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Prepare Russia to meet IPCC 2050, based on dynamic MFA approach for greenhouse gas emissions

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I hope that some of my scenarios would be useful for the aluminium production industry in Russia.

Uladzimir Volski

Trondheim, June 2012

ABSTRACT

An integrated MFA (Material Flow Analyse) model was developed for Russia, based on the year 2009. Integration was done between MFA, energy and greenhouse gas (GHG).

Technologies in all production related processes of aluminium cycle were analyzed. Energy consumption and emissions were calculated throughout the aluminium cycle. This technology information and calculations were used in my scenarios for possible reduction of emissions.

After the agreement with my supervisor the historical in-use stock was not done. Assumption here is that demand will increase.

A sensitivity analyze was not conducted due the fact that that type of analyze can not be used for large changes in the system.

If all scenarios are implemented then the decrease of total GHG emissions in aluminium production in Russia will equal to 22.3% and decrease in the total energy consumption will equal to 38,4%.

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1 INTRODUCTION

1.1 MATERIALS AND GLOBAL EMISSION

The world has serious problem with global climate change. According to the IPCC, the extent of climate change effects on individual regions can change over time. Increases in global from 1 to 3 degrees Celsius above 1990 levels can make serious change in different regions. Net annual costs will increase during time, as global temperatures increase. IPCC proved description of change in regions:

- North America: decreasing snowpack in mountains.
- Latin America: shifting of tropical forest by savannah, decreasing water availability for human consumption, agriculture.
- Europe: more frequent coastal flooding and increased erosion from storms and sea level rise, glacial retreat in mountainous areas, reductions of crop productivity in southern Europe.
- Africa: people are projected to be exposed to increased water stress, yields from rain-fed agriculture could be reduced by up to 50 present in some regions by 2020.
- Asia: Fresh water availability projected to decrease in Central, South, East and Southeast Asia by the 2050s, coastal areas will be at risk due to increased flooding, death rate from disease associated with floods and droughts expected to rise in some mountains regions (IPCC 2007)

The IPCC report recommends cutting in total annual global emissions of 50-80 % from 2000 levels by 2050 to stabilize the global mean temperature rise between 2.0 and 2.4 °C above present time. In 2006, the total carbon dioxide emissions were 28 giga tons of CO2 (GtCO2) (Allwood, Cullen, 2010).

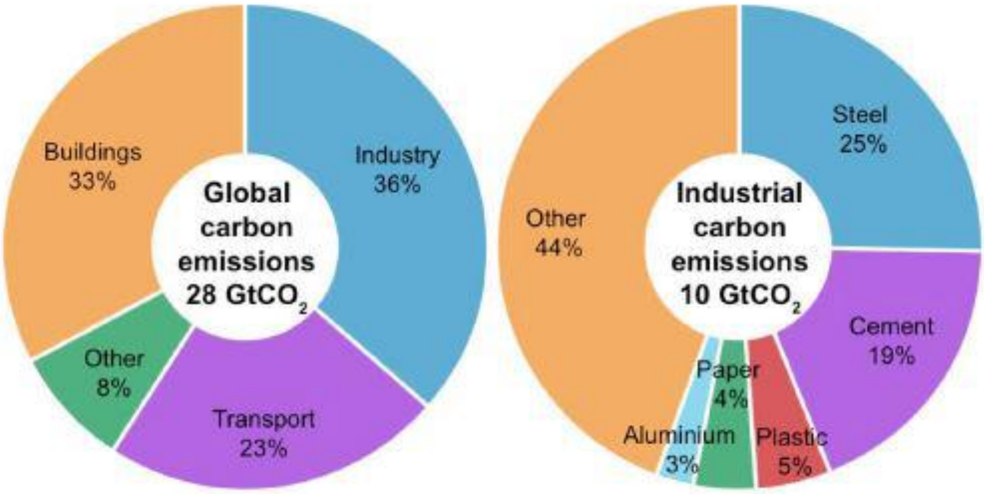


Figure 1-1- Global emissions of carbon dioxide by major sector and broken down within industry (Allwood, Cullen 2010)

Figure above shows present overage of different sectors. The largest contributing sector is industry that has 36% of total emissions in 2006. The amount of industrial carbon emissions is 10 giga tons of CO2 emissions globally and from this number aluminium has 3%. This is a small amount, but we should take into the account that amount will triple from 2006 to 2050. (Bernstein, Roy, 2007). The problem of reducing emissions is that the demand for materials is increasing. Significant growth in global consumption of materials related to the fact that there is a growth in global economy, which leads to an increase in consumption of materials for the construction of new houses, an increase of the transport system, etc. In this scenario, emission reductions must occur by reducing energy consumption, improving production technology of the material; manufacturing process must occur in one region. Increased demand for various materials is shown in the Figure from 1960 to 2050.

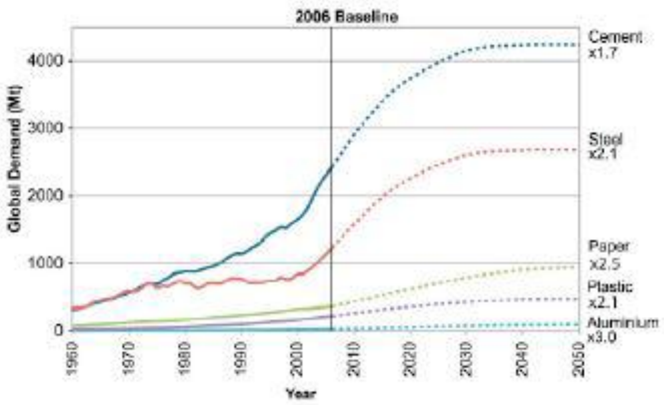


Figure 1-2- Demand for different materials from 1960 to 2050 (Allwood, Cullen, 2006)

Emissions are produced during the extraction/mining, production, manufacturing and use of the material. The life cycle is shown in Figure3.

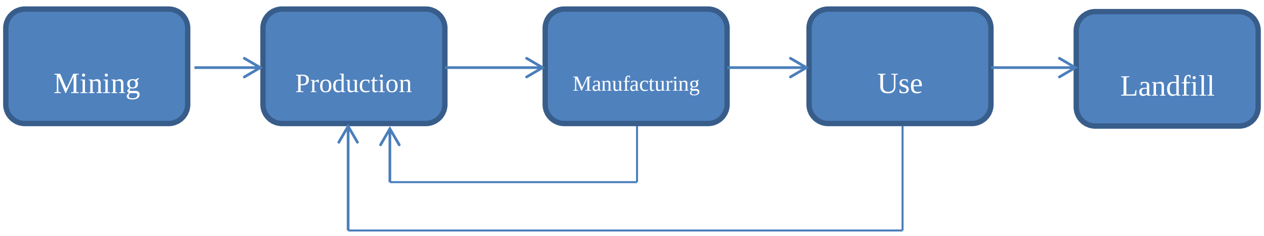


Figure 1-3- Life cycle of material

Emissions occur during the use of energy for each process in life cycle of material. The main source of emissions is electricity consumption, except for process “Use”. The product is made from various materials which are extracted from ore or recycled from used materials. Further use leads to either product become unusable and go to landfill or product is recycled. Production of material is a major source of emissions. Mining, Production, Manufacturing and Use processes are most important in addressing greenhouse gas emissions. Figure 3 is simple linear chain that is is more complex scheme in real life.

1.2 CONTEXT

In this paper I had a focus to use available literature. In some cases I could not find figures available for Russia, and then I used figures calculated for the globe, Europe or USA.

1.3 PROJECT AIM

Aluminium is one of the most versatile materials in our modern societies and the second-most used metal worldwide. While its primary production is very energy and greenhouse gas (GHG) emissions intensive, recycling can significantly reduce the consequent environmental impacts. Due to the fast penetration of aluminium in transportation, building, and packaging sectors, global aluminium consumption has doubled in the past two decades, and the future demand is anticipated to keep growing. The International Energy Agency estimated that global primary aluminium demand will triple in 2050. That would have enormous implications on GHG emissions, since IPCC suggested total global emissions to be cut 50%-80% by 2050.

Russia has second place of production of aluminium in the world (after China), and first place in export of aluminium. The formation process of the Russian industry, and in particular aluminium, after the reforms of the early 90-s is almost complete. Aluminum plants in Russia are currently under the control of the combined company RUSAL, which in 2007 was the world's largest producer of aluminium and alumina. Despite the cyclical recessions, in the long term, growth in world consumption will continue. That leads to increasing relevance for studies of the domestic aluminium industry and its environmental efficiency.

Motivation

- Russia's GDP will grow due increase of aluminium demand. Total GHG emissions will grow also. The problem of emission redaction to the atmosphere becomes urgent with the growth of aluminium production
- Primary aluminum production in Russia is collected in the world's largest giant factories. Only one of all existing aluminum plants in Russia was built after the 1990s. The absence of market

mechanisms for increase of electricity cost during the Soviet era, as well as low attention from the government to environmental issues, have led to use of old equipment in those giant factories. Aluminium production utilizes huge amounts of electricity. Rising costs of electricity for aluminium smelters affect the energy efficiency of aluminium production processes and drive equipment upgrades. Price increase of electricity should lead to the need of equipment modernization in aluminium plants in Russia. Equipment modernization can help to reduce energy consumption.

- Russia is big exporter of aluminium that leads to increase of domestic GHG emissions
- Russia has low recycling rate of aluminium from scrap and has a great potential to increase recycling rate.
- Due to the large emission from aluminium industry the better understanding of mitigation options for entire system is necessary.

Research questions

- How can we characterize contemporary aluminium cycle in Russia?
- What technologies are used for bauxite, alumina and aluminium production? What is energy average for those processes?
- What are direct and indirect emissions (associated with energy production, energy use, process emissions)?
- What are mitigation options (upgrade technology, increase recycling rate)?

Tasks

- System definition of aluminium cycle, including trade flows
- Analyze technologies in all production related processes of aluminium cycle (parameters of energy and emissions layers)
- Calculate energy consumption and emissions
- Make scenarios for possible reduction of emissions (technology, recycling %, trade)

1.4 REPORT OUTLINE

The paper is organized into four major parts. In Methodology chapter I described the theory behind material flow analysis and presented the definition of the global aluminium cycle. In System overview I enriched the global aluminium cycle with Russia specifics, integrated enriched cycle with energy and emissions, calculated and presented results for the model. Scenarios are another part, and together with discussion, they result into conclusion.

2 METHODOLOGY

Methodology chapter will provide en understanding for principles in analyses of global aluminium cycle. First, this chapter describes Material Flow Analysis (MFA) theory. Foundation of material flow analysis shows system definition of any material cycle. Afterwards, this theory is used more specific to present production. In our case it's global aluminium cycle. This cycle gives us general overview of processes and flows for aluminium. Sensitivity analysis shows how differences in flows have influence on system in general. And finally, I will discuss possibilities for reduction of greenhouse gas emissions.

2.1 MATERIAL FLOW ANALYSIS

2.1.1 FOUNDATION

Definition of Material Flow Analysis (MFA) is: "the systematic assessment of the flows and stocks of materials within a system defined in space and time." (Rechberger, 2004)

MFA is used to manage how materials are used and manufactured, to balance industrial input and output against natural ability of an ecosystem, to dematerialize industrial production, to create closed-cycle production practices, to organize models of energy use and emissions. MFA outline system of material flows and stocks, reduce the complexity of the system, while maintaining the basis for decision-making, evaluation of the flows and stocks by quantitatively check the mass balance, sensitivity and uncertainty. MFA present reproducible, clear, transparent results. Those results are used as a basis for resource management, environmental protection and waste, monitoring the accumulation or depletion, the future of environmental loads, development of environmentally beneficial products, processes and systems (Matthews, 2000)

MFA cycles describe the material flows over time. It is usually one year. Cycles also consider a specific geographic region. Cycles can be dedicated to the single production, as well for global overview. Each process in cycle must be balanced.

Simple diagram presents visual description of cycles in the figure below.

