Resources, Conservation and Recycling 103 (2015) 139–154

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

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

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ARTICLE INFO

Article history:
Received 23 January 2015
Received in revised form 15 June 2015
Accepted 15 June 2015

Keywords:
Aluminium
Mining
Systems dynamics
Reserves
Price

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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http://dx.doi.org/10.1016/j.resconrec.2015.06.008
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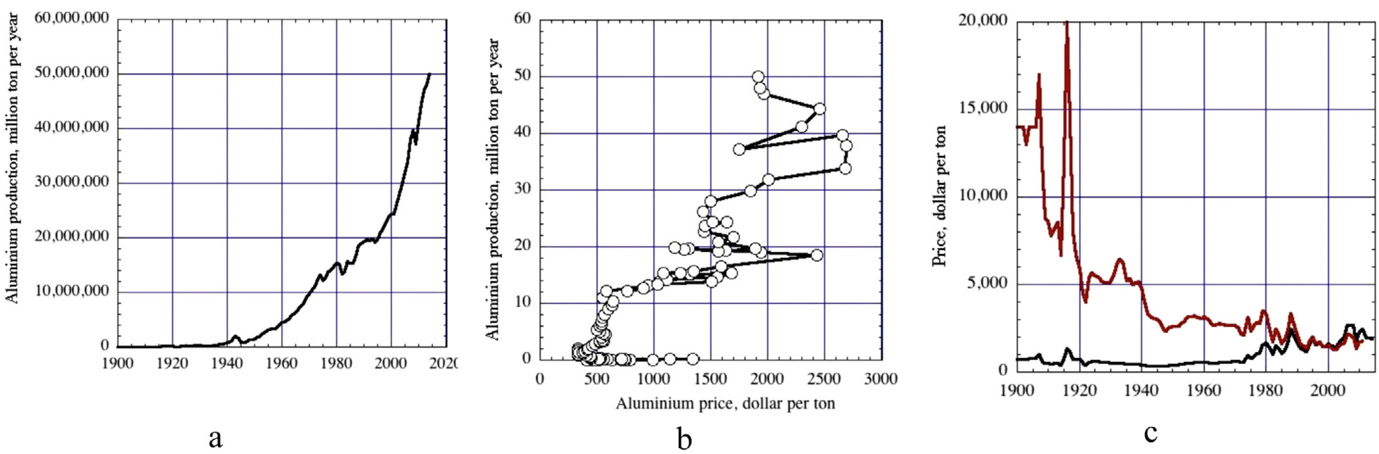


Fig. 1. (a) Global aluminium production since 1900 to the present; the amounts are expressed as million ton. (b) The price has not gone down with increasing amounts of production in the last 3 decades, suggesting that the demand is also increasing and taking everything produced. (c) The price in dollars 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, multi-regional 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 involved in market dynamics, such as the connection between market price, trade market stocks, and the effects of price on supply and demand. These cannot be considered without having a whole system of feedbacks, which leads to the need for systems dynamics types of models.

3. Scope and objectives

The scope of this study is to create an integrated systems dynamics model for the global aluminium cycle, based on best estimates on available extractable aluminium reserves, primary production rates, market supply rates and the global market price. Our objective was to generate the aluminium price inside the model from market fundamentals and a description of the price formation process, and to include market mechanisms and the dynamic effect on supply and demand. Feedbacks play an important role in our model, as it needs to be able to address what happens in the global aluminium cycle system when the reserves run low or empty, and mining decreases. The ALUMINIUM systems dynamics model presented in this paper assesses the sufficiency and sustainability of the global aluminium supply.

4. Methods and data sources

4.1. General principles

A number of methods have been combined for this study and they have been compiled in the following sections. In this study we apply the following fundamental assumptions: The principles of mass and energy balance apply everywhere. We assume that the official statistics for aluminium reserves and resources in rock formations have the correct order of magnitude. We assume that aluminium is sold as the physical metal and we ignore the derivatives trade in our economics model and the price mechanism. Derivatives trade is significant, but difficult to model and will be the subject of a separate study. Mass balances were applied throughout the system where mined aluminium plus recycled aluminium, equals accumulated aluminium in society plus what is recycled and lost irreversibly. Mined aluminium is what we extract from the geological ore reserves, and there is no other production of new metal; old aluminium metal is produced from recycling. Mined aluminium plus recycled aluminium is the total supply to society. Recycled aluminium refers to metal that is circulated in the system back from the stocks in society. The more we recycle aluminium, the less aluminium we need to mine to keep the same amount in society. Recycled aluminium is fed into society, and taken out of the system output and returned to the system input. Thus it is on both sides of the equation, and this is how the internal aluminium flux is kept high, even if the external aluminium input is low. If aluminium mining were to stop, supply may still come from recycling. Accumulated aluminium in society is metal kept in society and not lost, and aluminium lost irreversibly is what is lost in such a way that we cannot retrieve it again. Accumulated amount in society is important, as it gets stored in society for a substantial amount of time before it can be recycled, thus creating a delay in the system.

4.2. Systems analysis and systems dynamics

Systems analysis and systems dynamics was used to map the system, and find the feedback loops in the global aluminium system and is the main method used for predictions in this study. The built the systems dynamics model ALUMINIUM and used it to estimate supply, reserve development, aluminium price and stocks and flow in society in the time interval 1900–2400 AD. We analyse the aluminium system using flow charts based on box-arrow symbols. Causal loop diagrams are used to map the feedback loops in the system. The flow charts and the causal loop diagrams serve as the foundation drawings when the model is programmed in the STELLA® modelling environment (Forrester, 1971; Meadows et al., 1972, 1992, 2005; Meadows and Meadows, 1973; Senge, 1990; Sterman, 2000; McGarvey and Hannon, 2004; Senge et al., 2008; Sverdrup et al., 2014a,b). We use the causal loop diagrams together with the flow charts for developing conceptual model understanding and to see the whole feedback structures of the system. We use them for reading out where the intervention points in the system are, and to propose policy interventions and see where success is observed (Bartlett, 1999; Haraldsson and Sverdrup, 2004; Mason et al., 2011; Sverdrup et al., 2015). This method gives more detail, considers system properties better, but it demands more insight and is more difficult to parameterize. We have developed these kinds of natural resource sustainability assessment models earlier for a variety of metals and materials (Ragnarsdottir et al., 2011; Ragnarsdottir, 2008; Sverdrup and Ragnarsdottir, 2011, 2014; Kifle et al., 2012; Sverdrup et al., 2014a,b, 2015).

4.3. Hubbert's model

We used the Hubbert's model (see Hubbert, 1956, 1962, 1966, 1972, 1976 for the definition and use of the model, and examples by Bardi, 2005; Bardi and Lavacchi, 2009; Bassi et al., 2009; Holland, 2008; Nashawi et al., 2010; Singer, 2011, 2013; Ragnarsdottir et al., 2011; Ragnarsdottir, 2008; Sverdrup et al., 2013b). The equations used here are identical to those found in Sverdrup et al. (2013a) on natural resource use, in Sverdrup et al. (2014a,b) for copper and silver. Earlier, the Hubbert's curve model has been verified on field data from oil, coal, phosphorus and metal mining, demonstrating that it works well (Hubbert, 1956, 1966, 1972; Greene et al., 2003; Hirsch et al., 2005; Bardi and Yaxley, 2005).

