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Modelling global extraction, supply, price and depletion of the extractable geological resources with the LITHIUM model

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ABSTRACT

The global lithium supply dynamics, market price and duration of the available extractable amounts were explored using an integrated system dynamics model LITHIUM. The model simulations suggest that a maximum level of extraction may be reached 2060, followed by a slow decline in extraction. Because of recycling, the supply is kept up longer and the decline is slower. The supply will initially be sufficient for the demand from new electric vehicles, after 2050, prices may increase because as a feedback from stress to meet demand. After 2050 demand for batteries can no longer be met if the target is to replace all conventional vehicles and the price may rise. If our basic simulation assumptions are right, the lithium resources will be largely exhausted by 2400. The supply situation may be improved by additional efforts to increase recycling and product design to promote recycling ease. The analysis of available extractable resources suggests that resources are about 73 million ton lithium, far larger than several present estimates of resources. Introducing a new resource policy with significantly improved recycling and limiting irreversible lithium losses in the period 2015–2025 may significantly improve the lithium supply situation and potentially prevent lithium scarcity before 2100.

1. Introduction

Lithium is an important element for many new technologies, including batteries, ceramic materials and new types of alloys (Nassar et al., 2015; UNEP, 2011a,b,c,d, 2012, 2013a,b,c). Especially, development of the use of lithium for high-performance batteries have recently opened a new and expanding sector in the market. Fig. 1a shows the global lithium production to date (2015). We estimate from the curve in Fig. 1a that about 1 million ton lithium has been extracted to 2015. The lithium demand and production has gone up significantly during the last decade, much because of increased demand from rechargeable batteries and accumulators for power-tools and battery-packs for new electric transportation vehicles (Yoda and Ishihara, 1997, Tarascon and Armand, 2001; Ning and Popoc, 2004; Johnson et al., 2007; Tahil, 2007, 2008, 2010; Tytgat et al., 2008; Angerer et al., 2009; Gruber and Medina, 2010; Jacobson et al., 2011; Gruber et al., 2011; Heinberg, 2001; Jacobson and Delucci, 2011, Kushnir and Sandén, 2012, Grosjean et al., 2012; Goonan 2012; Stamp et al., 2012; Elshakaki and Graedel, 2013; Wang et al., 2014; Li et al., 2013; Gaines and Nelson, 2015; Speirs et al., 2014; Bradley and Jaskula, 2014; Richa et al., 2014; Sonoc and Jeswiet, 2014). Fig. 1b shows the lithium price for lithium carbonate or lithium hydroxide 1998 value-adjusted dollars per metric ton (2014). Most lithium is produced to lithium carbonate, lithium hydroxide or lithium chloride for further use. Only a small fraction is produced all the way to metal.

Much of the worlds' resources of lithium are limited to a small number of old salt-beds, associated with inland, high altitude salt-lakes or fossil remnants of such lakes (Andes and Rocky Mountains, Tibet Plateau, Anatolian plateau are examples). It is also associated with some lithium-bearing minerals in pegmatite formations (Kesler et al., 2012; King, 2015), located on the main continental shields. The main commercial sources of lithium extraction used today or one additional source possible in the future are (Mohr et al., 2012):

1. Brines from salt beds of former or existing salt lakes (Bolivia, Peru, Chile, Argentina, in California, Nevada and Utah, but also in Tibet, China, and in the deserts of Turkey and Iran) (Ober 1994, 2002; Helvaci et al., 2003; Aguilar-Fernandez 2009; Kesler et al., 2012; Munk 2011; Nickless et al., 2014; Tan et al., 2012). There are also deep sea brines, geothermal brines, oil field brines and some lithium in underground rock salt deposits. Contents are very variable between and within different brines, the contents are typically 0.035–0.3%, but in small zones it may reach 1%. High magnesium

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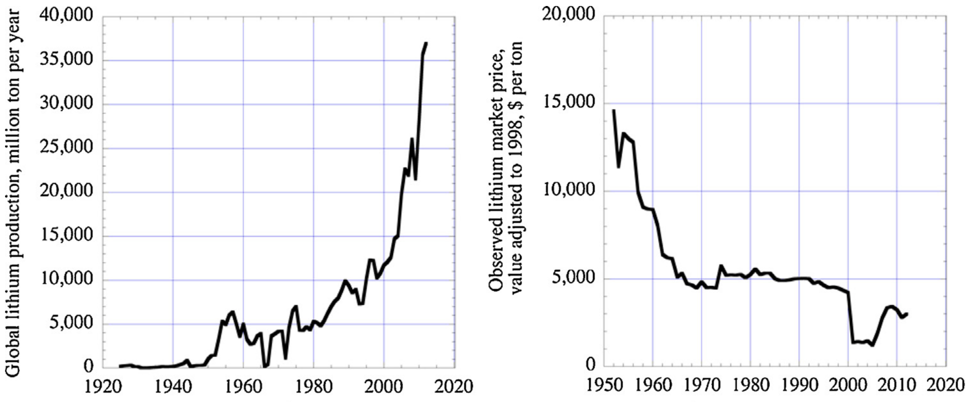

a: Production *b: Price*

Fig. 1. Diagram (a) shows the lithium production to date (USGS, 2015) as ton pure lithium. Diagram (b) shows the lithium price for the same time period in $ per ton, in dollar value-adjusted to 1998 (USGS, 2015).

content is a problem because it interferes with the extraction process.