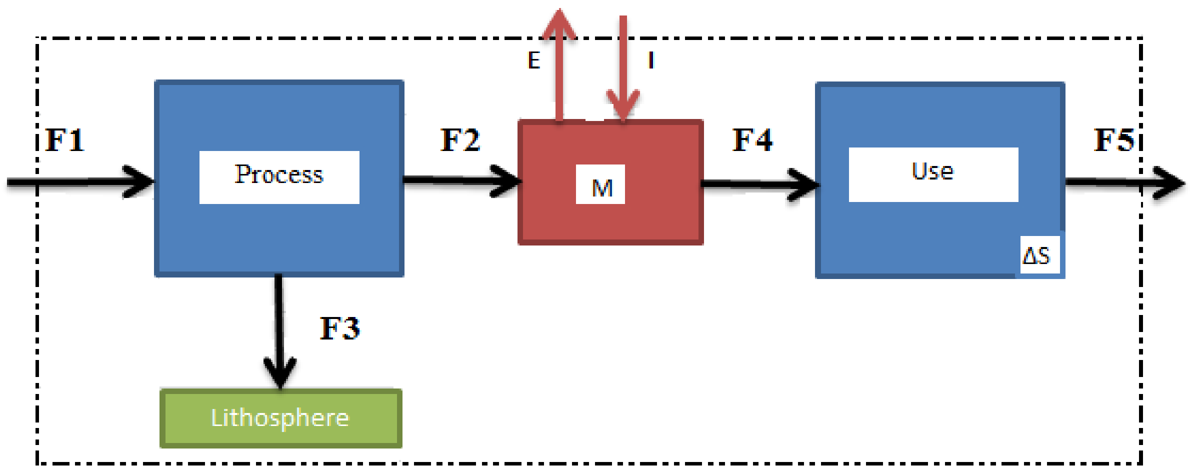


Figure 2-1- Material flow diagram that present processes (blue boxes), markets (red box), stocks (white box), lithosphere (green box), material flows (black arrows), trade (red arrows) and geographical system boundary. (Dahlström & Ekins, 2004)

Simple diagram table consists of:

- **Blue boxes** represent transformation processes of commodities and goods with balanced inputs and outputs of material flows.

- **Red box** represents market processes that include trade, domestic production and consumption.
- **White box** represents accumulated stock of products, providing services on the use of phase. Production processes increase the stock, while consumption processes decrease the stock.
- **Green box** is lithosphere that can be also presented as landfill.
- **Black arrows** represent domestic flows goods and products.
- **Red arrows** represent trade flows of goods and products, where I stands for import and E for export.

All processes must be balanced. That is, the sum of all incoming flows must be equal to the sum of all outgoing flows. If there is the stock of materials in the process, it must be also taken into the account, in order to achieve balance of process. This balance is represented by the following formula:

$$\Sigma I = \Delta S + \Sigma O \qquad \textbf{(Formula 2-1)}$$

Where:

I - inflow (t);

S - stock (t);

O - outflow (t);

Mass balance in the system is written only for the substance. If it is product, it must use coefficient that convert the product flows in the flow of the substance. Also, this coefficient can be used to calculate the unknown fluxes based on the known relationships between threads. For example, industry can use any metal ore for the production, this metal ore contains a portion of the pure metal. Material flow should consider only pure content without any impurities. Therefore the following formula should be used:

Me equivalent = M * K% **(Formula 2-2)**

Where:

Me $_{equivalent}$ – substance, that present all inflows (I) and outflows (O) (t);

M – total mass (t);

K - transfer coefficient that represent percent of substance in total mass;

Stock is calculated through input-output consideration with the mass balance principle over time and is represented in the following formula (Kristina Dahlström, March 2004):

$$\int_{t2}^{t1}(S)dt = \int_{t2}^{t1}(I - O)dt; \qquad \textbf{(Formula 2-3)}$$

Where:

t1, t2 – time period from the end of one year to the end of the next year and the flows are thus given as flow rates per year (year);

For the specific substance with already existing analysis, for example aluminium, formula shows interrelation between aluminium consumption per capita and gross domestic product per capita. 40 populous countries' aluminium was used for analysis. The formula is presented below (OECD, Materials Case Study 2: Aluminium, 2010):

$$Al/c = 29.41/\ (1 + e(-0.00021 * (GDP/c - 17000)) \qquad \text{(Formula 2-4)}$$

Where:

Al/c – aluminium consumption per capita (t/capita);

GDP/c - gross domestic product per capita (GDP/capita);

e - mathematical constant equal to 2.72;

If the aim is to find out amount of aluminium that should be produced for the given year in the given country, formula (4) is used, where GDP and population of this country must be from the same year.

Mass balance with the following formula is used for the transformation process:

$$F1 = F2 + F3 \qquad \text{(Formula 2-5)}$$

Where:

F1, F2 and F3 – flows of substance (t);

Formula (6) contains transfer coefficient that shows losses in the Process:

$$F3 = \alpha * F1 \qquad \text{(Formula 2-6)}$$

Where:

α – transfer coefficient that present loses in the process;

Market process contains import (I) and export (E) of product M from other countries. It is assumed that in this stage substance does not have any stocks during one year, all product goes for import or export to other countries.

$$F4 = F2 + I - E \qquad \text{(Formula 2-7)}$$

Where:

F4 – direct consumption (t);

In the process “USE”, substance is transformed into goods and products that human needs. Here we apply 2 methods: bottom-up and bottom-down.

In top-down approach, the system is broken down into sub-systems. Each sub-system is refined in details, until the entire specification is reduced to basic elements. Statistics of products and percent of substance those products contain are used in top-down approach.

In bottom-up approach systems are joined to give the rise for bigger system, thus make original systems into sub-systems of the emerged system. Historical consumption data is used for this method.

Outflow from process "USE" is calculated by formula (Prof. Dr. Daniel B. Mülle, Spring 2011):

$$F5t1 = \int_{t2}^{t1} L(t1, t1') * F4(t1')dt1' \qquad \text{(Formula 2-8)}$$

Where:

$L(t1, t1')$ - lifetime for products (year);

$$L(t1, t1') = \frac{1}{\sigma * \sqrt{2\pi}} * e^{\frac{t1 - t2 - \tau}{2\sigma^2}} \qquad \text{(Formula 2-9)}$$

Where

τ – average lifetime (year);

σ – standard deviation;

Energy use is divided into two types: primary and secondary. Primary energy is defined as direct use of the energy source or energy supply to users with no change. This energy is not subjected to any process of transformation or conversion. (Statistics, 1997)

Primary energy intensity from the literature is energy intensity of each process converted into input and output of this process. Primary energy use is calculated by multiplying mass flow and formula is:

$$ep = Ep * F \qquad \text{(Formula 2-10)}$$

Where:

e_p - primary energy use (MJ);

E_p - Primary energy intensity (MJ/t);

F- mass flow (t);

Secondary energy intensity is defined in the literature amount of energy that equals to production and transportation of one mega joule of energy necessarily for the process. Secondary energy requirement is the total energy for the process and calculated by formula:

$$es = Es * ep \qquad \text{(Formula 2-11)}$$

Where:

e_s – secondary energy requirement (MJ);

E_s - secondary energy intensity ($MJ/MJ_{delivered}$);

e_p - primary energy use (MJ)

Greenhouse gas (GHG) emissions are included in the system definition of material flow cycle. GHG are divided into primary, secondary and process emissions. Primary emissions rate is on-site global worming potential rate and is taken from source literature. Primary emissions are calculated by multiplying primary emissions intensity on primary energy use. Formula has view:

$$ip = Ip * ep \qquad \text{(Formula 2-12)}$$

Where

i_p - primary emissions (kg of common data elements (CDE));

I_p - primary emissions intensity (kg CDE/MJ);

e_p - primary energy use (MJ)

Value for secondary emissions rate, or off-site global warming potential rate, is taken from source literature. Secondary emissions are calculated by multiplying secondary emissions intensity on primary energy use. Formula has view:

$$is = Is * ep \qquad \text{(Formula 2-13)}$$

Where:

i_s - secondary emissions (kg CDE);

I_s - secondary emissions intensity (kg CDE/MJ);

e_p - primary energy use (MJ)

Process emissions are on-site non-fuel related GHG emissions for global warming potential. Process emissions rate is taken from source literature. Process emissions are calculating by multiplying process emissions intensity on mass flow:

$$p = P * F \qquad \text{(Formula 2-14)}$$

Where:

p – process emissions intensity (kg CDE/t of substance);

P – process emissions (kg CDE);

F – mass flow

In the future, it is necessary to determine the material, under investigation. This is to ensure a more careful consideration of three levels: mass flow, energy and pollution.

2.1.2 Curve Fitting

Curve fitting is the process of building curve, and is suitable for a series of data points that might be subject to restrictions. Curve fitting may include any interpolation, which fits to the required data, or smoothing, that roughly corresponds to the data. In the regression analysis, more attention is paid to the statistical inference, such as the uncertainty present in the curve. This analysis is suitable for data with random errors (I.D., 1993).

Curve fitting method is used in my study to analyze production processes of primary aluminium, to make historical analysis of technology improvements in energy use and to calculate future consumption of aluminium.

Many scientific publications have used curve fitting process for analyze. For example, Organization for Economic Co-operation and Development (OECD, Materials Case Study 2: Aluminium, 2010) shows dependence in consumption of aluminium per capita in different countries versus GDP per capita. This dependence calculated for different years and is shown in the table below:

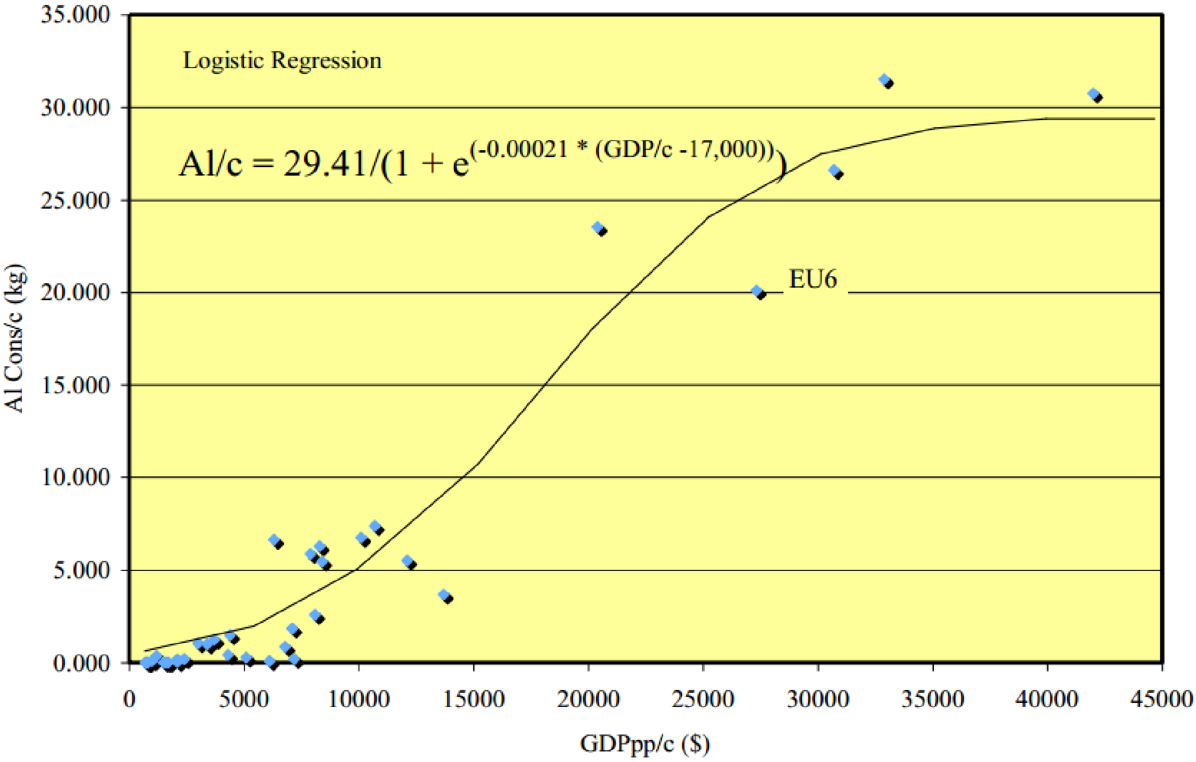


Figure 2-2 Aluminium consumption per capita versus GDP per capita (OECD, 2010)

In this chart, function curve fitting is used to show rate based on aluminium consumption per capita and GDP per capita. The figure provides an overview and allows finding out expected aluminium consumption for the country, provided that GDP is known.