4.4. Input data and reserve estimates in particular

The reserves were estimated using data from the published literature; one important source is the US Geological Survey's resources mapping programme. Data and information, qualitative and quantitative was gathered from a number of sources and earlier studies where it is readily available in open sources (Osborn, 1948; Turner, 2008; Fitzgerald et al., 1990; Smirnov and Tikhonov, 1991; Smirnov, 1992, 1996; US-EPA, 1993; Allen and Behamanesh, 1994; Stockwell, 1999; Norgate and Rankin, 2000, 2002; Heinberg, 2001; Dahlström et al., 2004; Bardi, 2005, 2007, 2008, 2009, 2013; Gordon et al., 2006; Martchek, 2006; Cohen, 2007; Johnson et al., 2007; Tran, 2007; Bardi and Pagani, 2008; Radetzki, 2008, 2012; Brewster, 2009; Geoscience Australia, 2009; Rauch and Pacyna, 2009; Roper, 2009; Rauch, 2009; MinEx Consultants, 2010; Morrigan, 2010; McMillan et al., 2010; Rayzman et al., 2010; Wang and Graedel, 2010; Crowson, 2011; Fischer-Kowalski et al., 2011; Bangs, 2011; GARC, 2011; Graedel et al., 2011; Ragnarsdottir et al., 2011; Chen and Graedel, 2012a,b; ICMM, 2012; Norsk Hydro, 2012; Wübbeke, 2012; Gang et al., 2013; Liu et al., 2011, 2013; Liu and Müller, 2013a,b; Ciacci et al., 2013; Campbell, 2013; Løvik et al., 2014; Müller et al., 2014; International Energy Agency, 2014; Ramkumar, 2014; Reck and Graedel, 2012; Sverdrup et al., 2013b; UNCTAD, 2000; UNEP, 2011a,b, 2013a,b,c; USGS, 2005, 2007, 2008, 2013; United Nations, 2003). We assess the ultimately recoverable aluminium reserves (URR), as the presently extractable metal amounts along with potential resources that may become reserves at increased prices; we also assess the division between presently known extractable amounts and estimated as hidden extractable amounts, by reviewing the available scientific literature and from corporate information (Heinberg, 2001; Rauch and Pacyna, 2009; Rauch, 2009; Singer, 2011, 2013; Singer and Menzie, 2010). The

Table 1
Distribution of the world's recoverable amounts of aluminium ore in tons, the ore grades used in the ALUMINIUM model simulations. These are the extractable amounts as estimated for the year 1900 before the large expansion in aluminium production began. Amounts are in million ton aluminium.

Type	Known amounts	Hidden amount	Total amounts	Detected bauxite, but considered as unavailable resources for mining
High quality	300	9,700	7,000	8,400
Low quality	400	9,600	10,000	12,500
Nepheline and other minerals	200	3,000	3,200	25,100
Sum	900	22,300	23,200	46,000

estimates of URR vary significantly with time, and depends on many factors. The extractable amounts may be adjusted based on renewed assessment of how recoverable a resource is, as well as be reassessed based on purely political aspects. We have defined extractable amounts as a resource that is extractable physically, provided the extraction price can be paid. Resources are deposits with aluminium contents that could perhaps in theory be extracted, but where the extractability has not been assessed. The reasons for this may be several, often because they are far outside technical reach, that they are very expensive to extract or somehow blocked from exploitation.

Nepheline is an alternative source for aluminium to bauxite. The known and anticipated global nepheline reserves are considerably smaller than the bauxite reserves (Tables 1 and 2). In this study URR is distributed between the quality classifications high grade, low grade and nepheline ores. As the aluminium extraction efficiency with declining ore grade ultimately goes down, URR will converge on a final limit with time (Sverdrup et al., 2014b). When the ore grade goes down, we will have to handle larger and larger amounts of rock and the mining cost will go up (Sverdrup et al., 2014b; Mudd, 2010; Tilton, 2002, 2009, 2012; Tilton and Lagos, 2007).

Here we estimate URR as the sum of the presently recoverable amounts plus what has been mined to present (Table 3). Table 1 shows the distribution or aluminium ore expressed as aluminium content, distributed among known reserve qualities and estimated hidden amounts in ton. URR has a range from 15 billion ton aluminium to as much as 46 billion ton aluminium depending on the interpretation of the data. Mining costs are strongly connected to energy prices as expressed by for example the oil price. The lower the ore grade, the less metal is recoverable from the metal ore deposits in terms of yield. This puts an upper limit on the possible operational size of the URR (Prior et al., 2013; Sverdrup et al., 2014a).

Input for the global population size to the demand calculation was derived using the FoF-model (Ragnarsdottir et al., 2011; Sverdrup and Ragnarsdottir, 2011). The FoF-model uses a model similar to the standard UN population model (United Nations, 2003), but it has been enhanced with a food production module limited by available phosphorus supply (as a food proxy). The available ore deposit data was inspected for inconsistencies and adjustments were made when the available input data were not internally consistent. We had to make expert judgment about what are the most likely parameter values to use on some occasions. Aluminium has a specific density of 2700 kg/m^3, whereas for steel and iron this is about 7900 kg/m^3. In replacement, because of strength and density differences, 1000 kg of steel can be replaced by approximately 500–600 kg of aluminium.

Table 1 shows the distribution of the world's recoverable amounts of bauxite ore in tons of aluminium, distributed to ore grades as we have set it up in the ALUMINIUM model for starting the runs. Table 2 lists aluminium reserves, either proven or highly probable, by country according to the literature cited above in the text.

Table 3 shows estimates of the global aluminium reserves by different authors at different times (Roper, 2009; USGS, 2011; Rauch, 2009; Rauch and Pacyna, 2009; Norsk Hydro, 2012). A general impression given by many published studies of aluminium reserve estimates, is that there is a lot of aluminium deposits, but many of these are probably not economic or technically viable reserves, even at substantially higher aluminium prices. The stock-in-use in society is about 500–700 million ton, and we estimate that 1800–1900 million ton aluminium has been dug up and produced to metal. This suggests that we have retained as stock in society about 40–50% of the mined aluminium.

Energy plays an important role for evaluating the impact of aluminium production and for evaluating to which extent the aluminium production can be increased and whether aluminium can be a substitute for other materials like iron, steel, stainless steel, copper, bronze or zinc alloys. The energy use for iron and aluminium production in MJ per kg metal (Smirnov and Tikhonov, 1991; Smirnov, 1992, 1996; Norgate and Rankin, 2000, 2002) is shown in Table 4. This data was used as input to the model simulations. Aluminium is tightly bound to oxygen in the ore and in the rocks where it occurs (Sverdrup, 1990). Bauxite is one of the minerals where the extraction energy cost is the lowest. Working from

Table 2
All known aluminium extractable amounts make up 16.2 billion ton, dug up aluminium is 1.9 billion ton, giving an URR of about 18.1 billion ton expressed as aluminium metal in this estimate.

Country	Reserves fully exploitable	Resources, unassessed access to extraction	Sum of all	Country	Amount fully extractable	Potential resources, unassessed access to extraction	Sum of all
	Billion ton aluminium				billion ton aluminium		
Vietnam	11.000	5.400	16.400	Greece	0.600	0.650	1.250
Guinea	7.400	8.600	16.000	Suriname	0.600	0.600	1.200
Australia	6.200	7.900	14.100	Venezuela	0.320	0.350	0.680
Brazil	3.600	2.500	6.100	Russia	0.200	0.250	0.450
Jamaica	2.000	2.500	4.500	Sierra Leone	0.180	0.250	0.430
India	0.900	1.400	2.300	Kazakstan	0.160	0.450	0.610
Guyana	0.850	0.900	1.750	Others	3.300	3.800	7.100
China	0.830	2.300	3.130	Sum	34.600	38.000	72.600
Aluminium					16.200	17.900	34.100

Table 3
Different estimates of the total aluminium resources as a basis for mining of alumina according to the literature listed in the text. The reserve base is available as extractable, but only with higher extraction costs and more mining waste.

Source	Million ton expressed as aluminium					
	Known reserves bauxite	Known reserves aluminium content	Reserve base bauxite	Reserve base aluminium metal	Aluminium metal dug up to date	URR
Roper (2009)	–	–	40,000	18,800	1,900	20,700
USGS (2011)	29,000	13,700	44,000	20,700	1,900	22,600
Rauch (2009)	–	16,000	34,040	–	1,900	17,900
Norsk Hydro (2012)	29,000	13,700	65,000	30,550	1,800	46,050
Averages	29,000	14,470	49,900	23,350	1,900	26,813

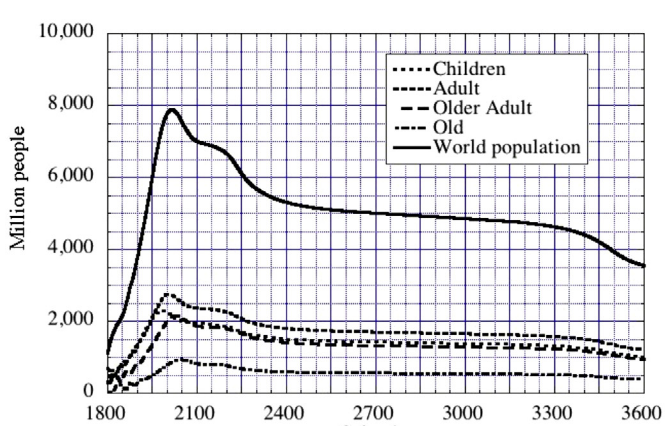
Table 4
Energy need for different metal production pathways, depending on starting raw material and final metal product. 1 MJ = 2.388 × 10^{-5} t oil equivalents.