Lithium-containing minerals where spodumene ($Li_2Al_2SiO_6$), amblygonite ($LiAlPO_4F$) and lepidolite ($K_2Li_3F_3Si_7O_{20}$) are the most important minerals. Spodumene has 8% weight of lithium in the pure mineral, it is the industrially most important mineral source (Canada, Finland, Sweden, Australia, Russia). When lower grades are considered, a range of minerals would serve as sources for lithium. In lower grade ores, larger lithium resources are known (Kunaz, 1994; Eilu, 2011; Kesler et al., 2012; Vladimirov et al., 2012; Luong et al., 2013; Nickless et al., 2014; King, 2015; Outotec, 2015). Typical lithium rock deposits contain 0.5–2% lithium in the rock matrix, this is concentrated up to 2–4% in the enrichment process. The rest of the rock is minerals with no lithium content.

Clays that contain lithium. The possibly largest lithium-bearing clay deposits are not yet being exploited on any scale. The clays subject to mining mostly originate from weathered lithium-bearing rock. (Hectorite, smectite, montmorillonite, illite; Starkey, 1982; Lien, 1985; Crocker et al., 1988; Siame, 2011; Kesler et al., 2012, Sonoc and Jeswiet, 2014; Nickless et al., 2014; Outotec, 2015). The clays contain 0.2–0.35% lithium by weight.

Salt brines (saline lakes in the Andes, Turkey and Tibet) are the main source today (50%), but extraction from minerals is also significant (40%), whereas extraction from clays is modest (10%) (Mohr et al., 2012). The salt brine obtained from the saline lakes is leached selectively for lithium in several steps, and in the process magnesium, sodium and potassium salts are produced in addition to lithium hydroxide or carbonate. In the lithium mines of South America, boric acid is often also recovered. For pegmatitic minerals (Bedrock resources), the procedure is different. The mined mineral is crushed and treated with flotation to produce concentrate. The concentrate is heated in a calcination kiln to 1100 °C, making it more reactive to sulphuric acid. A mixture of finely ground calcinated spodumene mineral and sulphuric acid is heated to 250 °C, reacting to form lithium sulphate. The lithium sulphate is dissolved in water. The lithium sulphate solution is reacted with soda ash, precipitating insoluble lithium carbonate from the solution. The carbonate is separated and dried for sale or use in the production of other lithium compounds (Colton, 1957; Lien, 1985; SGS, 2010; Swanson, 2012). From clays, the lithium is selectively leached using acid or organic solvents, the process requires many steps and is demanding to operate (Crocker et al., 1988).

Extraction from ocean seawater, using evaporation ponds and selective extraction has been discussed, but so far, no project has been realized in any significant scale. The energy demands for such methods are very large, and they are only feasible if energy is very cheap. At the point of writing, energy is cheap because of political processes going on in the Middle East. There is no certainty that cheap oil will persist.

Uses of lithium are in 2010 (Baylis, 2010; Walker, 2011; Polinares, 2012; Fox-Davies, 2013; 2014): ceramics and glass; 29%, batteries; 27%, other unspecified uses; 16%, greases and lubricants; 12%, castings and light weight specialty aluminium and magnesium alloys; 5%, air conditioning, cooling media; 4%, polymers; 4%, aluminium production; 3%, drugs; 2%.

2. Objectives and scope

Our goal was develop a simple model for the global lithium cycle in order to assess the sustainability of lithium use in new technologies. Special focus will be paid to production of rechargeable batteries for a future electric vehicle production, and to different strategies for recycling and the sensitivity of the supply to the size of the extractable amounts of lithium from different sources.

3. Earlier work

Ziemann et al. (2010, 2012) is in the process of developing a mass flow model for lithium, where simple linear mass balances are rolled forward one year at a time. Angerer et al. (2009) modelled the global supply, assuming 50 and 85% of all cars to be electric vehicles in the future. Carles (2010) modelled global lithium using a stock-and-flow model. Mohr et al. (2012) developed a model for the global lithium supply, based on modified asymmetric version of Hubbert's type of model, and used it for supply sustainability assessments for the period 1900–2200 AD, looking at three different scenarios for URR. In earlier studies, the authors have developed system dynamics models for a number of metals: gold (GOLD: Sverdrup et al., 2012a,b), rare earths (Kifle et al., 2012), copper (COPPER: Sverdrup et al., 2014b), silver (SILVER: Sverdrup et al., 2014a), aluminium (ALUMINIUM: Sverdrup et al., 2015), iron, manganese, chromium and nickel (IRON, STEEL, Sverdrup et al., 2015) and platinum group metals (PGM Sverdrup and Ragnarsdottir, 2016).

The models reported in earlier publications are not true dynamic models and lack the feedback structure expected from a system dynamics model. The earlier models do not include any effect of price on demand, supply or and recycling. The present models are fully integrated dynamics models, overcoming many of the weaknesses of earlier models. In the present model and the earlier models of the authors, one of the major advances were the development of a reality-based metal price model, allowing for price estimation from market fundamentals inside the models, without