2.1.3 Sensitivity Analysis

Sensitivity analysis is based on prediction of the system results using variables that affect the outcome of the system. Sensitivity analysis is a method of assessing the impact of individual parameters or combinations of several parameters on the simulation results. MFA uses this method to determine the most important parameters of the system of material flows. This is necessary in order to determine, what are the most important parameters, which influence change in the system. It is important to remember that this analysis can't be used for large changes in the parameters. Combination of parameters is necessary in order to see no-linear dependence of the material flows when parameters are changed.

My assumption is that small changes in parameters used in my paper are not significant. As I already mentioned, sensitivity analyze can not be used for large changes in the system. Sensitivity analyze is not done in this paper.

Lynette Cheah and etc. in his publication is using sensitivity analysis to present scenarios of future aluminium smelting energy requirements and the corresponding energy embodied in aluminium contained in vehicles (Lynette Cheah, 2009). Sensitivity analysis given in the paper describes the effectiveness of various changes, such as aluminium production and use in vehicles to reduce the projected energy demand (Figure 2-3). For this purpose, the sensitivity analysis is used to study the effect of various energy embodied in the following:

- efficiency improvements in primary aluminium processing;
- the extent of secondary/recycled aluminium use in vehicles;
- the extent of sheet aluminium parts use in vehicles;

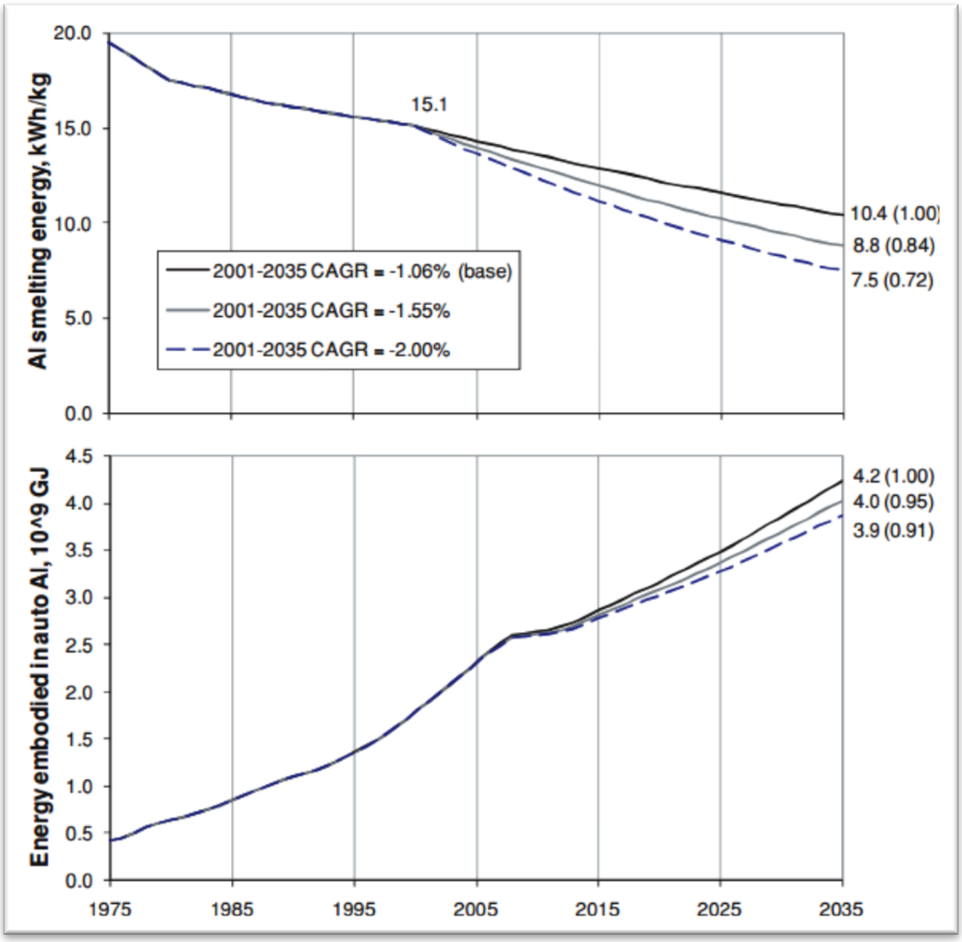


Figure 2-3 - Scenarios of future aluminium smelting energy requirements (top) and the corresponding energy embodied in aluminium contained in vehicles (bottom) (relative fraction of 2035 projection compared to base scenario in parentheses) (Lynette Cheah, 2009).

The results obtained on embodied energy are based on a baseline assumption that aluminium smelting energy requirements will decrease at a compounded rate of −1.06% per annum. At this rate of improvement, the smelting energy requirement would be expected to decrease from 15.1 kWh/kg aluminium in 2000 to 12.2 kWh/kg by 2020 and eventually reach 10.4 kWh/kg by 2035 (Lynette Cheah, 2009) The same analysis made for -1.55% and -2% per annum.

The analysis in this project was used to provide guidance on what parameters must be use and which have the biggest potential for system-wide impact of emissions and requires detailed study.

2.2 SYSTEM DEFINITION

2.2.1 Global Aluminium Cycle

Aluminium is the main element of a subgroup of the third group of the third period of the periodic table of chemical elements of Mendeleyev, with atomic number 13, denoted by Al (Lat. Aluminium). Aluminium refers to the group of light metals. Aluminium is the most common metal and the third most abundant chemical element in the earth's crust (after oxygen and silicon). Simple aluminium compounds can be characterized with lightweight, paramagnetic metal silver-white colour, easily amenable to melding, casting, and machining. Aluminium has high thermal and electrical conductivity, corrosion resistance due to the rapid formation of stable oxide film that protects the surface from further interaction. Aluminium metal is too reactive chemically to occur natively. Instead, it is found combined in over 270 different minerals (Services, May 2009). The percentage of aluminium content in the Earth's crust according to various researchers ranges from 7.45 to 8.14% by weight of the Earth's crust (N.V. Koronovski, 2004). In nature, aluminium due to the high chemical activity occurs almost exclusively in the form of compounds. Some of them are: Bauxite - Al2O3 · H2O, nephelines - KNa3 [AlSiO4] 4, alunite, aluminas (mixture of kaolin and sand), limestone, magnetite, corundum (sapphire, ruby, emery, feldspars, kaolinite, beryl (emerald, aquamarine), chrysobery. However, native aluminium makes formation in certain specific reducing conditions (Oleinikov B.V.. Okrugin A.V., 1984)

Aluminium has a lot of more exceptional properties, including:

- resistance to rust by coating the metal in the air to thin, solid, colorless oxide film;
- the ability to "pull" the oxygen from the oxides of other metals;
- high solubility in dilute mineral acids to form salts, but the absence of any interaction with organic and nitric acid;
- the ability to create on the surface a solid and a thick aluminium oxide film with concentrated nitric acid, so the metal does not react with acids;
- slight solubility of aluminium compounds in alkalis;
- high stability of the crystalline aluminium oxide - corundum - to acids and alkalis;
- high plasticity;

- capacity for machining - forging, rolling, stamping, polishing, pressing and drawing, and welding - gas, and other contact; resistance to the marine and fresh water .

The following can be made from aluminium and its compounds: electric cables, various elements of building structures, aluminium foil for food products and technological needs, kitchen utensils, paint "silver", aluminium tape for pipelines of oil and gasoline, aluminium alloy with copper and magnesium (duralumin) is used for the production of aircraft and automobile parts, frost- and heat-resistant high-strength aluminium alloys are used for a variety of protective and decorative coatings, packaging materials, aluminium tape for blinds and ceiling construction, cans, flammable and explosive mixtures, ammonal, pyrotechnic compositions, powder with the oxides of metals for welding of rails, use incendiary munitions, rocket fuel, raw materials for ceramics, laser materials, synthetic rubies, adsorbent for the purification of gases and liquids, catalyst for certain organic reactions, water purifiers, mordant for dyeing fabrics, leather tanning, paper sizing, wood preservation, catalyst for the synthesis of polymers and rubber and much more (MFRM, 2007).

Aluminium products, including tape and aluminium, have one distinct advantage over products of a similar nature and purpose. It has a low cost with high performance characteristics such as:

- good performance in all climates, under different temperature drops;
- durability;
- resistance to corrosion;
- ease;
- strength;
- visual appeal;
- acoustic and thermal insulation;
- ability to stain;
- plasticity, the ability to easily take any form (MFRM, 2007).

Aluminium can be a part of the solution for a Sustainable Future. Aluminium is a unique metal that is strong, durable, flexible, impermeable and light-weight; it does not rust and is 100 percent recyclable. It comes in a variety of surface finishes and can take many forms, allowing its use in a vast array of products (IAI, Story of Aluminium, 2011).

Global aluminium cycle has 5 main stages: primary production of aluminium, semi-manufacturing, manufacturing, use, recycling and waste management (Table 2-1). Primary production of aluminium has several consecutive stages. First one is bauxite mining, where ore is extracted from lithosphere. Next stage is refining, where alumna is extracted from ore by use of Bayer process. Ingot is a product of smelting process (Hall–Héroult process) of aluminium scrap from refining and remitting. All of those primary production stages have losses in the form of mining residue, red mud, spent potline and dross, that primary has aluminium from ingot casting process. Aluminium ingot is produced from the primary route (ore) and from secondary route (scrap).Semi-manufacturing, manufacturing; use and waste management processes are enlarged in the figure below to demonstrate that they are broken down in several models of parallel processes/stages.

Table 2-1 System definition of aluminium mass flow cycle

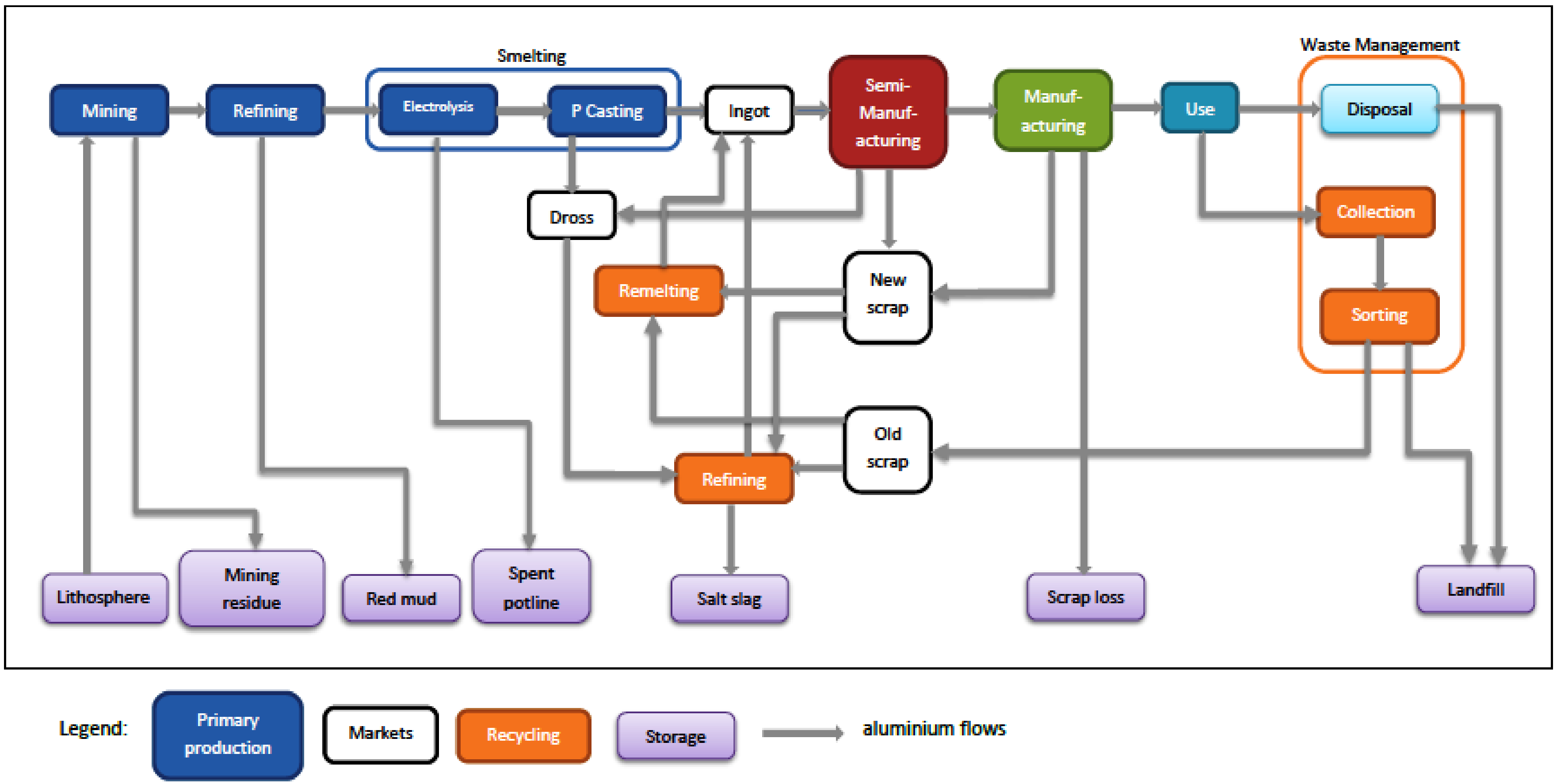


Table - System definition for the aluminium mass flow cycle

2.2.2 Primary production of aluminium

Materials flows presented below in the table cover the primary production of aluminium, including bauxite mining (open pit), alumina production (Bayer process), electrolytic smelting (Hall-Heroult process) and the production of secondary aluminium. Materials flow data used in my report, are from the year 2008. The Russian model was developed for various process stages in aluminium production from bauxite. The main starting point of cycle is aluminium ore bauxite, which holds 26% of raw aluminium. Ingot holds 99%, or 7% of raw aluminium. Smelting is the most energy consuming stage in primary production of aluminium. This energy is used in electrolysis. Smelting process has additional 2 stages: electrolysis and primary ingot casting processes.

