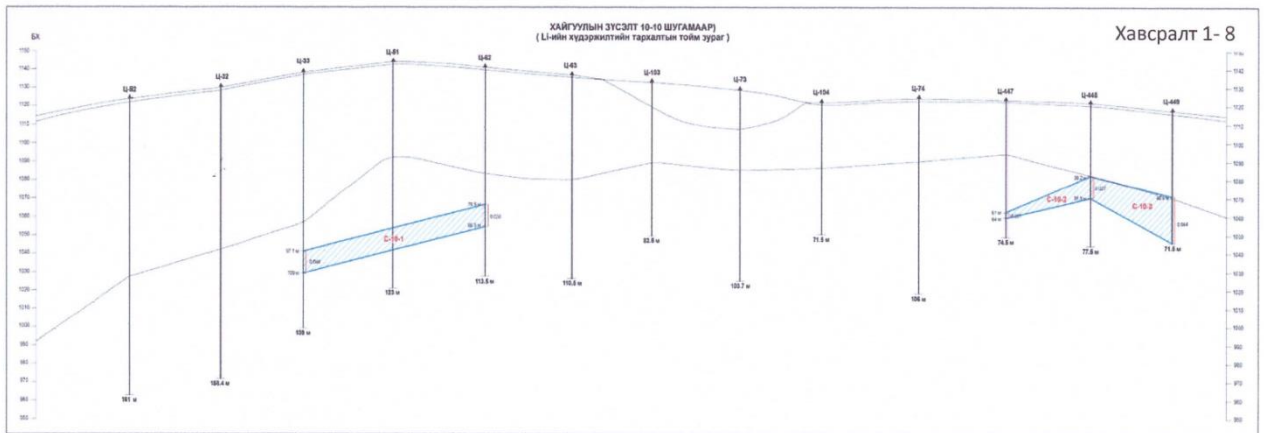
ХАЙГУУЛЫН ШУГАМ 8 - 8



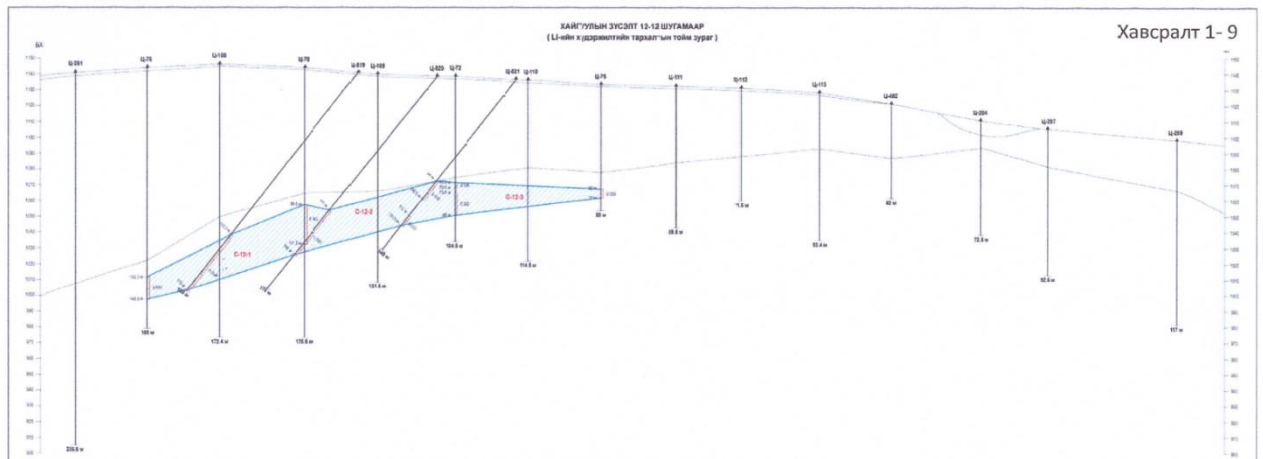
ХАЙГУУЛЫН ШУГАМ 9 - 9



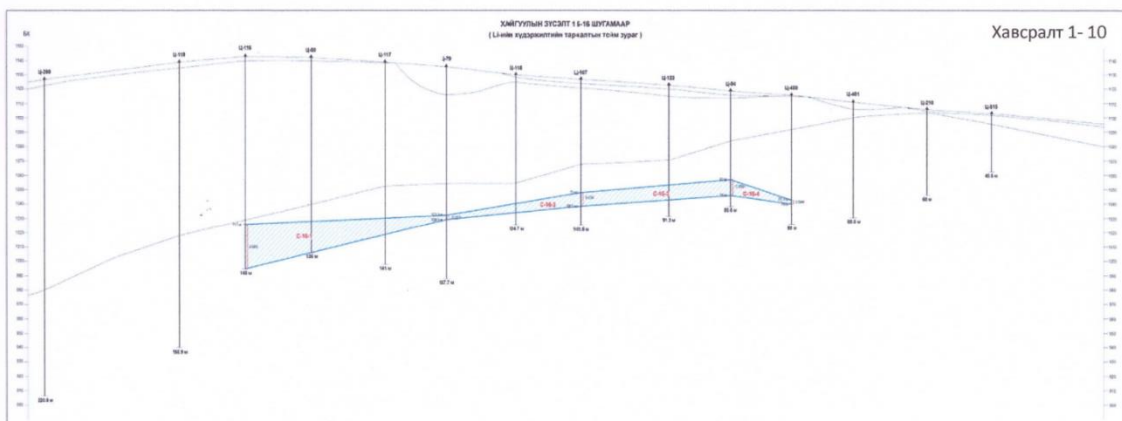
ХАЙГУУЛЫН ШУГАМ 10 - 10



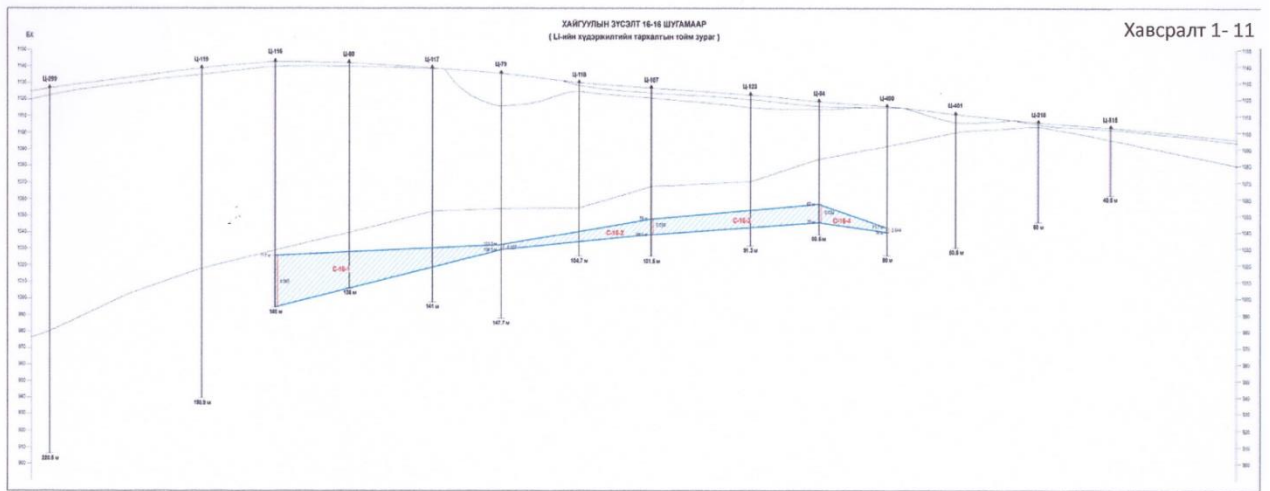
ХАЙГУУЛЫН ШУГАМ 12 - 12



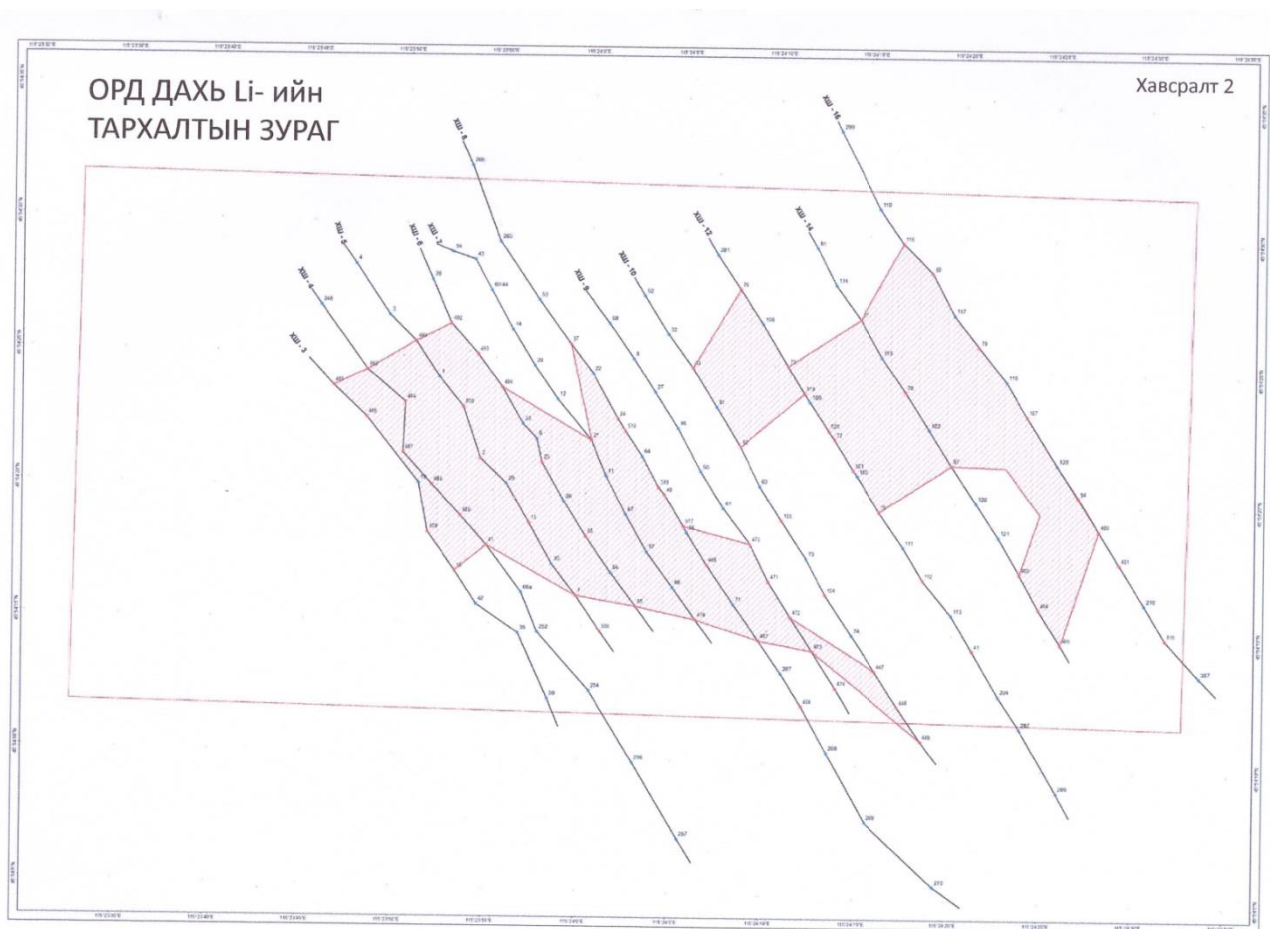
ХАЙГУУЛЫН ШУГАМ 14 - 14



ХАЙГУУЛЫН ШУГАМ 16 - 16



- Lithium Deposit:



- Lithium composition of each segments:

№	ХШ-ийн дугаар	Блокийн дугаар	Блокийн талбай, м2	Зузаан, м	Дундаж агуулга, %
1	3-3	C-3-1-1	3,781.61	24.45	0.040
		C-3-1-2	552.39	10.1	0.049