Metal made	Pathway from	Energy need (MJ/kg)	Multiple of the least energy demanding step
Aluminium	Recycled aluminium scrap	11–17	1
	High quality bauxite	227–300	20
	Low quality bauxite	250–342	25
	Nepheline rock	250–350	30
	Muscovite or feldspar rock	500–1400	65
Steel	Recycled steel scrap	6–15	1
	Iron scrap	20–40	3
	Iron ore plus alloy metals	40–100	7–10
Iron	Iron ore	20–25	3
	Bog ore	100–150	16

recycled aluminium uses 5–8% of the energy for making aluminium from bauxite ore to metal. The cost of recycling metal from metallic scrap is similar for iron and aluminium, but as soon as the material is derived from ore, the difference is large. The energy cost of making steel from ore is only 7–12% of that of making aluminium from bauxite ore, and this explains why aluminium is more expensive than iron.

Fig. 2a shows the population from the FoF-model (Ragnarsdottir et al., 2011; Sverdrup and Ragnarsdottir, 2011), used as input to set world market aluminium demand. The population size goes through a maximum this century and then declines, caused by phosphorus shortages. Our model stricter than the United Nations population model, which assumes that there will never be any resource limitations affecting population growth (birth rate, mortality rate). The FoF-model is less strict than the *Limits to Growth* model population outputs (Meadows et al., 1972, 1992, 2005), which related population size to bulk available resources in general. The aluminium demand is driven mainly by population size and the affluency. Higher price acts as a brake on demand.

Fig. 2b shows the stock in use per person in the world, expressed as kg per person. Here we give stocks in use in different countries are for 2013, with the saturation level and time of saturation in brackets: USA 540 kg/person (600 kg/person, 2020), Netherlands 500 kg/person (540 kg/person, 2020), Germany 410 kg/person (540 kg/person, 2023), Australia 370 kg/person (460 kg/person 2023), Japan 320 kg/person (350 kg/person, 2018), France 240 kg/person (380 kg/person, 2030), Great Britain 220 kg/person (380 kg/person 2030), China 55 kg/person (380 kg/person, 2035), India 7 kg/person (250 kg/person, 2080). At a stock-in-use level above 400 kg aluminium per person, the demand seems to stagnate towards the maintenance supply for infrastructure and short-term consumption (Fig. 2b). The current global average stock is estimated at about 90–121 kg/person.



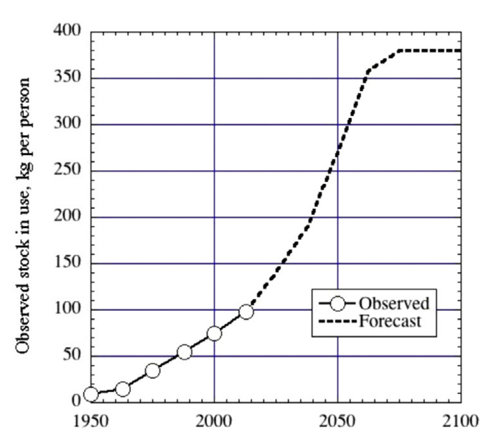


Fig. 2. (a) Earth population as a function of time. The population was derived from a FoF-model run (Ragnarsdottir et al., 2011; Sverdrup and Ragnarsdottir, 2011) and used for input to the ALUMINIUM model. Note that this differs from the standard UN estimates that for political reasons do not allow any food restrictions to populations growth. (b) Aluminium stock in use per person in the world, expressed as kg per person. This was used to generate the demand used as input data to the ALUMINIUM model.

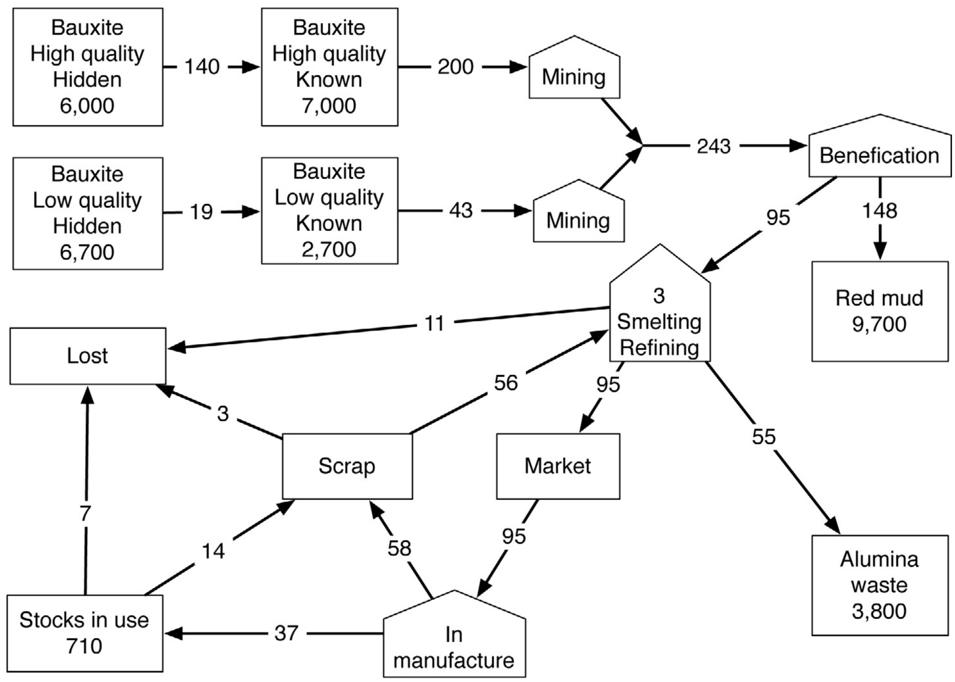


Fig. 3. Flow chart for the aluminium system in 2000. The numbers are stocks in million ton aluminium (boxes), and flows in million ton material (bauxite, alumina, waste, after refining: aluminium except for alumina waste) per year (arrows). This structure is mirrored in the STELLA version of the model.

4.5. The ALUMINIUM model

Fig. 3 shows a simplified flow chart for aluminium for 2010. The numbers adopted using data from Rauch and Pacyna (2009), Rauch (2009) and others and fitted to the structure of the ALUMINIUM model. The ALUMINIUM model is based on mass balance expressed differential equations, and solved numerically in STELLA with a 4-step Runge-Kutta method, using a 0.02 year time-step in the integration from 1900 to 2400. The ALUMINIUM model a number of stocks and flows:

(1) Extractable amounts aluminium
  (a) High quality ore expressed as aluminium (low silica content)
    (i) Hidden
    (ii) Known
  (b) Low quality ore expressed as aluminium (higher silica content, some contaminants)
    (iii) Hidden
    (iv) Known
(2) In society
  (a) aluminium trade market stock
  (b) stock-in-use aluminium in society
  (c) scrapped aluminium not yet lost or recycled

The basic driving mechanism of mining comes from profits and availability of a mineable reserve used in the model, but affected by the mining cost and how that is modified with capital costs, oil price and ore grade. A lower ore grade implies that more rock must be moved to mine the aluminium. The implication is that a higher aluminium price is necessary to keep the aluminium production up. The price must stay above the production costs and is set by the amount in the trade market. The amount in the trade market depends on the balance between deliveries into the market from production and the shipments from the market, in response to world market demand. The causal loop diagram in Fig. 4 shows how the mining operation is driven by profit. This profit is driven by the aluminium price and aluminium amount extracted, but balanced by the cost of operation. The cost of operation is mainly determined by two important factors beside cost of investments, the energy price ad the ore grade. The price in the model is set by the amount in the market and the fact that it must stay above the production costs. It depends on the balance between deliveries into the market from production and the shipments from the market in response to world market demand. The price also drives the urge for recycling of aluminium stock from society. The demand is driven mainly by population size and the affluence of society. Higher price acts as a brake on demand.