Greenhouse gases are a major pollutant from aluminum production. Those gases are result of fossil fuel combustion, carbon anode consumption and perfluorocarbons from anode effects. In addition to greenhouse gases, aluminum smelters also discharge other atmospheric emissions, as well as some solid wastes (spent potline) and liquid effluents.

Process	**Air emissions**	**Effluents**	**By-products and solid wastes**
Alumina refining	Particulate	Waste water containing starch, sand, and caustic	Red mud, sodium oxalate
Anode production	Particulates, fluorides, polycyclic aromatic hydrocarbons, SO_2, PCDD/PCDF	Waste water containing suspended solids, fluorides, and organics	Carbon dust, tar, refractory waste
Aluminium smelting	CO, CO_2, SO_2, fluorides (gaseous and particulate), perfluorocarbons (CF_4, C_2F_6), polycyclic aromatic hydrocarbons, PCDD/PCDF	Wet air pollution control effluents (wet electrostatic precipitator)	Spent potliners, wet air pollution control wastes, sludges

Table 2-2 Air Emissions and Effluents in the aluminium processes

Based on the Krasnoyarsk study (Kucherenko et al. 2001)

There are two main greenhouse gases produced during the primary production of aluminium. Carbon dioxide (CO2) is a product of electrolytic reaction and perfluorocarbons (PFCs) is a product of brief process upset periods known as anode effects. (The Aluminium sector Greenhouse Gas Protocol, 2006)

2.2.2.1 Bauxite mining

Over 90% of the world's total bauxite reserves are concentrated in 18 countries with tropical or subtropical climates. It is no coincidence, since the best bauxite deposits are confined to the so-called lateritic Coram, formed as a result of prolonged weathering of aluminosilicate rocks in the hot humid climate. About nine tenths of the world's bauxite (in kilos) is in the laterite deposits. The largest total reserves have Guinea (20 billion tons), Australia (7 billion tons), Brazil (6 billion tons), Vietnam (3 billion tons), India (2.5 billion tones) and Indonesia (2 billion tons). Russia does not have sufficient reserves for domestic consumption of bauxite, and has less than 1% of the world reserves. North Ural district does hove most of the high quality bauxite in Russia. There are some bauxite deposits in Boksitogorsky district of Leningrad region. The most promising deposits of bauxite is the Middle Timan group of fields in the north-west of the Republic of Komi (Board, 2006) Russia compensates the lack of bauxite with nepheline ore.

Primary production of aluminium starts with extraction of bauxite ore. The aluminium industry consumes near 90% of mined bauxite, the rest is used in abrasives, cement, ceramics, chemical, metallurgical flux, refractories, and other products (Bray, 2010b). There are three main types of bauxite:

- Trihydrate that mainly consists of gibbsite, Al2O3 • 3H2O
- Monohydrate, that mostly consists of boehmite, Al2O3 • H2O
- Mixed bauxite, which is composed of gibbsite and boehmite (OECD, 2010).

Bauxite ore contains from 31 to 52 percent of Alumina. The middle average is about 41% (IAI, 2009b). My study examines the flow of metallurgical grade bauxite ore used to produce aluminium. That type of ore contains from 50 to 55% of Al2O3 (OECD, 2010).

2.2.2.2 *Bauxite mining*

The vast majority of the bauxite ore in the world is extracted by open cut methods. Before mining start, it is necessary to remove topsoil. That helps to topsoil preservation and subsequent rehabilitation of mines. Bauxite ore bodies range from 2 to 20 meters in thickness (IAI, 2009b).

Table 2-3, shows the flow for bauxite mining process. This figure is based on a description of bauxite mining at the Alcoa-owned Juruti Mine in Brazil

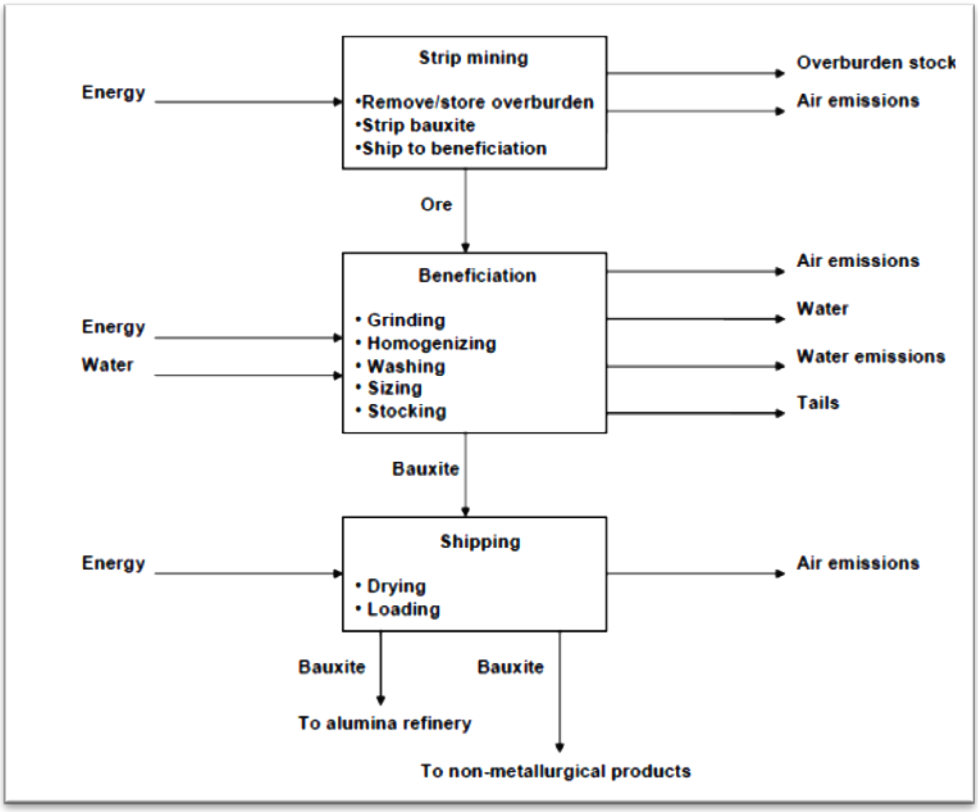


Table 2-3 – Material flow of bauxite mining (OECD, 2010)

From this table we see that use of energy in bauxite mining has consequences in form of air emissions, water emissions and tails. But according to International Aluminium Institute, bauxite mining has only 0,2% of greenhouse gases emissions from primary production of aluminium. (IAI, 2009b)

The greatest difference between pre- and post-mining land use is a trade of farming (11 to 20 percent) for native forest (49 to 60 percent) (IAI, 2009b).

2.2.2.3 Nepheline mining

After World War II Russia has become world leader in use of nepheline . For the first time the method of complex processing of nepheline (nepheline concentrate) was made in 1949 at aluminium factory Volkhov. Russia and other countries, that do not have reliable reserves of bauxite, become very interested in this technology. Outside the Russia, Iran is another country that had built its first plant pilot (one thousand tons of alumina per day) with the help of VAMI (Russia) to learn the process (Azarshahr pilot plant).

Nepheline ores ($(Na,K)AlSiO_4$) are used as the primary aluminium in Russia. Kia-developed Shaltyrskoe mine in the Kemerovo region and deposits Kukisvumchor, Yukspor, Rasvumchor on the Kola Peninsula are the main regions. The total reserves of nepheline ores in Russia is about 7 billion tons of proven and 5 million tons in the current economic exploitation. The profitability of those developments is in question (Board, 2006).

In addition to bauxite I also study the flow of nepheline ore used to produce aluminium.

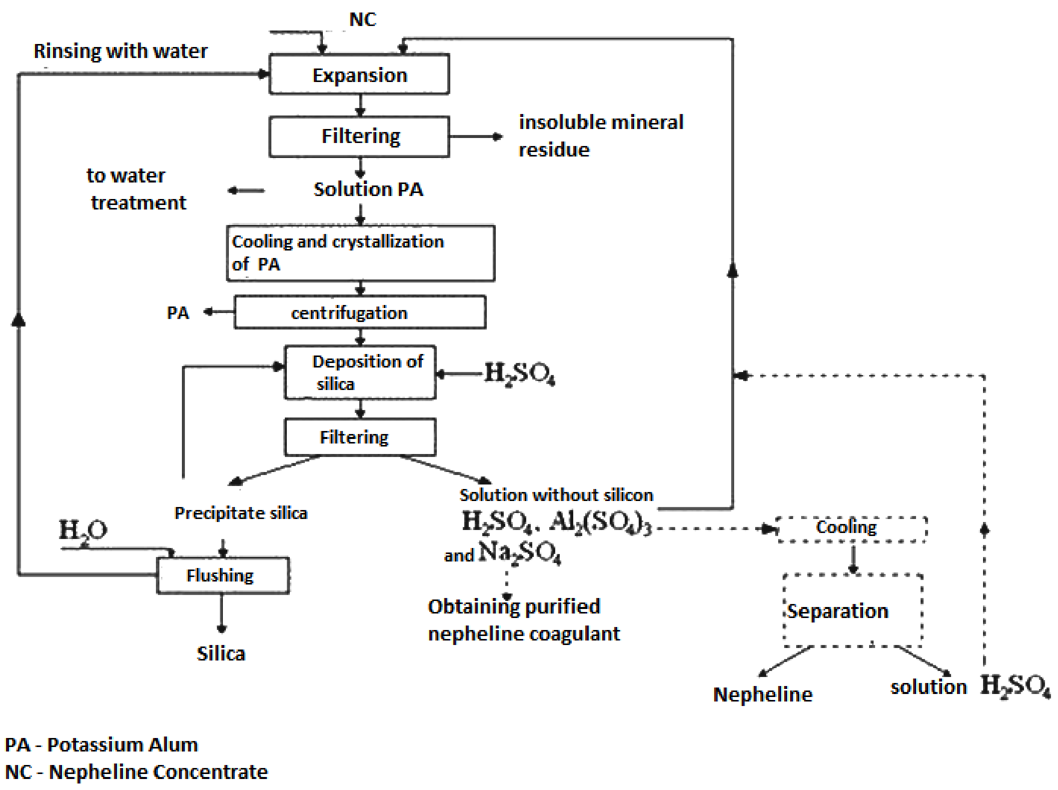


Figure 2-4 - Flow chart of process for production of nepheline, nepheline coagulant alum and silica (Velyaev, 2012)

Nepheline has more than 20% of Al2O3, Na_2O and K_2O, less than 10% SiO_2. Less than 55% nepheline can be processed in production of alumina, cement and other chemical products. These production methods remove the nepheline syenite from the apatite tailings. First nepheline syenite is calcined with limestone, and the product is a mixture of $CaSiO_3$ and Na_2O*Al2O_3. Than leaching by caustic soda and treatment with CO2 results in alumina and by-products.

