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Aluminium for the future: Modelling the global production, market supply, demand, price and long term development of the global reserves

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ABSTRACT

The reserves, production from mines, supply of aluminium to society and mass fluxes of aluminium in society was assessed using an integrated systems dynamics model (ALUMINIUM) in order to reconstruct the past and investigate potential future scenarios. The investigations for input data show that the mineable aluminium reserves are large, but finite. We get an average value for the ultimately recoverable reserve to be about 20–25 billion ton aluminium. The production of aluminium at present is 50 million ton per year. Continuing business-as-usual consumption with sustained global population growth above 7 billion people combined with a decline in cheap fossil fuels, aluminium may in the long perspective be a more expensive product than today. Should the event of a need for substituting a significant part of copper, iron, steel and stainless steel with aluminium arise, the time to scarcity for aluminium could become an issue within the next four decades. Ultimately, continuation of the aluminium production may in the future become limited by access to energy. Whereas aluminium primary production may go through a peak in the next decades, supply to society will not reach a peak before the end of the century, because of recycling from the stock in society. The model suggests that the supply level will decline to 2014 level sometime around 2250, or 230 years into the future.

1. Introduction

Aluminium is the second most important metal for modern human civilization. In this paper, we will use integrated model to assess the long term outlook for future aluminium primary production and supply of aluminium to society. Special attention will be made with respect to recycling and aluminium conservation and accumulation in society, considering dynamic feedbacks from market mechanisms and policy. The model developed for this study, generate world market aluminium price internally from the interactions of demand and supply through market mechanisms.

Fifty million ton aluminium metal per year was produced in 2015 (USGS, 2015). Overall the aluminium production has grown an average of 2.5% per year for the last 25 years. Fig. 1a shows the global aluminium production since 1900 to the present; the price has not gone down with increasing amounts of production, suggesting that the demand is increasing and taking everything that is produced (Fig. 1b). Historically, primary aluminium production has been gradually made more energy efficient, and most of the mining is now located in low wage, developing countries. At the same time, no major change in ore quality has occurred yet. Only iron has a larger mine production than aluminium with about 1450 million ton iron mined per year. Aluminium mining and smelting amounts to about 50 million ton per year at present. This constitutes 97% of all global metalmaking. Before 1920, aluminium was produced in insignificant amounts, but with the development of new production processes, the metal became important when it could be relatively cheaply produced in large amounts.

Bauxite is the main ore for aluminium, and by far the most cost efficient source of aluminium extraction. Bauxite, a mixture of aluminium and iron oxides, is dug up from large open pit mines; it formed as a result of weathering of plutonic rocks in tropical or former tropical areas. Bauxite consists of the minerals gibbsite ($Al(OH)_3$), boemite (γ-AlO(OH)) and diaspore α-AlO(OH), and mixed in are kaolinite ($Al_2Si_5(OH)_4$), the iron bearing minerals goetite (FeO(OH)) and haematite (Fe_2O_3) and small amounts of anatase (TiO_2). Red mud is the waste after refining bauxite to alumina (Al_2O_3), and the amounts produced are very large; red mud is

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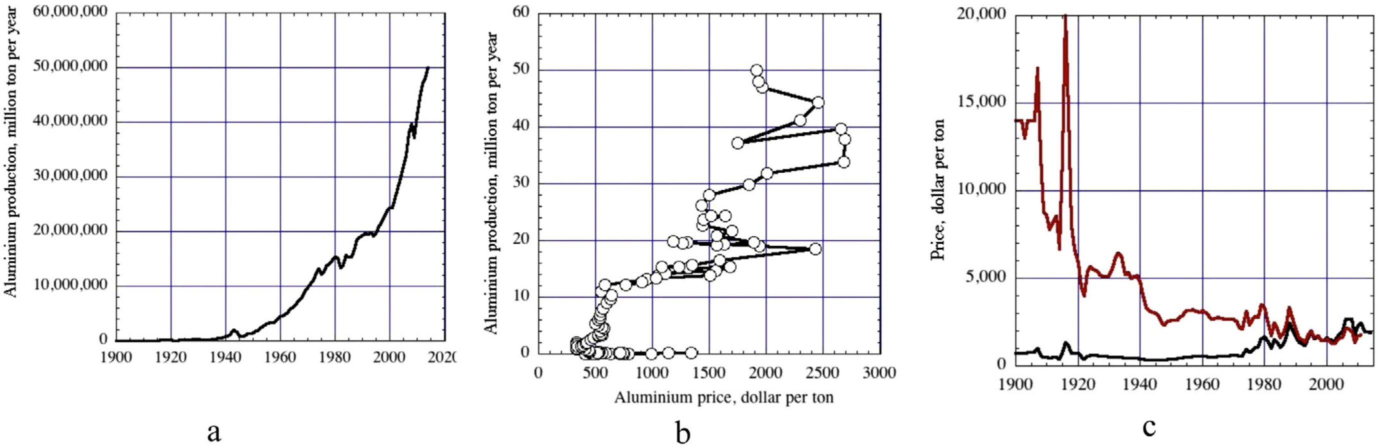

Fig. 1. (a) Global aluminium production since 1900 to the present; the amounts are expressed as million ton. (b) The price has not gone down with increasing amounts of production in the last 3 decades, suggesting that the demand is also increasing and taking everything produced. (c) The price in dollars is shown in the lower black line (same as in (b)), and the red line gives price that is inflation adjusted using 1998 as reference.

caustic and represents an environmental hazard. It is formed when bauxite is treated with hot alkali solutions; the resulting aluminium hydroxides are later burned to get alumina. This alumina is then reduced in aluminium smelters in the presence of coal, resulting in roughly 1.2 tons of CO_2 for each ton of aluminium metal (e.g. Sverdrup and Ragnarsdottir, 2014).