The pricing mechanism in the model has been adjusted to how the aluminium market has worked in the past and how it has recently changed. Metal trading is supposed to operate as follows: The traders come to the trading floor with their lots to sell or to buy, and adjusts their sales or purchase amounts as the price goes up and down. If demand is higher than production, the price goes up; in the opposite case the price is moved down. This is a self-adjusting mechanism that balances the trade by adjusting the prices until the demand to buy an amount at a price match the offers to sell an amount at a price. The buyer offer to purchase more at a lower price or less at a higher price, and the sellers offer to sell less at a lower price or more at a higher price. When the price and amount match, the price is set. This is based on personal observation on the trading floors at the metal markets in New York and London by the authors. Fig. 5 shows the ALUMINIUM model as a causal loop diagram for the whole world aluminium system. The aluminium ore is divided into two qualities, one high quality bauxite grade with low content of silica as an impurity in the alumina. The low quality has higher silica content, making it more expensive to reduce to aluminium; it consists of low grade bauxite and other types of low grade alumina and nepheline (Fig. 6).

5. Results

5.1. Outputs from the ALUMINIUM model

Fig. 7 shows the past and future aluminium mining rate, expressed as aluminium primary production from bauxite ore, and

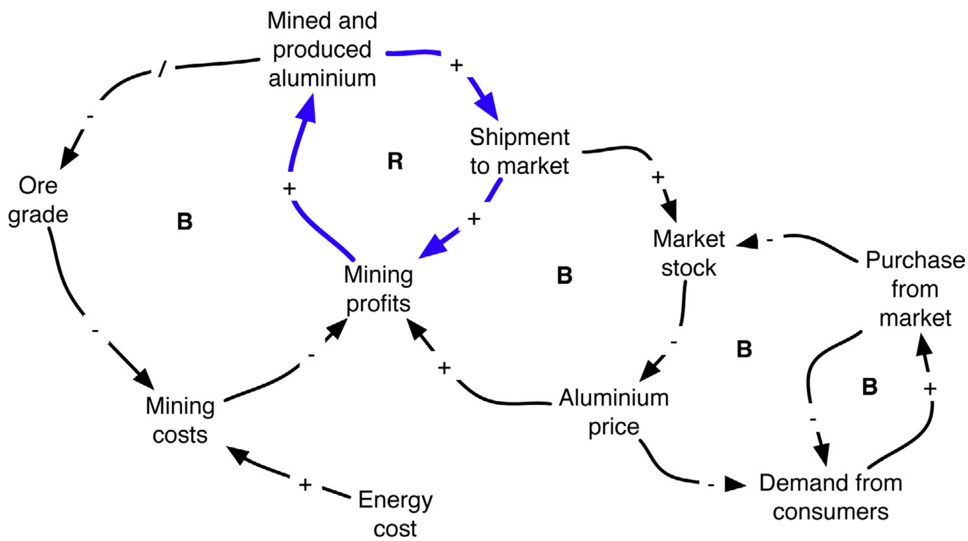


Fig. 4. Causal loop diagram of the price model used in the ALUMINIUM model. The model has a core reinforcing part, market with an R. It is surrounded by two coupled balancing loops, marked with B. To one side, the balancing loop has two coupled balancing back-loops. Mining is profit driven.

supply to the market. The dots represent the observed primary production rate ("aluminium mining"). Fig. 7b shows the primary production as compared the amount recycled from society and to the total supply to markets. Fig. 7c shows cumulative discovery or extractable amounts, cumulative mining, cumulative supply to society and cumulative losses. Note that the supply to society is considerably larger than the amount mined, because of significant recycling. Fig. 7d shows the mining from high and low quality reserves, low quality is prioritized down as long as good quality ore is available. Note that after about 2020, recycling is predicted to become the most important source of aluminium. That will be the time of scrap aluminium.

Fig. 8a shows an overview over the development of the reserves of aluminium in bauxite, known extractable amounts, hidden extractable amounts and all extractable amounts. Fig. 8b shows the cumulative amount of red mud produced from 1900 to 2400, expressed in million ton. Red Mud is a waste by-product of alumina production. Red mud is at present either dumped in nature (10%), stored in ponds (30%), and stored as dewatered dry piles (60%) that can be reclaimed as land. Normally, bauxite ore contains about 20% aluminium. About 50% of the alumina weight will be converted to aluminium metal in the smelter. Thus, to produce 50 million ton aluminium per year, about 250 million ton of bauxite per year is needed, and 200 million ton wet or solid waste is created (Fig. 8b).

Fig. 9a shows the trade market size, the amount scrapped and the amount in the trade market. Fig. 9b shows the ratio of recycled material to the flux into the market. The large stock in society allows for a high degree of recycling, even after the mines become exhausted. After 2050, more than half the aluminium metal supplied to society will come from recycled metal (Fig. 9b). Overall, today a much smaller proportion is recycled aluminium as we are still building up the stock-in-use, making the recycled fraction appear as low. The recycling rate is frequently urged by state authorities to do more, helping to keep the recycling higher than what just money and market mechanisms alone can do. Such campaigns are taking place in many countries at present. Factor *X* which is defined as the ratio of the internal flux to the net systems input. Factor *X* has a value of about 2 to 2.5 until about 2020, when it slowly increases to reach a maximum value of 5 around by 2250. Fig. 10a shows the stock-per-person, the supply per person in kg per person and year and the target aluminium demand. The simulation shows that stock per person and supply per person will flatten out and stay constant from about 2045 to 2400. Outputs from the ALUMINIUM model (Fig. 10a) suggest that aluminium production will not grow forever, but it will stop at a saturation level of 280 kg/person, a supply of 16 kg per person per year. For comparison, the level of Germany is 410 kg/person, Britain is 220 kg per person and France is 260 kg per person. After 2100, the aluminium market reaches a high level and remains there for a substantial time into the future (UNEP, 2010, 2011a,b, 2013a,b). Rauch (2009) mapped stocks-in-use for aluminium, iron, copper and zinc and related this to GDP for some countries. He found that the stock in use was linearly proportional to the country's GDP. Stock of aluminium in use was equal to 13.5×10^6 GDP. This suggests that the de-coupling presented by Fischer-Kowalski et al. (2011) is in reality not taking place for aluminium, and when all externalities are taken into account and have been brought into the model, thene there is no decoupling of primary value production with respect to natural resources.

Fig. 10b shows the simulated world market aluminium price as compared with the observed data. We get $r^2 = 0.81$ which is very good, and confirms that we can make valid use of the price predictions inside the model to drive dynamic market feedbacks on demand, supply and production.

The ALUMINIUM model operates with two ore qualities and the diagram shows the development of average ore quality with time. The best ore is mined first, and this causes the ore quality to go down with time. The high quality ore containes about 20% aluminium, we have set the low quality to have an average content of 5%. We can see in Fig. 11 that after 2100, the ore quality will start to decrease. This is an indicator for increased cost of production and increased world market price for aluminium. At some point it may become more cost-competitive to mine the large stock-in-society.

5.2. Model field test on data

We have tested the model on data from the past (1900–2015), in order to assess whether the model has a reasonable performance. Since the ALUMINIUM model reliably reconstructs the observations of the past, then it can be used with confidence for future predictions (2015–2400) and for scenarios. We have tested the ALUMINIUM model performance on several aspects:

(1) Mining rate with time as recorded 1910–2015 (USGS, 2014) (Figs. Fig. 1, 7a and 12a).
(2) The estimated stock in society (Table 5 and Fig. 12b).