		C-3-2-1	1,578.67	29.6	0.030
		C-3-2-2	5,046.29	32.6	0.042
			10,958.95	24.2	0.040
2	4-4	C-4-1-1	2,999.16	52.0	0.043
		C-4-1-2	2,156.23	36.7	0.043
		C-4-1-3	760.01	15.2	0.045
		C-4-2-1	688.67	11.8	0.039
		C-4-2-2	1,126.51	22.6	0.046
		C-4-2-3	2,472.31	50.8	0.042
		C-4-2-4	2,240.18	48.8	0.037
		C-4-3-1	344.25	6.0	0.029
		C-4-3-2	386.46	6.7	0.047
		C-4-3-3	349.67	6.1	0.034
		C-4-3-4	402.46	6.9	0.041
		C-4-3-5	825.86	16.2	0.046
		C-4-4-1	274.50	4.7	0.031
		C-4-4-2	453.43	7.7	0.031
		C-4-4-3	751.57	15.1	0.047
		C-4-4-4	1,175.59	24.1	0.058
		C-4-4-5	900.81	19.6	0.046
	18,307.68	20.6	0.041		
3	5-5	C-5-1-1	2,478.91	26.4	0.046
		C-5-1-2	1,779.03	18.9	0.044
		C-5-1-3	4,280.94	66.6	0.050
		C-5-1-4	1,654.99	17.1	0.042
		C-5-1-5	4,354.01	45.5	0.064
		C-5-1-6	3,039.46	28.8	0.036
		C-5-2-1	1,243.52	13.2	0.057
		C-5-2-2	911.89	14.5	0.064
		C-5-2-3	586.46	6.1	0.053
		C-5-2-4	262.06	2.6	0.047
			20,591.25	23.955	0.05011
4	6-6	C-6-1-1	446.76	9.5	0.042
		C-6-1-2	1,130.09	23.3	0.041
		C-6-1-3	591.37	12.6	0.046
		C-6-1-4	931.78	19.1	0.051
		C-6-1-5	8,567.01	85.8	0.055
		C-6-1-6	6,263.93	62.7	0.049