The content of substances in the nepheline ore are presented in the table below.

SiO2	TiO2	**Al2O3**	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O	H2O	P2O5
54.99	0.6	**20.96**	2.25	2.05	0.15	0.77	2.31	8.23	5.58	1.47	0.13

Table 2-4 Substances in the nepheline ore in % (Barker, 1983)

Comparison of bauxite and nepheline ores shows that the percentage content of alumina is 2 times higher in bauxite ores than in nepheline. Therefore, nepheline process has a much higher cost than the Bayer process for bauxite, and becomes economically justifiable only when all the by-products can be sold. Russia is using nepheline ores in production due to the fact that there is a shortage of raw materials for production of alumina.

2.2.2.4 Alumina refining

Four different processes are identified in the current production of alumina: the Bayer process, the Cinter process, Bayer-Sinter (combined) process and the Nepheline-based process (Zheng Luo, 2007). In this chapter I described only two processes, the Bayer process and the Nepheline-based process. This is due the following:

- The Bayer process is the most widely used form of alumina extraction. Most of the world's bauxite production (approximately 85%) is used as feedstock for the production of alumina by the wet chemical method of caustic leach process known as Bayer (USGS, 2011);
- High energy consumption has been the drawback of the Sinter process, which requires 30-40 GJ/tones alumina in comparison to 11GJ/tone for the Bayer process (Zheng Luo, 2007);
- Bayer-Sinter process consumes from 34.15 to 52.17 GJ/tone for production of alumina that makes this method even more power-consuming than the Sinter process (Smith, 2008).
- Lower alumina content of nepheline ore, requires the handling of a greater volume of material (4.8 tones to one tone of alumina) in the Nepheline-based process. But production of alumina from nepheline ore exists and wildly used in Russia (Zheng Luo, 2007). Russia is the main country of my study.

The Bayer process is presented in the following figure:

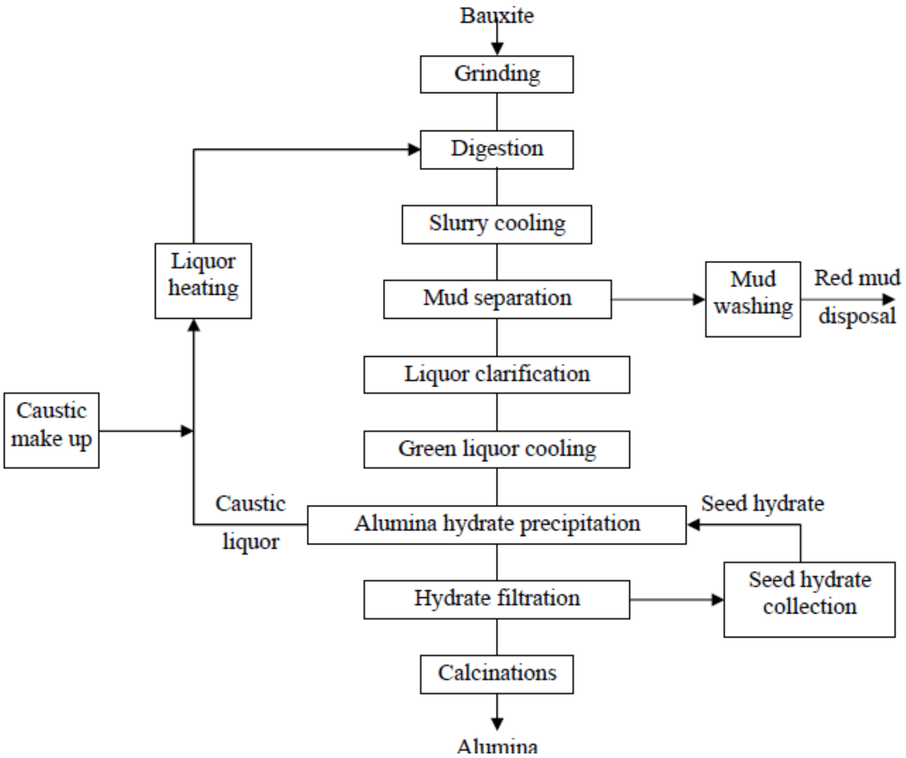


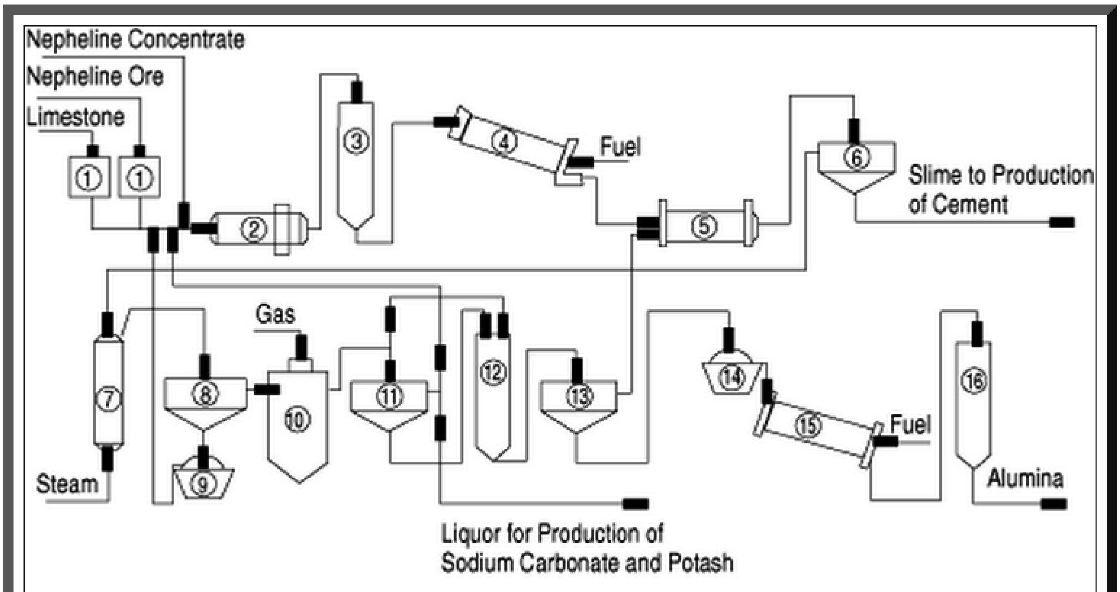
Figure 2-5 – Visualization of the Bayer process (Zheng Luo, 2007)

In the Bayer process, bauxite is worked out by washing with a hot solution of sodium hydroxide. This converts the aluminium oxide in the ore to sodium aluminate. The other components of bauxite do not dissolve. The solution is clarified by filtering off the solid impurities. The mixture of solid impurities is called red mud, and presents a disposal problem. After that, the alkaline solution is cooled, and aluminium hydroxide precipitates as a white, fluffy solid (Harris D. C., 1998).

In the Bayer process bauxite is refined to produce alumina. Bauxite contains 30–54% aluminium oxide (Al_2O_3), the rest is a mixture of silica, various iron oxides, and titanium dioxide (Harris, McLachlan, & Clark, 1998).

In total other alumina production processes stands for only 17% of the world's alumina, and most of them is used in China and Russia.

Process framework for alumina production in Russia by nepheline ore is shown in the figure below.



The flowsheet for alumina production from nepheline ore. 1—crushing; 2—wet grinding; 3—correction of pulp; 4—sintering; 5—leaching; 6—thickening and washng; 7—desilication of liquor; 8—thickening of white mud; 9—filtration of white mud; 10—carbonization of liquor; 11—thickening of seed; 12—precipitation; 13—thickening; 14—filtration; 15—calcination; 16—silo for alumina.

Figure 2-6 – Visualization of the Nepheline-based process at Volkhov aluminium smelter in Russia (Smirnov, 1996)

Concentrate used in production contains 27-28% Al2O3, 44% SiO2, and approximately 20% R2O (Na2O + K2O). Russian scientists improved technology for treatment of the nepheline concentrates by sintering concentrate with limestone. The method enabled complete re-use for production of by-products like cement, soda, potash, and alumina.

The high temperature reaction of sintering requires a significant amount of fuel. This is the main course for why Nepheline-based process significantly contributes to greenhouse gas emissions in the aluminium cycle. The number is about 11% of the total emissions in the cycle (IAI, 2009)

2.2.2.5 Electrolysis

Alumina is purified to the liquid metal aluminium through a process of electrolysis, the so-called Hall-Héroult process. Typical Hall-Héroult cell is presented in the figure below:

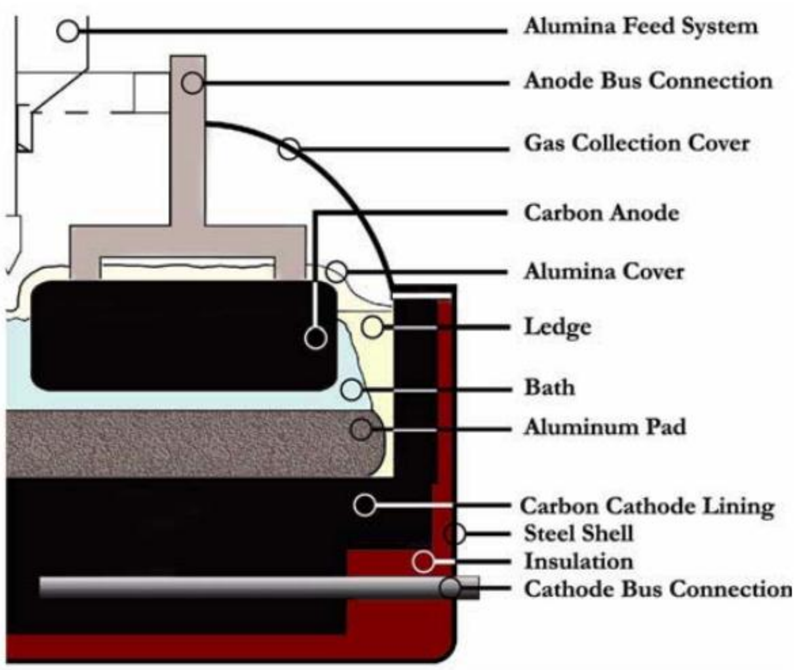


Figure 2-7– Visualization of the Hall-Héroult aluminium electrolytic cell (U.S., 2007)

In the Hall-Héroult process alumina is dissolved in molten cryolite bath at a temperature of 960^{o} C is electrolyzed. The cells are connected in series so electrical current can pass through a bath from a carbon anode to the cathode. Alumina is in the molten bath. When alumina concentration in the electrolyte bath is too low, the bath itself would start the electrolytic reaction with the carbon in the anode, the so-called anode effect. This effect generates two types of PFC gases: CF4 and C2F6. Liquid aluminium is collected at the cathode in the bottom of the cell and oxygen reaction with carbon anode results in carbon dioxide. The carbon anodes are therefore continuously consumed during the process. The molten aluminium is periodically withdrawn from the cells into crucibles by vacuum siphon. The crucibles are transported to the casting plant and the aluminium is emptied into heated holding furnaces. Alloying additives are added into these furnaces under controlled temperature. Various aluminium technologies differ in the type of used anode, method by which the pot is worked or the anode is introduced into the cell (Zheng Luo, 2007). The main technologies are Prebake and Soderberg.

In the Prebake, cells have several pots of anodes that are formed and baked prior to consumption in the pots. Technology has two options: Centre Worked Prebake (CWPB) and Side Worked Prebake (SWPB). These options depend on how alumina is introduced into the cell, where the pot work takes place. In CWPB cells, alumina goes into center of the cell by longitude. While in the SWPB, alumina is added along the longitudinal sides of the cell. Prebake version is defined as the Point of the Feed Prebake (PFPB, see Figure 2-8) and represents the state of technology in primary production. Compared with CWPB, PFPB is a better way of alumina supply into the cell, provides more precise control for alumina concentration in the bath, and produces less precipitation and easier in temperature stabilization. These advantages give higher current, low power consumption and low emissions. All new plants use the PFPB.

Baked anodes are made in a separate anode plant, from a mixture of calcined petroleum coke and coal tar pitch. These anode plants are often an integral part of the aluminium production plant (Zheng Luo, 2007).