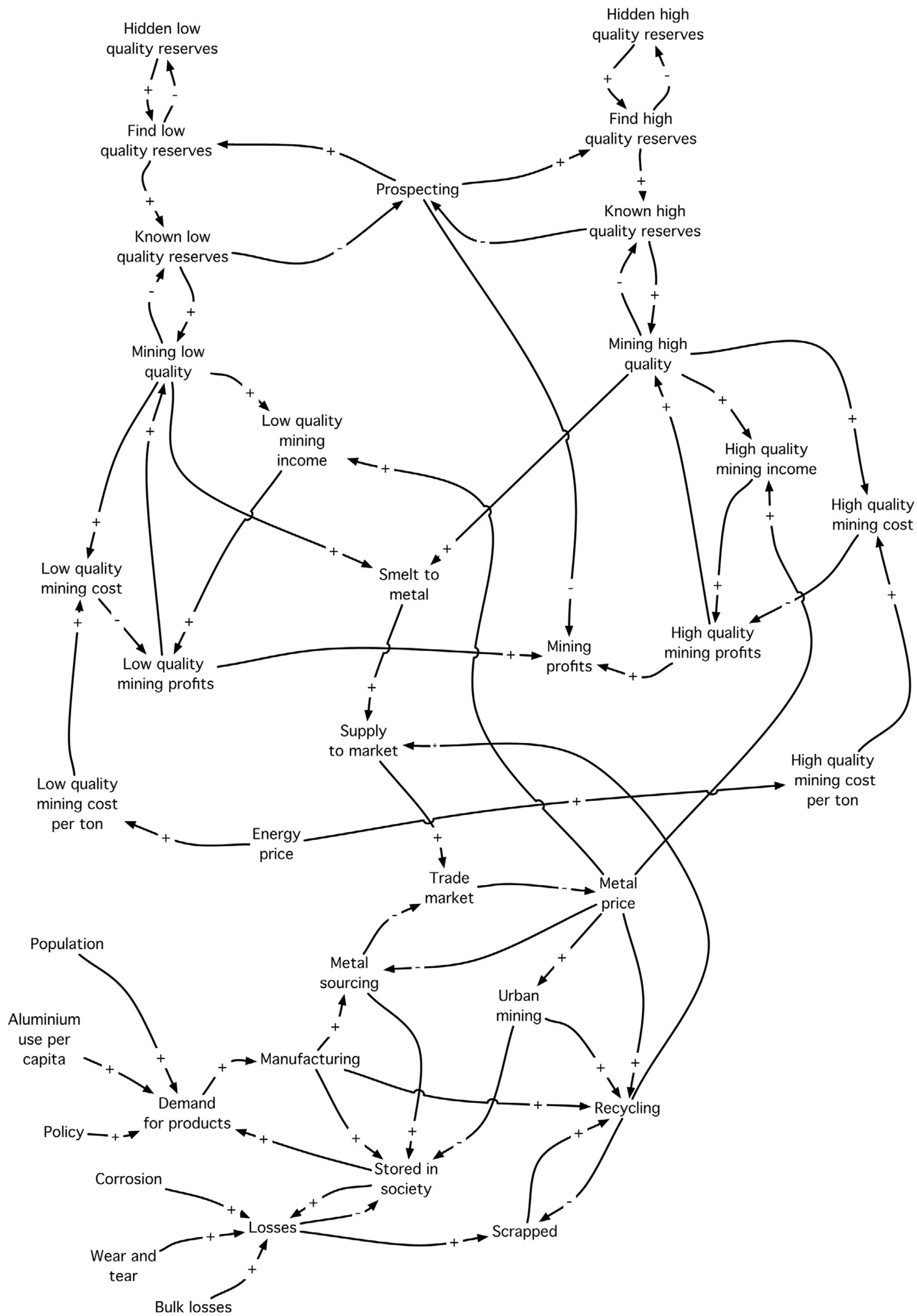


Fig. 5. The aluminium model shown as a causal loop diagram for the whole world aluminium system. The price mechanism shown in Fig. 4 is incorporated in the large diagram above.

(3) The development of the world market aluminium price (USGS, 2014) (Figs. 10b and 12c).
(4) The recycling rate as a percentage of total supply to the market (Fig. 9b and Table 5).
(5) The known extractable reserve at present (Table 5).

For the estimated stock in society we use data by UNEP (2010, 2011a,b, 2013a,b), Rauch and Pacyna (2009), and Rauch (2009), (Table 5). Fig. 12a shows a comparison of observed and simulated aluminium mining rates. The correlation coefficient is $r^2 = 0.97$, it is hard to do better. The production curve shows no sharp

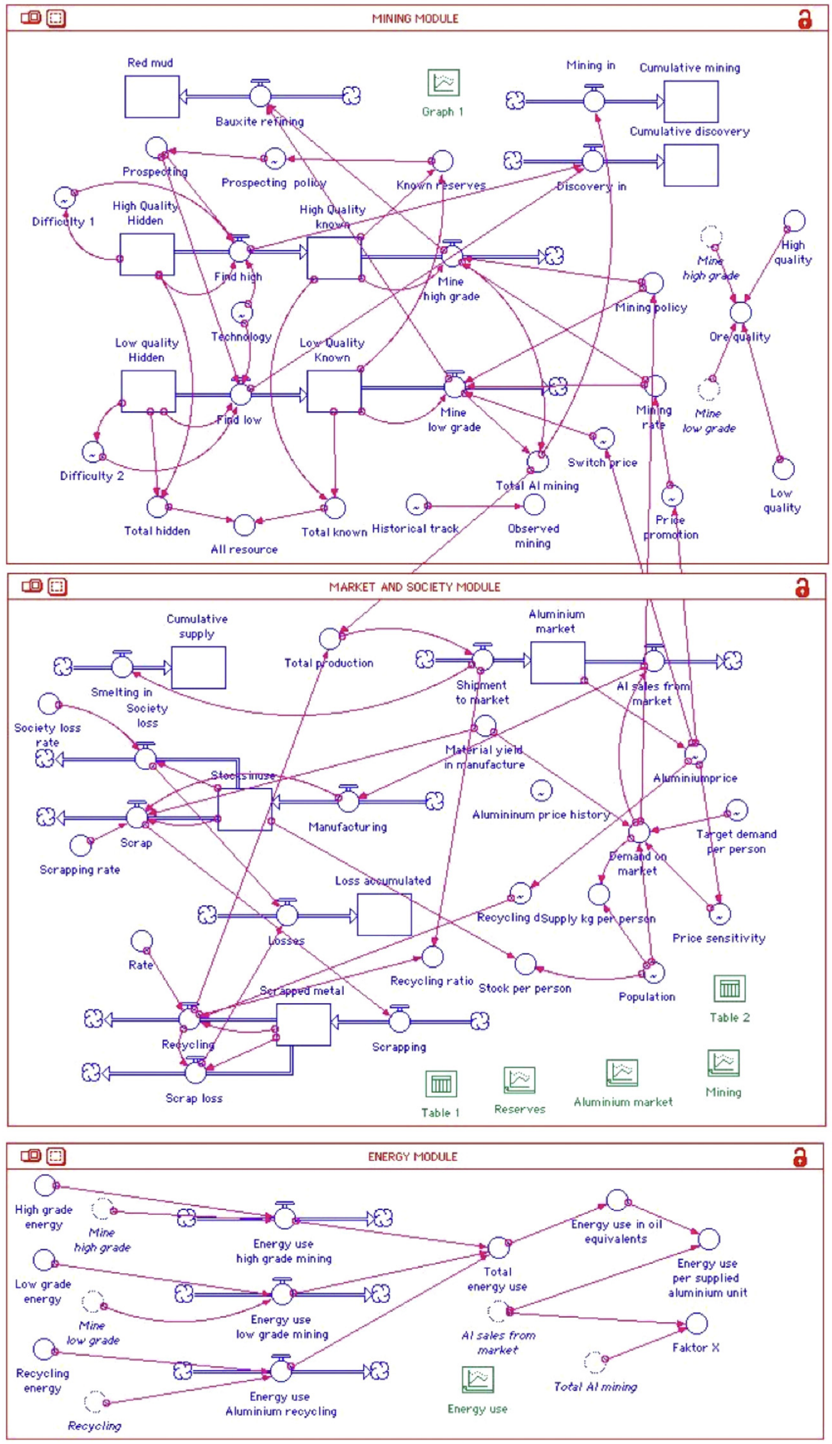


Fig. 6. The STELLA diagram for the aluminum model is shown with stocks, flows and connection lines. The STELLA model is based on the causal loop diagram and the flow chart shown earlier.

bends and the test is not difficult. Fig. 11b shows a comparison of observed stock-in-use and stock-in-use simulated by the ALUMINIUM model. The correlation between observed stock-in-use and that simulated by the model is $r^2 = 0.96$. The correlation for the price simulation (Fig. 12c) is reasonable, considering how sensitive the price mechanism is to changes, we get $r^2 = 0.81$.