Making aluminium from other ore than bauxite is not economic at present, but may be in the future if bauxite reserves should run out. A good quality bauxite ore has a low content of alkali metals (CaO, MgO, Na_2O, K_2O), low contents of iron oxy(hydr)oxides (FeO(OH)), Fe_2O_3, Fe_3O_4) and titanium oxide (TiO_2), and especially low content of silica (SiO_2). Bauxite ore quality is in the first stages of declining reserve quality at present, a diagnostic indicator that identifies a need to asses the future of bauxite mining and aluminium supply (Alumina Limited, 2012). Nepheline ($NaAlSiO_4$), a feltspatoid, is the only mineral so far used for alumina production (in Russia, about 800,000 ton alumina per year was produced in 2015); per weight nepheline contains 44% alumina, the Russian ore has 24–28% alumina bulk content (Smirnov, 1996; Sverdrup, 1990). Kaliophilite ($KAlSiO_4$) is the potassium end member of the same type of mineral and there is a continuous solid solution between them ($Na_xK_{(1-x)}AlSiO_4$); it is an alternative mineral substrates for alumina production. Going on to more tightly bound alumina-silicates for aluminium extraction would increase the energy costs of the aluminium metal production significantly. The cost rises proportionally with the alkali metal–oxygen bonding energy of the minerals. The production pathway is known for aluminium extraction from many aluminium-silicate minerals, but the costs are excessive compared to the present aluminium market price. Although aluminium is very abundant on Earth, most of it is tighly bound into aluminosilicates, requiring prohibitive amounts of energy to take it out of for example granite rock. Therefore, despite making up 8% of the crust, most aluminium is unavailable for extracting the metal. Aluminium production depends on bauxite and feldspatoids that can economically be reduced to metal.

2. Earlier research into modelling of the global aluminium cycle

The Global Aluminium ReCycling model (GARC, 2011) was developed by the International Aluminium Institute. It is a Mass Flow Analysis type of model that uses parallel mass balances that are advanced one year at a time. This way, time-dependent trajectories are created as an expansion of modified business-as-usual versions. It does not involve crosslinking between mass balances and cannot accommodate iterative feedback loops in the system. The Mass Flow Analysis models can infer price development through statistical correlations, but looped system causalities are not possible in the methodology. But for some purposes, they are sufficient and quite practical as they are easy to make.

Ramkumar (2014) made a stock-driven, trade-linked, multiregional model of the global aluminium cycle; it is a semi-dynamic econometric model, based on a regression formula calibrated on times-series. Econometric models normally use statistical relationships instead of causalities and the use of feedbacks is very limited or not existent. Econometric models are unable to generate commodity prices from causalities, and can only predict system behaviour that has been previously observed. Since econometric models operate on statistical correlations, the relationships do not distinguish between correlation and causation, and may at times represent spurious connections.

Many researchers used Material Flow Analysis modelling for metals, including Bangs (2011), Chen and Graedel (2012a,b), Chen and Shi, 2012, Ciacci et al. (2013), Gang et al. (2013), Hatayama et al. (2007), Liu and Müller (2012, 2013a,b) and Müller et al. (2014). Mass Flow Analysis models are simplified and normally linearized models, and can answer relatively simple questions efficiently. However, if we are asking questions related to causalities, non-linearities and feedback effects, they are not a sufficient tool for future scenarios.

Recycling and flows were mapped by Hatayama et al. (2009), Liu and Müller (2013a,b), Modaresi et al. (2014), Rauch (2009), Rauch and Pacyna (2009), Graedel and Erdmann (2012), UNEP (2010, 2011a,b, 2013a,b), McMillan et al. (2010), Wang and Graedel (2010). They present snapshots of mass flows and some considerations on how they may change, but these efforts do not model any systems dynamics in the global aluminium system. They are however very important for validation of the dynamic models as they describe past record of flows and stocks and record what happened in the past. Hubbert's model was used by Roper (2009), Ragnarsdottir et al. (2011), Sverdrup et al. (2013a–c), and Sverdrup and Ragnarsdottir (2014). Hubbert's model is empirically based and does not include any defined feedbacks in any way. Hubbert's model is a very simplified model, and can answer simple questions of production in a business as usual scenario.

Several features of the aluminium system cannot be investigated unless we use models that incorporate feedbacks in the model formulations (Meadows et al., 1974; Haraldsson and Sverdrup, 2004; Sverdrup et al., 2014a,b; Sverdrup and Ragnarsdottir, 2014). Important in the global cycling of major commodity are the factors