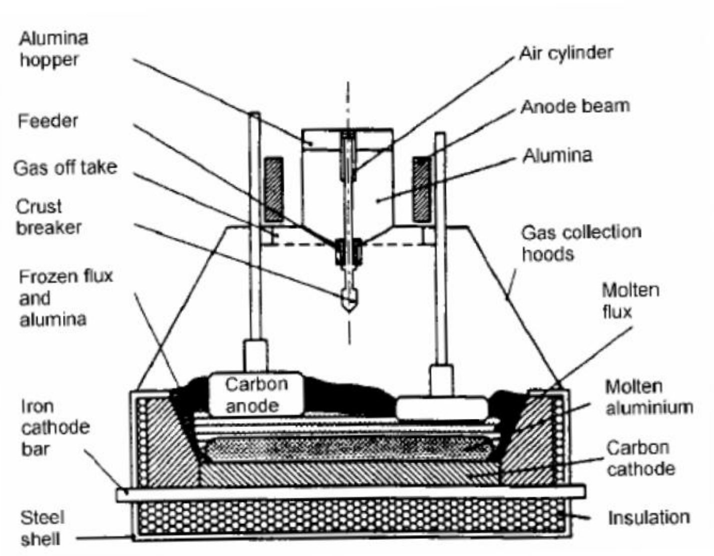


Figure 2-8 – Visualization of Prebake cell (Zheng Luo, 2007)

Soderberg cells use a single, monolithic carbon anode, which is added to the paste and baked in the cell itself through the heat emanating from the molten bath. There are two variants of Soderberg technology: Vertical Stud Soderberg (VSS) and Horizontal Stud Soderberg (HSS). Variation is in whether electricity is introduced into a cell. In VSS cells, electrical connectors or pins are arranged vertically at the top of the anode, but in the HSS cell, it is in the horizontal plate along the longitudinal length on both sides of the cell. Soderberg cells were popular from 1940 to 1960 period and generally are less effective than the burned cells in way of capturing and collecting fluorine and hydrocarbons produced in the process. With this technology it is more expensive to comply with environmental and health regulations. This is the main reason why Soderberg technology was gradually replaced by Prebake technology.

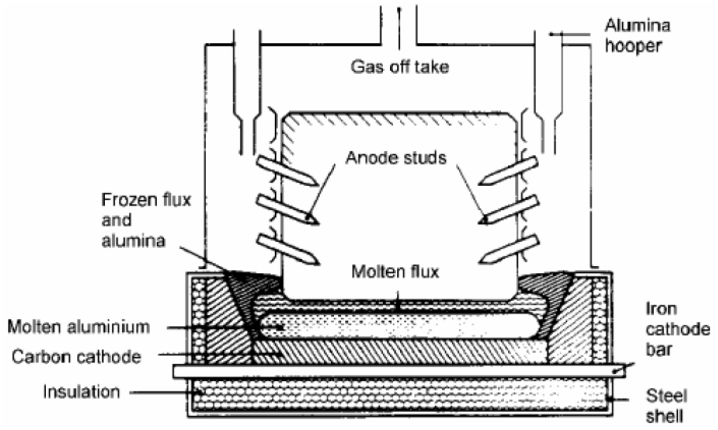


Figure 2-9 – Visualization of Soderberg cell (Zheng Luo, 2007)

Ecological analyze of various types of smelting technologies is presented in Table 2-5, where PFPB is Centre Worked Prebake with a Point Feed System; CWPB is Centre Worked Prebake with a Bar Break Feed System; SWPB is Side Worked Prebake; HSS is Horizontal Stud Soderberg; VSS is Vertical Stud Soderberg.

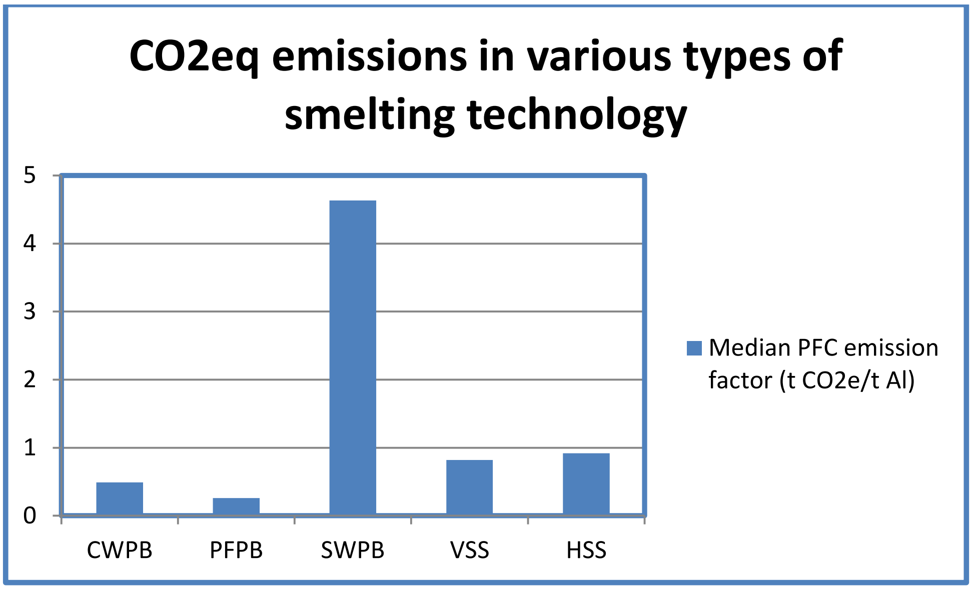


Table 2-5 - Perfluorocarbon emission results (IAI, 2010)

The IAI has employed this methodology, of using median PFC emissions performance (as CO2e) per technology. This is the basis for calculation of the global PFC emissions inventory from aluminium production.

The IPCC report recommends cutting annual global emissions by 2050 in total of 50-85 % of2000 levels. GHG emissions from electricity production for electrolysis account for 55% of total cycle emissions (IAI, 2009). For primary aluminium production it is necessary to do a shift from smelting technology to PFPB.

IAI made a presentation of aluminium smelting technology categories from 1990 to 2009. A shift in technology types has had an impact on PFC emissions, with modern and low PFC-emitting Point Fed Prebake (PFPB) technology now dominating the global technology mix. PFPB have had relative increase in production share from 32% in 1990 to 83% in 2009 (IAI, 2010). Future scenario for technologies use in primary production of aluminium is done until 2030 (Zheng Luo, 2007). By compare these two figures below it is possible to make analyze of technology mix until 2050.

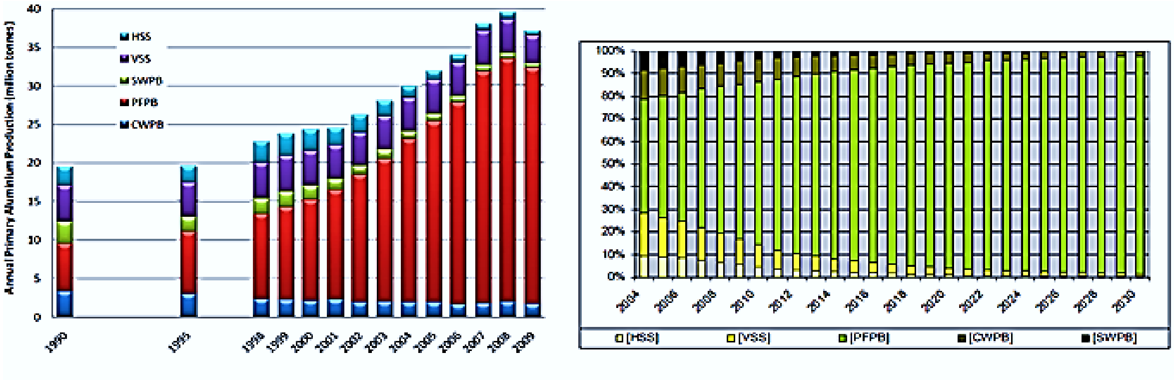


Figure 2-10- Share of technology (IAI, 2010 and Zheng Luo, 2007)

Analyze from the figure above shows that by 2030 more than 95% of aluminium smelting will be done using PFPB technology. Today there are a number of research initiatives within production of primary aluminium. One of the most important aims is to reduce energy consumption and emissions (Commission, 2001). These initiatives include:

• Inert anodes. Carbon free anodes is dimensionally stable, they are slowly consumed, and release oxygen, not CO2. The use of inert anodes eliminates the need for a carbon anode plant (and the emissions of polycyclic aromatic hydrocarbons from the process).

• Wetted cathodes. It is a new cathode materials or coatings instead of existing cathode materials. Wetted cathodes enable energy efficiency.

• Vertical electrodes. These electrodes allow for low-temperature electrolysis. This process involves a consumable metal alloy anode, a cathode of the electrolytic bath and hydrated, which is kept saturated with alumina at relatively low temperature of 750 ° C with the help of free alumina particles suspended in the bath. This technology can produce primary aluminium metal with lower power consumption, lower cost and reduced environmental degradation than conventional Hall-Héroult.

• Dry Cell Technology. This technology is characterized by used of coating aluminium cathode cell with titanium dibromide and removal of the metal pad, that reduces the distance between the anode and the cathode. By distance reduction, the required voltage of cells and heat loss are also reduces.

• Carbothermic technology. Technology looks at aluminum production through a chemical reaction that occurs inside the reactor. That requires much less physical space than the Hall-Héroult reaction. This process will significantly reduce energy consumption and the elimination of PFC emissions from carbon anode effects, hazardous spent pot liners, and hydrocarbon emissions associated with the baking supplies carbon anodes.

Inert anodes in combination with wetted cathode and compared to the traditional Hall-Héroult cells, are expected to provide the following:

- 10 percent reduction in operational costs (elimination of carbon anode plant and labor costs associated with replacing anodes)
- 5 percent increase in cell productivity
- 41 percent reduction in greenhouse gas emissions (USDOE, 2007)

The environmental benefit of wetted cathode technology is related to the emissions associated with the electricity production. The electricity production (14.4 kWh/kg of aluminium) for a modern Hall-Héroult cell emits 5.04 kg of carbon dioxide equivalents (CDE) for each kilogram of aluminium produced. A wetted-sloped cathode cell with a 2.0 cm ACD will lower the CDE emission associated with electricity generation and transmission by nearly 21 percent to 3.98 kg CDE/kg of aluminium produced (USDOE, 2007).

Two innovative technological changes the Hall-Héroult are soaked drained cathode and an inert anode. They are located on the near horizon for energy efficiency. These technologies can modify the existing series of electrolysis and supporting infrastructure. A wetted cathode is expected to lower the energy consumption of the Hall-Héroult cells by 18 percent compared with the modern Hall-Héroult cells. This report defines the current cell as one that operates at 4.6 V and 95 percent from the current distribution voltage. The combination of an inert anode with a wetted cathode could provide a 22-percent reduction in energy consumption and eliminate cells emissions of CO2 (USDOE, 2007).

The theoretical minimum energy consumption in carbothermic reduction of alumina is 7.32 kWh/kg. Compared to the 14.4 kWh/kg from a modern Hall-Héroult Cell this represents a 37 percent reduction in energy use.

The theoretical minimum energy consumption in aluminium production from kaolinite is 5.76 kWh/kg and is 8 percent lower than CDE emissions than Hall-Héroult facilities (USDOE, 2007).

Sum of anode energy consumption and anode emissions effect gives 17% of total industry GHG emissions (IAI, 2009)

2.2.2.6 Primary Ingot Casting

This process starts with the unload of materials in a storage place. Operations associated with this ingot proses include:

- pre-treatment of hot metal (cleaning and auxiliary heating);
- scrap recovery and processing of internal processes;
- dosing, metal processing and casting operations;
- homogenization, cutting and packaging operations;
- maintenance and repair of machinery and equipment;
- treatment of process air, liquids and solids.

The primary ingot molten metal is syphoned from the pots and is sent to a resident of the complex castings, which is found in every smelter. In some cases, due to the proximity of the molten, metal is transported directly into the form of casting foundry. The molten metal is transferred to the mixer and brought to the specific composition of the alloy. In some cases, depending on application and composition of the bath in pots, some impurities can be removed.

When the alloying is complete, the melt is fluxed to remove impurities and reduce gas content. The fluxing consists of a combination of slow bubbling of nitrogen and chlorine, and carbon monoxide, argon and chlorine through the metal. Flux can also be accomplished with the built-in drainage, which performs some functions of specialized unit decontamination.