Table 5 shows further tests on individual points in time. For some types of aluminium products, the recycling rate can be very much higher, such as beverage cans or scrap generated internally in manufacturing industry (Liu et al., 2013; Løvik et al., 2014). It is estimated that the total extractable resources are at least 55–75 billion metric tons bauxite when assumed but yet undiscovered bauxite resources are included. In recent years, prospecting has increased the reserves more rapidly than the rate of extraction: from 1995 to 2011, 2.7 billon metric tons bauxite were extracted, but in that time the reserves increased from 23 billion metric tons bauxite to 29 billion metric tons bauxite (Norsk Hydro, 2012). The average of data on extractable bauxite for 2014, requires the model to start

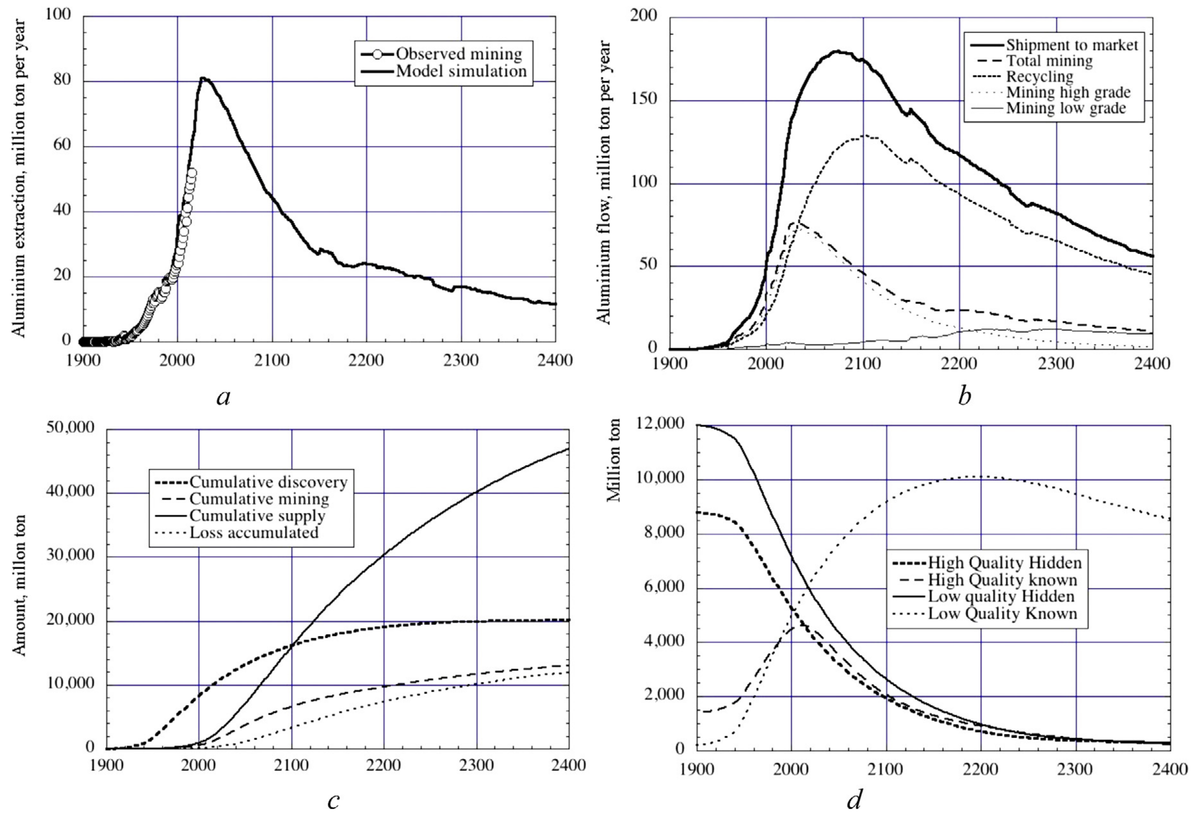


Fig. 7. Diagram (a) shows the total mining and compares observed mining (open circles) and ALUMINIUM model output. Diagram (b) gives the total mining amount, the total supply into the market, and how much comes from recycling. Diagram (c) shows cumulative amounts mined, cumulative supply, cumulative discovered and cumulative losses, expressed as million ton aluminium content. Diagram (d) shows the reserves in the ground, high quality hidden and known, low quality hidden and known and how they develop over time. Amounts are million ton aluminium.

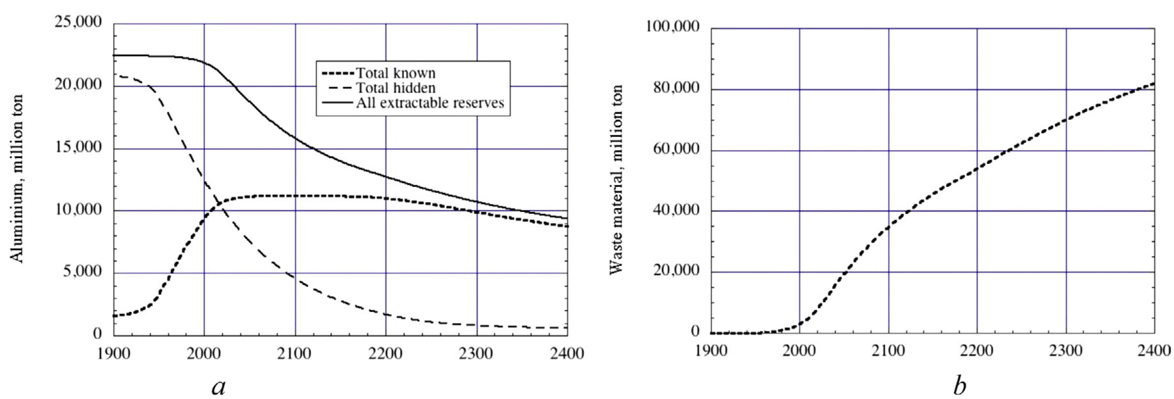


Fig. 8. Diagram (a) shows total known aluminium in the total known and hidden extractable amounts. All amounts are million ton aluminium metal. Diagram (b) shows the cumulative amount of red mud produced from 1900 to 2400, expressed in million ton red mud waste material.

Table 5
ALUMINIUM model tests on individual points in time for some parameters.

Source of information	Total amount extractable bauxite	Stocks in use, million ton	Known reserves, million ton	Stocks in use, kg per person	Recycling ratio %
Rauch and Pacyna (2009), for year 2002		493	16,000	76	
Rauch (2009) for year 2000		504		80	
UNEP (2011a,b) in year 2011		560		80	25
Aluminium Association, in year 2011					32
Ramkumar (2014) in year 2014		710		97	
USGS (2013) in year 2012	22,300		7000		
Liu et al. (2013) in year 2005		636		94	
Norsk Hydro (2012) for 1950–2011	29,000	694	10,000	100	18–28
Average of data	*25,650*	*600*	*11,000*	*88*	*25*
ALUMINIUM model in year 2014	22,400	710	9700	98	25–30

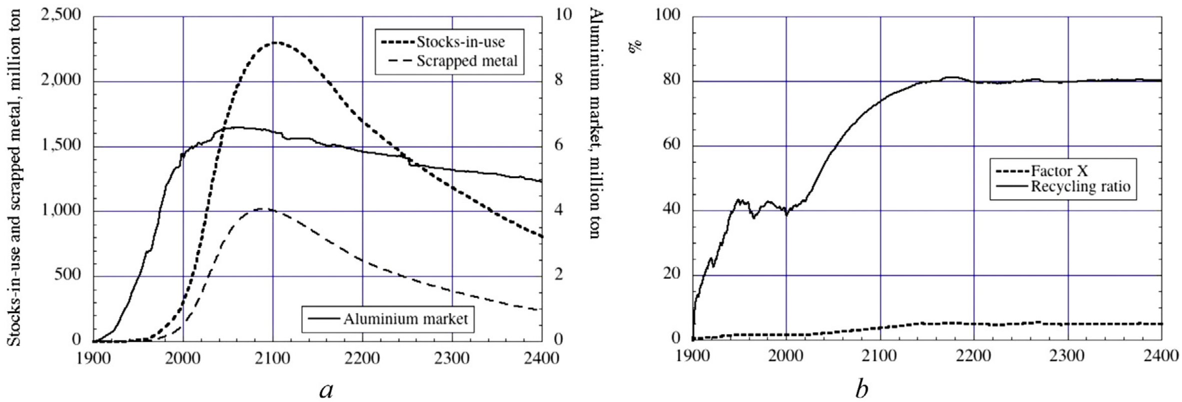


Fig. 9. Diagram (a) shows the ALUMINIUM model outputs for stock-in-use, scrapped metal stock and aluminium market size. Diagram (b) shows the factor X, and the ratio of recycled material to the flux into the market.