		C-6-1-7	1,090.20	11.0	0.036
		C-6-2-1	1,724.74	36.9	0.040
		C-6-2-2	2,085.33	43.1	0.041
			22,831.22	33.8	0.044
5	7-7	C-7	13,981.86	57.9	0.064
6	8-8	C-8-1	4,397.14	40.7	0.061
		C-8-2	1,955.34	18.9	0.041
		C-8-3	1,734.51	18.2	0.041
		C-8-4	2,938.75	27.8	0.055
			25,007.60	26.4	0.049
7	9-9	C-9-1	1,473.99	30.9	0.051
		C-9-2	624.95	17.2	0.041
		C-9-3	258.58	5.5	0.038
			2,357.52	17.9	0.043
8	10-10	C-10-1	1,274.31	12.0	0.038
		C-10-2	384.71	7.7	0.039
		C-10-3	891.34	18.7	0.036
			2,550.36	12.8	0.038
9	12-12	C-12-1	2,518.11	22.0	0.031
		C-12-2	2,310.75	23.8	0.029
		C-12-3	973.40	11.9	0.041
			5,802.25	19.3	0.034
10	14-14	C-14-1-1	1,647.18	16.6	0.056
		C-14-1-2	996.90	10.1	0.036
		C-14-1-3	1,644.06	13.0	0.045
		C-14-2-1	409.18	8.9	0.043
		C-14-2-2	749.13	13.0	0.027
			5,446.46	12.3	0.041
11	16-16	C-16-1	2,537.95	17.3	0.045
		C-16-2	622.51	6.3	0.033
		C-16-3	1,147.65	10.3	0.035
		C-16-4	311.49	7.0	0.037
			4,619.60	10.175	0.037

- Total lithium reserve and concentration:

Li-ийн хүдэржилтийн тойм нөөцийн тооцоо

№	Блокийн дугаар	Шугамын дугаар	Дундаж			Зүсэлтийн зай, м	Эзлэхүүн, м3	Нягт, т/м3	Хүснэгт №3	
			Талбай, м2	Зузаан, м	Агуулга, %				Нөөц, тн	
									Хүдэр	Металл
1	3-4	3	10959.0	24.2	0.040	43.6	638,012.5	2.63	1,677,973.0	683.37
		4	18307.7	20.6	0.041					
		Дундаж	14633.3		0.041					
2	4-5	4	18307.7	20.6	0.041	60.8	1,182,527.5	2.63	3,110,047.4	1,420.90
		5	20591.3	24.0	0.050					
		Дундаж	19449.5		0.046					
3	5-6	5	20591.3	24.0	0.050	51.5	1,118,128.8	2.63	2,940,678.7	1,389.86
		6	22831.2	33.8	0.044					
		Дундаж	21711.2		0.047					
4	6-7	6	22831.2	33.8	0.044	49	901,920.5	2.63	2,372,051.0	1,279.92
		7	13981.9	57.9	0.064					
		Дундаж	18406.5		0.054					
5	7-8	7	13981.9	57.9	0.064	50	974,736.6	2.63	2,563,557.1	1,446.01
		8	25007.6	26.4	0.049					
		Дундаж	19494.7		0.056					
6	8-9	8	25007.6	26.4	0.049	51	697,810.5	2.63	1,835,241.5	848.61
		9	2357.5	17.9	0.043					
		Дундаж	13682.6		0.046					
7	9-10	9	2357.5	17.9	0.043	50	122,696.9	2.63	322,692.8	130.15
		10	2550.4	12.8	0.038					
		Дундаж	2453.9		0.040					
8	10-12	10	2550.4	12.8	0.038	103	430,159.6	2.63	1,131,319.7	402.80
		12	5802.3	19.3	0.034					
		Дундаж	4176.3		0.036					
9	12-14	12	5802.3	19.3	0.034	98	551,186.9	2.63	1,449,621.5	542.22
		14	5446.5	12.3	0.041					
		Дундаж	5624.4		0.037					
10	14-16	14	5446.5	12.3	0.041	100	503,303.0	2.63	1,323,686.9	519.38
		16	4619.6	10.2	0.037					
		Дундаж	5033.0		0.039					
		НИЙТ ДҮН	124,665.5		0.044			18,726,869.61	8,663.22	