Fluxing removes trapped gases and inorganic particles by floatation on the metal surface. This dross (impurity) is skimmed off. The skimming process also takes some aluminium together with dross, and as a rule, the further processing for this mass is to recover the aluminium content and to make products used in the abrasives industry, and insulation.

Depending on the application, the metal is handled through the built-in filter for removal of oxides that may have formed. Then this metal is thrown into ingots by different methods: the open molds, through direct chill molds for various production forms, electromagnetic molds for some sheet ingot, and through continuous casters of aluminium coils (AAS, 2000).

Ingot casting stands for 1% of the aluminium industry GHG emissions (IAI, 2009).Semi-Manufacturing

Semi-manufacturing industry produce a wide range of products from 0.005-mm thin foil to the massive blocks of the motor vehicle. Aluminium is delivered to the manufacturing industry in nine main categories of shapes:

- Sheet rolling. Thickness comprised between 0.2 and 6 mm, sheet is the most common aluminium rolled product.

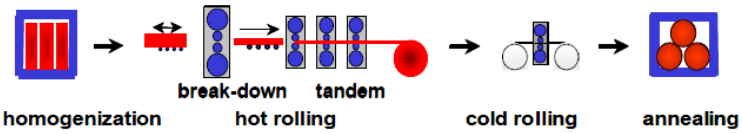


Figure 2-11 - Main process steps in aluminium sheet production (EAA, 2008)

As it is illustrated in the Figure 2-11 - Main process steps in aluminium sheet production, ingot is preheated to about 500 ° C for successive pass through a hot rolling mill. Here ingot is reduced to a thickness of about 4 - 6 mm. The band of the hot rolling mill continues to cold rolling mill, that is usually stands in the same place. The final thickness of cold rolled sheet is ranging from 0.2 to 2 mm. The sheet production from sawn ingot up to finished sheet generates about 380 kg of scrap for each ton of sheet. This scrap is recycled into new ingot through remelting which is usually performed on-site in integrated cast houses (EAA, 2008).

- Foil rolling. Aluminium foil is used in a variety of sensors, and in some alloys for various applications. It is available in thicknesses from 5 microns to 200 microns. The foil production from as-cast ingot up to finished sheet generates about 600 kg of scrap by ton of foil. These scrap are recycled into new ingot through remelting (EAA, 2008).
- Shape castings. Shape casting or the casting of engineered designs enables the production of simple and complex parts that meet a wide variety of needs. The process produces parts weighing ounces to parts weighing several tons. Figure 2-12 – Typical aluminium product shape casting operations shows operations of a typical aluminium shape casting foundry (U.S., 2007).

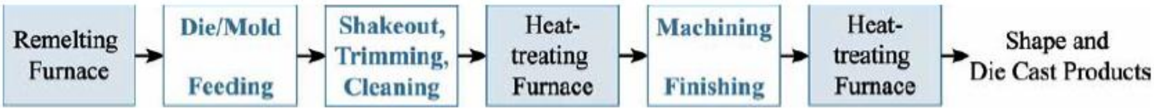


Figure 2-12 – Typical aluminium product shape casting operations (U.S., 2007)

Shape casting has typical yield of only 45 percent and requires about 2.56 kWh/kg of cast product.

- Wire drawing. This process is simple in concept. The wire is prepared at the beginning of its decline, strikes, filing, rolling or pressing, so that it will pass through the matrix, then pulled the wire through the mouthpiece. As the wire is pulled through the crystal, its volume remains the same as the diameter decreases, the length increases.

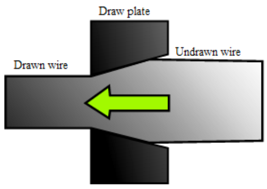


Figure 2-13 – Wire drawing concept (Degarmo, 2003)

- Can production. Production of aluminium beverage cans begins with conversion of ingots in the canned and cover stock coil, which can then be transformed into bodies and cover the jar factory. In the hot rolling of aluminium, ingots are preheated and fed through a hot reversing mill. In reversing mill, coil passes back and forth between the rollers and the thickness is reduced from the original thickness with a corresponding increase in length. After the return, plates are served on a continuous hot rolling mill, where the thickness is further reduced. Loss, in the form of aluminium scrap, is 299.7 kg 1000 kg of final product production and energy consumption are 4102 MJ (Americas, 2010).
- Extrusion. The starting material for the production of extruded aluminium is extrusion ingot that is a few meters long cylinder with a diameter range typically from 20 to 50 cm. The ends (top and tails), blanks, usually cut to bring the house into a direct smelting. Before the extrusion, billet usually is preheated to around 450 ° C - 500 ° C. At these temperatures the flow stress of aluminium alloys is very low and by applying pressure with the ram at one end, a piece of metal passes through the steel die, located at the other end of the container for the production of profiles, cross-sectional shape of which is determined by the shape of the die.

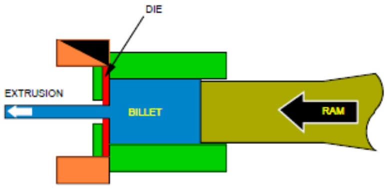


Figure 2-14 - Extrusion process principle (EAA, 2008)

The extrusion from cast billet up to finished profile generates about 320 kg of scrap by tone of extrusion. These scrap are recycled into new ingot through re-melting (EAA, 2008).

- Powder and paste. Aluminium powder is produced by use of pure molten metal, aluminium, compressed gas stream and turning it into fine droplets, which are then consolidated and collected. These powders are estimated based on the size, composition and application. The range of particle sizes of the product are made so you can control to some extent, different nozzle opening, air pressure and other factors. A wide range of particle sizes is available from 5 microns to 1000 microns (Industry, 2010).
- Other metallurgy:
  - Deoxidizer steel processing
  - Alloying in steels
  - Aluminothermy reduction processes
  - Corrosion-resistant coatings for steel products

Those processes are using low percent of aluminium and are described in the ”Other” group.

- Other

Those 9 other groups can be divided into smaller under groups. For example: Russia is using Russian Standard of aluminium products. Semi-manufacturing products and products made of aluminium and aluminium alloys from the Russia production companies are divided into the following:

1 Castings (blanks have forms: planar, cylindrical solid, hollow cylindrical, T-shaped. Variation of mass is from 20 to 15000 kilograms.)

2 Flat-rolled products

2.1 Plates, sheets, strip (blanks have thickness from 0.2-mm to 150-mm, width from 100-mm to 3000-mm and length from 1200-mm to27500-mm)

2.2 Heat exchangers (Maximum size that is producing: 1000x3600x1.5 mm)

2.3 Foil (thickness from 0.005-mm to 0.25-mm)

3 Extrusions

3.1 Rods (blanks have form of round, square, hexagonal, wires and Ø4-500)

3.2 Strips (3-200x40-700)

3.3 Profiles (Ø 20-600)

3.4 Panels (370-2100x3-17x75-80)

3.5 Pipes (8-12060)

3.6 Lightweight drill pipe (73x172)

4 Forging stamping products manufacturing

4.1 Forgings (under 3000 kg)

4.2 Stampings (under 2000 kg)

4.3 Wheels (R13-R16, 22.5 x 8.25;   22.5 x 9;   22.5 x 11.75)

5 Aluminium cans (0.33 l; 0.5l) (Alfa-Metal, 2011)

There are a big amount of sizes within these under groups. Russia has a big potential for export of aluminium semi-products.

Russian manufacturers of aluminium-containing products are operating below capacity. This indicates significant growth potential in the Russian aluminium market. This reduced capacity utilization rate is a result of a great share of imported products containing aluminium. This is mostly explained by a lack of protection for Russian producers of aluminium-based products, as well as an insufficient control for law execution. The restrictions on the import of finished and semi-finished aluminium-based products to Russia would help local producers to increase the capacity utilization rate, thus triggering the demand for aluminium in Russia (RUSSAL, 2011).

2.2.3 Manufacturing

In the manufacturing of aluminium, metal is used to create the final products for consumption. Figure 2-15 – Breakdown of aluminium shares in other industries in Russia, 2008 numbers shows shares of the aluminium in other industries in Russia.

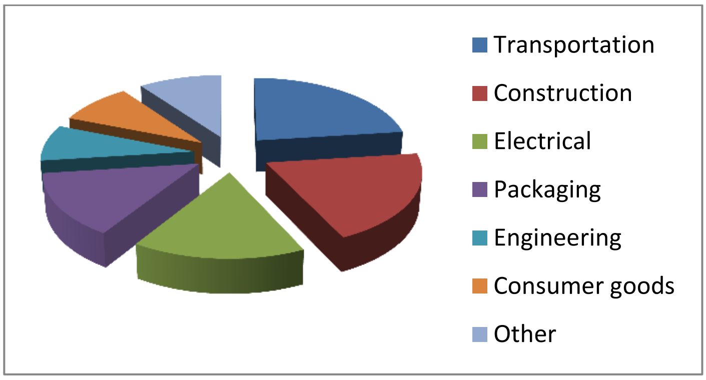


Figure 2-15 – Breakdown of aluminium shares in other industries in Russia, 2008 numbers (Finmarket, 2009)

The most intensive used are in transportation (23%), construction (20%), electrical products (16%), packaging (14%), engineering (8%), consumer goods (9%). Their total share of aluminium in the structure of consumption is 90%. According to marked analyzers, the domestic demand for high-tech aluminium products will significantly increase in the future (Finmarket, 2009).

The main industries that are using aluminium in their products are listed along with specific product applications in the table below.

Industry	**Products**
Transportation	Engine, transmission, chassis, suspension and steering, wheels, heat exchanger, brakes, closures, body and IP beams, heat shields, bumper beams, automotive frame and body panel, radiators, road signs, wheels, railway wagons and ships, aerospace
Construction	Roofing, cladding, windows and door frames, curtain walling, facades, conservatories and partitioning
Electrical	Wires, conductors, transformers and capacitors, lighting appliances
Packaging	Food containers, beverage cans, bottles, foil
Engineering	Pipes, ladders, scaffolding, fasteners, hardware, office and

	medical equipment, heat transfer equipment
Consumer goods	Refrigerators, freezers, washing machines, stoves, dishwashers, dishes, TV antennas, bicycle
Other	Welding wire, paint, explosives, chemical powders

Table 2-6 – Aluminium industries and their products containing aluminium (Inline-P, 2011), (Alfa-Metal, 2011), (Americas, 2010), (Industry, 2010), (Cooper, 2010)

Aluminium is found in many other products, so it's hard to say about the amount of energy used and pollution spent and received in the manufacture of the final product. Therefore, the calculation used here is a very rough estimation. It is difficult to get information about the data from many manufacturers in Russia.

2.2.3.1 Use

The main global end use of aluminium is in construction, packaging, electrical equipment, transport, machinery, consumer durables, powder metallurgy and deoxidation of steel. The share rates are visualized in the figure below.