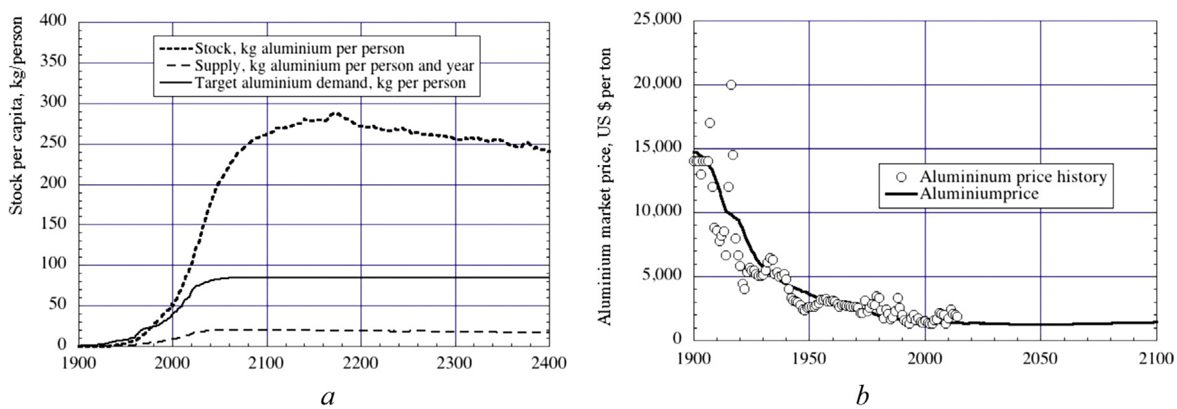


Fig. 10. Diagram (a) shows the predicted the stock-per-person simulated by the ALUMINIUM model, along with the supply per person in kg per person and year and the target demand. Diagram (b) shows the ALUMINIUM simulation of the aluminium price with the observed data added in ($r^2 = 0.81$).

with the rights size for URR, have a reasonable distribution between known and hidden, and make reasonable predictions for discovery and mining. Apparently, that seems to work (Table 5).

6. Discussion

6.1. Outputs from the Hubbert's model

The output from Hubbert's model is shown in Fig. 13. The model was set up with six different aluminium reserve regions in the model, each curve contributing to the whole global curve. The model as applied suggest a stagnation in aluminium extraction by 2025 and that the extraction rate will stay relatively high after an initial decline after the post peak decline. The results can be shaped to a large degree by setting the parameters, and with such a small set of extraction data, the curve cannot be uniquely defined.

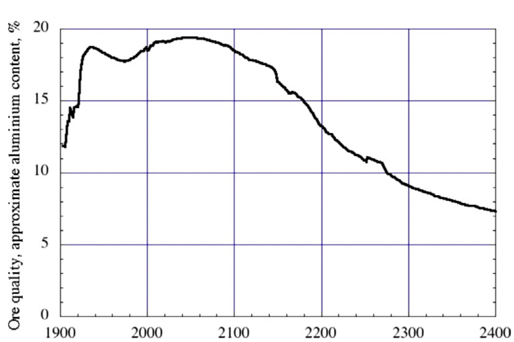


Fig. 11. Simulated development of ore quality with time.

6.2. On the prospect of aluminium scarcity

If we combine the ALUMINIUM model (Fig. 7) outputs and the Hubbert's model (Fig. 13), they suggest peak production to occur somewhere in the period 2025–2050. The ALUMINIUM model suggests that the supply curve reaches maximum about 2080–2090. The supply to society will slowly decline after the peak, and the supply level of 2014 will be reached in the times around 2275 AD (See Fig. 7b).

It is apparent from our study that there will be no aluminium shortage in the near future, and the aluminium price is predicted to stay stable on a relative scale for a long time. Only in the very long perspective, after 3000 AD will the bauxite reserves have been used up at the present rate of depletion and the stock-in-use been depleted by recycling and lower replacement rates. However, before that happens, the ore quality will decline (Fig. 11). Based on field fact, the best ore qualities are mined first, causing ore quality to go down. Whether the aluminium supply is sustainable depends on this perspective on time. The reserves of bauxite are still increasing as a result of prospecting, suggesting that we are maybe 20–40 years from a definite peak production. Resource scarcity manifests itself gradually through three stages:

- The first stage comes immediately when the peak has been reached, when demand still goes up, but production is flat or slowly declining. The scarcity is manifested through increased

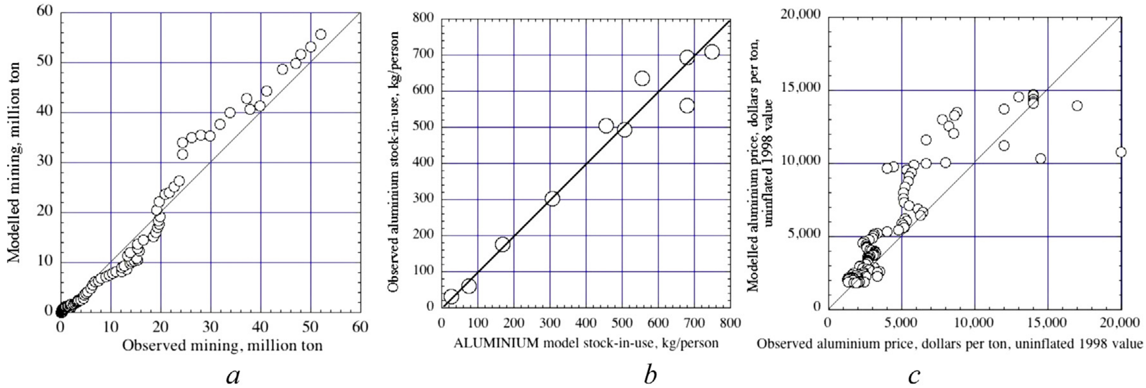


Fig. 12. Comparison of observed and simulated mining rates. Diagram (a) shows fit with data (circles) over time. All amounts are million ton aluminium. Diagram (b) Comparison of all available observed data for stock-in-use and the stock-in-use simulated by the ALUMINIUM model. Diagram (c) shows a comparison of observed value-adjusted aluminium price (circles) and the ALUMINIUM model simulated price.

prices. There will be no material shortage, as increased prices will simultaneously decrease demand. A diagnostic indicator is that even if prices go up, production cannot be increased above the former demand (2050–2100).

- The second stage is when the production decreases, and the price will further increase and there will be capacity limitations to supply. Demand will be further decreased by high prices, but because of limited reserves, supply will not go up because of increased prices (2100–2250).
- Later, at an advanced stage of extractable resources decline, the ore quality also goes down, pushing production prices up (Fig. 11, from 2130 to 2200). To make 50 million ton aluminium per year from a 5% grade ore instead of a 20% grade ore will increase the waste created from 250 million ton per year to 1000 million ton per year. It is self-evident that that increase in waste will cost money to produce, transport and safely store.
- The last stage is when the production has gone down significantly, and material supply is restricted, making practices of mass consumption impossible (2250–2400).

6.3. Energy, decoupling and substitution

There is another element that relates to iron and copper. Aluminium may replace these two metals in some of their applications, but far from completely. The production of iron is 1450 million ton per year, whereas aluminium mining is about 50 million ton per year, the total aluminium supply to society is about 100 million ton per year. It can be seen that aluminium would never be able to replace all iron. Iron may become more expensive after 2100, and if aluminium should be replacing iron on a large scale, then the aluminium supply situation may change completely. If we assume for a hypothetical argument that we can replace half of all iron with aluminium, it would require 670 million ton iron to be replaced by about 300 million ton aluminium. The energy requirement would rise from 670 million × 1000 × 22 MJ/kg = 14.5 trillion MJ to 300 million × 1000 × 230 MJ/kg = 69 trillion MJ, which would be 4.8 times more energy. Aluminium takes up about 2.7% of the global energy expenditure today, and increasing this to 13% in a time when fossil fuels supply will go down, seems more than what would be feasible in reality.

At present, the reserves to production ratio is about 400 years for aluminium, but doubling the production to 100 million ton aluminium per year would cut that ratio to half; increasing it to 300 million ton aluminium per year would reduce the reserve to production ratio to 60 years and the production would demand 36% of the present global energy production. It is self-evident that we simply do not have the available energy for such an amount of aluminium production, nor do we have the aluminium reserves to sustain it for any length of time. Then scarcity and high prices may definitely be a future prospect even for aluminium. Copper production is about 16 million ton per year, total copper supply to the market was about 28 million ton per year in 2014 and copper will soon pass through peak production and decline after about 2025–2035 (Sverdrup et al., 2014a). If this is to be replaced with aluminium, then aluminium production must increase with 8–10 million ton aluminium per year. The result of our analysis is that the realism of substitution seems to be limited for the big volume metals. Imagine an extraction rate 5 times the aluminium extraction rate of today (everyone has as much aluminium as every American citizen, implying a global extraction of 250 million ton per year), then the aluminium reserves will have been exhausted by the year of 2200.

Fig. 14a shows the energy demand for all aluminium produced, usinging the values shown in Table 2, to calculate the total energy

Hubbert' model parameters			
Reserve, million ton aluminium	b	P_{MAX}, million ton per year	T_{Peak}
680	0.100	17	1986
1,600	0.100	45	2025
2,670	0.060	40	2060
2,330	0.060	35	2108
4,000	0.015	15	2225
3,200	0.010	8	2450
14,480			

Hubbert's model diagram

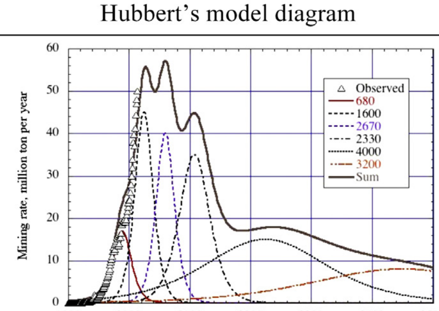


Fig. 13. Hubbert's model assessment for aluminium extraction from bauxite.

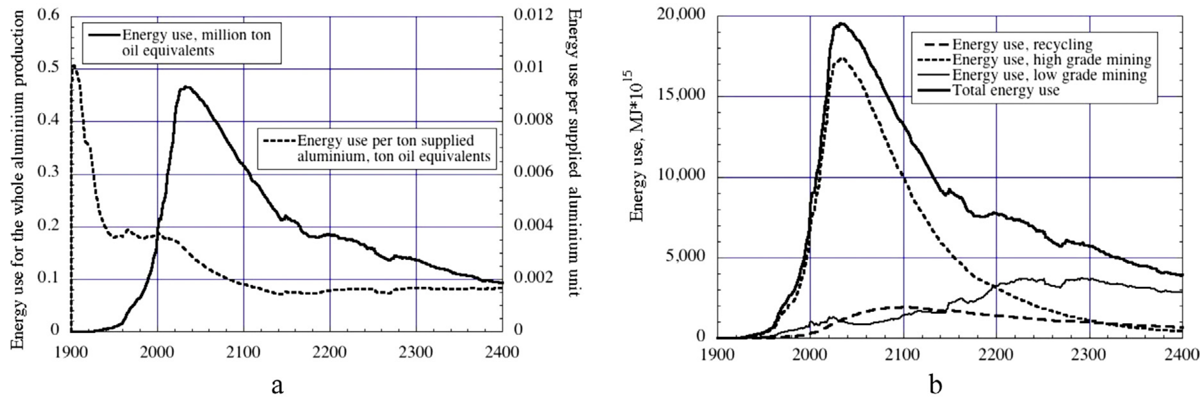


Fig. 14. The total energy use for aluminium production over time. Diagram (a) shows the total energy use in million ton oil eqivalents, and the energy use per aluminium weight unit produced. Diagram (b) shows energy use for the amount recycled aluminium, the high grade mining, the low grade mining and the sum of all energy used to supply aluminium.

use for aluminium production over time. Fig. 14b shows energy use for the amount recycled aluminium, the high grade and the low grade mining contributions, and the sum of all used to supply aluminium. It can be seen that the energy use per ton aluminium decrease with time as the contribution from recycling becomes larger. Then the energy use decreases faster than the production decreases. In 2014, the energy use for aluminium production was 0.320 million ton oil equivalents per year, at the peak in 2050, it will be 0.44 million ton oil equivalents per year. In 2014, the global oil production was 3700 million ton oil equivalents, the global energy production was 12,400 million ton oil equivalents. Aluminium production requires the energy as electricity, and the energy use for aluminium is about 50% of all hydroelectricity produced in 2014. Of note is that when hydrocarbons are used for electricity generation, but the efficiency in conversion is at best about 40%, and normally this ends up at closer to 30%. If all the aluminium were to be supplied with fossil fuels energy, it would consume about 8% of the total global energy. A significant shortage of fossil fuels predicted by Campbell (2013) after 2080–2100 may upset the aluminium production system and cause significant metal price rises, caused by both energy availability limitations and increased energy price.

6.4. Recycling

The recycling rates given by the ALUMINIUM model are about the same as what is reported in the literature. For some items like beverage cans, the recycling rate is high; for lots of other uses such as for example packaging, it is sometimes non-existent. The present observed recycling estimates are offset by the fact that much aluminium is still being built into our infrastructures, and thus will eventually be recycled, but only after a delay of many decades (Hatayama et al., 2007, 2009). The retention time in society seems to be on the order of several decades, or 30–60 years. However, aluminium in daily consumer goods like beverage cans, only have a market life in terms of weeks or months, and even if recycling in cans is 85%, that is still not good enough to prevent loosing all the aluminium in that cycle within months. For such high turnover use, an alternative is to use have even higher recycling or change material altogether.

6.5. Time, long term perspectives and sustainability

For some few people, 100 years is within living memory, and it is the minimum time horizon of professional pension fund management. For our children and grandchildren, these longer perspectives are important (MacIntosh and Edwards-Jones, 2000; Greer, 2008; Jackson, 2009; Randers, 2012). For aluminium, the delays in the system are long and scenarios that run to the year 2400 seem appropriate. We know for a fact that the principle of mass balance will be valid 400 years into the future. We know that if we think about sustainable society, then a number of basic conditions must be in place, setting our assumptions at known positions for a very long time (Diamond, 1997, 2005; Heinberg, 2005, 2011). We assume that society will be a civilized society under rule of law and democracy. If we put aside wishes for miracles to occur, then we must assume that what we know today will be known then, and that must be sufficient to solve the situation that may come up and the problematic issues that may occur (Diamond, 1997, 2005; Turner, 2012). Some of these issues we know all too well (global chemical pollution, climate change, land degradation), and we know that they have long delays.

7. Conclusions

We conclude concerning the aluminium supply, stocks in use and ore reserves as follows:

- Supply to the market will peak around year 2080 and decline after that, reaching 2014 level in about 2300. Recycling will peak around the year 2100 and decrease with the stock-in-society after that. Primary extraction from bauxite will peak in the next decade 2020–2030, unless extra effort is made to increase mining efforts. This will, however, require a higher market price for aluminium.
- After 2030, recycling or urban mining will be the major source of aluminium. This will be the age of scrap metal, and probably provide the basis for growing many new companies and enterprises.
- Bauxite reserves may potentially run out, but more than one century from now. The aluminium production from mining will reach a peak about year 2030 and decline begins after 2040, because of diminishing ore grades and increasing energy prices.
- Aluminium scarcity will manifest itself as increasing metal price, and supply limits may likely come from energy limitations and not only reserves running low. The increased price will change demand and considerations for what aluminium is used for. The global society will probably run out of money and energy before there is a real lack of bauxite to make aluminium (Aleklett, 2007).
- It does not seem possible to substitute a significant fraction of the iron supply with aluminium. Nor will it be possible to increase the global aluminium production very much more, without upsetting the global energy balance.

Very large bauxite or aluminium reserves are available, but they are not inexhaustible. It is doubtful that we have enough carbon-based energy available to exhaust the reserves, because the amount carbon needed for alumina reduction may be difficult to source. At a production of 250 million ton aluminium per year, the production would consume about 14% of the present total global energy production. That would amount to about 1600 million ton oil equivalents per year as electricity. The global energy production is to about 85% from fossil fuels, and by 2100 the energy production from fossil fuels may have declined to about half (Campbell, 2013). Then the energy consumption used to maintain an aluminium production at the present level will consume an ever increasing fraction of the total global energy. That would significantly upset global energy prices and transfer to the aluminium market price. Thus, we may run out of energy and money to buy it, long before we run out of aluminium metal.

Acknowledgements

This work started as part of the CONVERGE FP7-Environment research project funded by the European Commission (2009–2013). This work is now a part of the work done for the SIMRESS project, supported by the German Federal Ministry of the Environment (BMU), Berlin and the Federal Environmental Protection Agency (UBA), Dessau, Germany. Project officer at UBA is Dr. Ullrich Lorenz. Dr. Ashok Khosla and Dr. Ernst U. Weizsäcker at the UN-IRP and the Club of Rome are thanked for encouraging our work and emphasizing the importance of considering future material limits in policy development considerations.

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