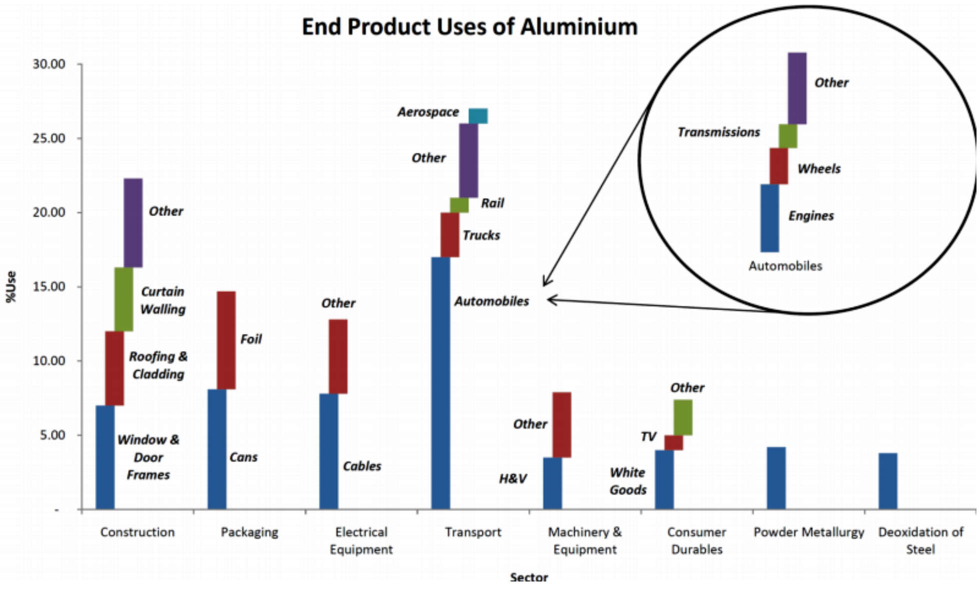


Figure 2-16 – Aluminium end product use (Cambridge, 2010)

Construction has 22% of the total use, where window frames stands for 7% and curtain walling for 4%, roofing and exterior cladding stands for 5%. Decorative and protective profiled cladding is often made from rolled aluminium sheet. Aluminium is an attractive, light-weight, and increasingly used material in construction. Transport industry stands for 27% of the total use, where automobiles have 17%. Aluminium is increasingly used in transport industry as its lightweight properties allow better fuel economy, and reduced carbon dioxide emissions over the product lifetime. Packaging industry stands for 15%, where cans stands for 8%, Foil and other for 7%. 75% of beverage cans are made from aluminium. Electrical equipment accounts for 13%, where electrical cables for 8%. Aluminium is more favorable than copper due to a lower total cost. This is despite that fact that aluminium conductors have to be larger due increased electrical resistivity. Cables for industrial, commercial and residential buildings may contain a number of insulated conductors in a common jacket, consisting of aluminium armour. Machinery and other equipment stands for 8%, where heating and ventilation systems for 4%. Combined with high strength and durability, aluminium is a favorable choice in heating and ventilation systems. Consumer durable use is 7%, where white goods consume 4%. 50% of all aluminium used in the household is used in refrigerators, freezers and washing machines. Refrigerators and freezers contain refrigeration units, and therefore use significant amount of aluminium. In addition, aluminium is used in the cooling system, panels and accessories. Powder metallurgy stands for 4%. Powder metallurgy is a process that allows production of both complex and simple form to have ready-made sizes, reducing the subsequent stages of processing. A mixture of elemental and pre-alloyed powders compacted in the crystal. Powders were then sintered to form a pure form of the final product. Deoxidation of steel accounts for 4%. Deoxidizing reagents are added to the melt in order to remove oxygen from the molten steel. About 1 kg of aluminium is required to restore each ton of steel (Cambridge, 2010).

In-use stock of aluminium is growing when GDP is growing for a specific country. These analyses was made by (OECD, 2010) in European countries and described in this document section for Curve Fitting. Global analyze was made by (Martchek, 2006) and is shown on the figure below.

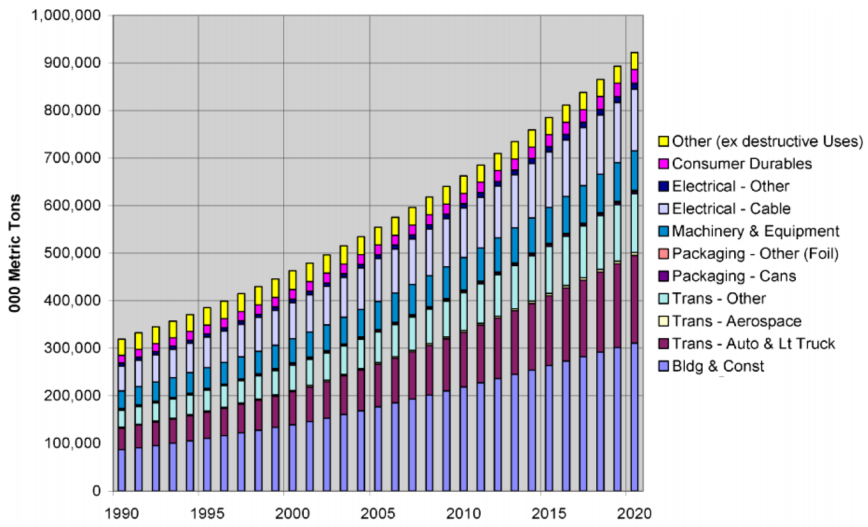


Figure 2-17 – Projects future product inventories volumes by market segment (Martchek, 2006)

2.2.3.2 Waste Management and Recycling

Compared to the production of primary aluminium, recycling of aluminium products consumes as little as 5% of the energy and emits only 5% of the greenhouse gas. Recycling is a major aspect of continued aluminium use, as more than a third of all the aluminium currently produced globally originates from the old, traded and new scrap. The high value of aluminium scrap has always been a major incentive for re-use, independently of the legislative and political initiatives. For some products, the growth of environmental problems and increased social responsibility helped to increase recycling activities, in orders to save resources and to avoid clog. The recycling performance of the aluminium industry can be described by different indicators, namely the overall and the end-of-life recycling efficiency rate. These indicators are splited into the end of-life collection rate and the processing rate (IAI, 2009). Estimated recycling rates for aluminium used in the transport and building sectors are very high (85% to 95%). Between 30% and close to 100% of aluminium cans are found to be collected and recycled, depending on the region.

The recycled product may be the same as the original product (window frame recycled back into a window frame) but is more often a completely different product (cylinder head recycled into a gearbox). Global end-use markets for finished aluminium products is presented in the figure below.

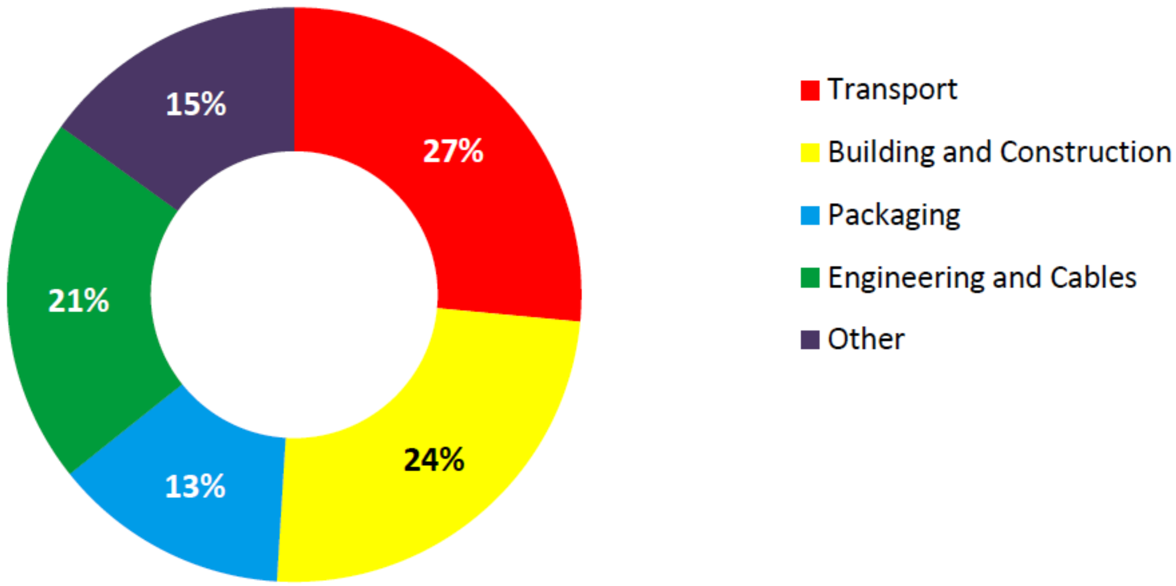


Figure 2-18 – **Global end-use markets for finished aluminium (IAI, 2009)**

Transportation is the most important field of application for aluminium worldwide. In 2009 the average passenger car contained between 120 and 150 kg of aluminium. In case of building and construction, typically building will have four major stages in life cycle: construction, exploitation (mainly heating, lighting and air conditioning), maintenance and end-of-life management. In Europe the collection rate of all aluminium packaging is about 50%. The collection rates of used beverage cans vary from country to country from 30% to close to 100% (75% in Russia) (IAI, 2009).

Climate change is the paramount environmental issue for the global industry. The full process for manufacturing of new stocks of aluminium is responsible for 1% of the global human-induced greenhouse gas emissions, which scientists with the United Nations' Intergovernmental Panel on Climate Change (IPCC) identify as a cause of unnaturally accelerated rates of global warming (IAI, 2009).

Waste management is divided into 3 main processes:

- Disposal – where old scrap instead of going into recycle chain goes to landfill directly;
- Collection – is an important process because old scrap after exploitation process is going to recycling. World average is shown in the Table 2-7 and represents very high recyclable rates for some industry sectors, while some other categories have a big potential in increase.

	Collection %	Collection %
	1990	2000
Buildings	69	70
Autos & Light Trucks	75	75
Aerospace	76	75
Other Transport	76	75
Containers	61	59
Packaging – Foil	13	16
Machinery	40	44
Electrical Cable	45	51
Electrical Other	30	33
Consumer Durables	20	21

Table 2-7 – Example of global average worldwide collection (recycle) rates and melting recoveries by market (Martchek, 2006)

- Sorting – is a process after collection. Here old scrap is inspected and sorted for remelting, refining or landfill.

2.2.3.3 Remelting and refining of scrap

Several melting processes are used. The choice of process depends upon a number of variables. These include the composition of the waste, the processes that are available in a given plant and the economic planning and scheduling priorities. A breakdown of the most common melting technologies is given in the Table 2-8. Molten metal fluxing (to treat the molten metal: chemical adjustment, cleaning, yield maximization, degassing) and filtration technology has been developed to produce aluminium alloys of the correct quality. Remelters mainly use reverberators furnaces, so “scrap remelting” model is based on this furnace technology only. Refiners use a combination of rotary and reverberators furnaces which represent about 90% of their furnace technology, while induction technology is quite marginal. As a result, the “scrap recycling” model is based on a mix of rotary and reverberators furnace technologies (EAA, 2008).

Furnace type		Principal application	Specificities / features	Comments
Reverberatory	Standard	Melting larger volumes of clean scrap and primary feedstock	- Large metal capacity (<=100t). - Few restrictions on feed stock sizes. - Low or no salt flux use - Main co-products: mainly dross	- High yields due to quality of feedstock - Molten metal pumps sometimes used
	Side Well	As above, but enables efficient recovery of some finer feedstocks.	- Large metal capacity. - Wide range of feedstock possible. - Main co-products: dross only	- High yields possible depending upon quality of feedstock - Molten metal pumps sometimes used
	Sloping Hearth	Separation of Al from higher melting point metal contamination (i.e. iron/steel)	- Very efficient at removing high melting point contaminants. - Lower thermal efficiency - Main co-product: mainly dross	- Sometimes incorporated into other furnace types. - Yield dependent on level of contamination.
Rotary	Fixed Axis	Recycling a wide range of feedstocks	- No feedstock restrictions - Large charge volumes possible (<50t) - Feedstock size may be restricted - Relatively high usage of salt flux. - Main co-product: salt slag	- Resultant salt slags can be reprocessed.
	Tilting	As above	- As above, but lower use of salt flux. - Feedstock size may be restricted - Main co-product: salt slag	- Tends to be used for lower scrap grades.
Induction (not used in models)	Coreless	Melting of cleaner scrap or primary feedstock	- High yields obtained. - No salt flux required. - Flexible use (batch and continuous processing possible) - Relatively small load (<10t) - Restricted feedstock type - Feedstock size may be restricted	High cost (electricity)
	Channel	As above.	- High yields obtained. - No combustion gases - No salt flux required -As above, but able to have larger capacities(~20-25t)	High cost (electricity)

Table 2-8 - Furnace types and specificities for aluminium recycling (EAA E. a., 2008).

Usually, refiners and remelters report their (gross) metal yield by comparing their outputs of metal ingots with their scrap inputs, as values between 70% and 95%.

3 MODEL DESCRIPTION

This Chapter is divided into 3 main parts: mass, energy and emissions layers. I will provide a description of material flows, types of energy and emissions. In the material flow part I give an analyze of Russian aluminium cycle. Than this analyze model is integrated with energy use and GHG emissions. The final analyze is based on present and future situation in aluminium production in Russia. I have been using different types of literature and other sources. I also was forced to do some assumptions due lack of available information specifically for Russia. These assumptions are written in the chapter text.

3.1 SYSTEM OVERVIEW

An integrated model of MFA (Mass Flow Analyse) covers all significant emissions of greenhouse gases created in the aluminium industry as a result of consumption of aluminium in the community. Integration occurs at three levels, as shown in figure below.

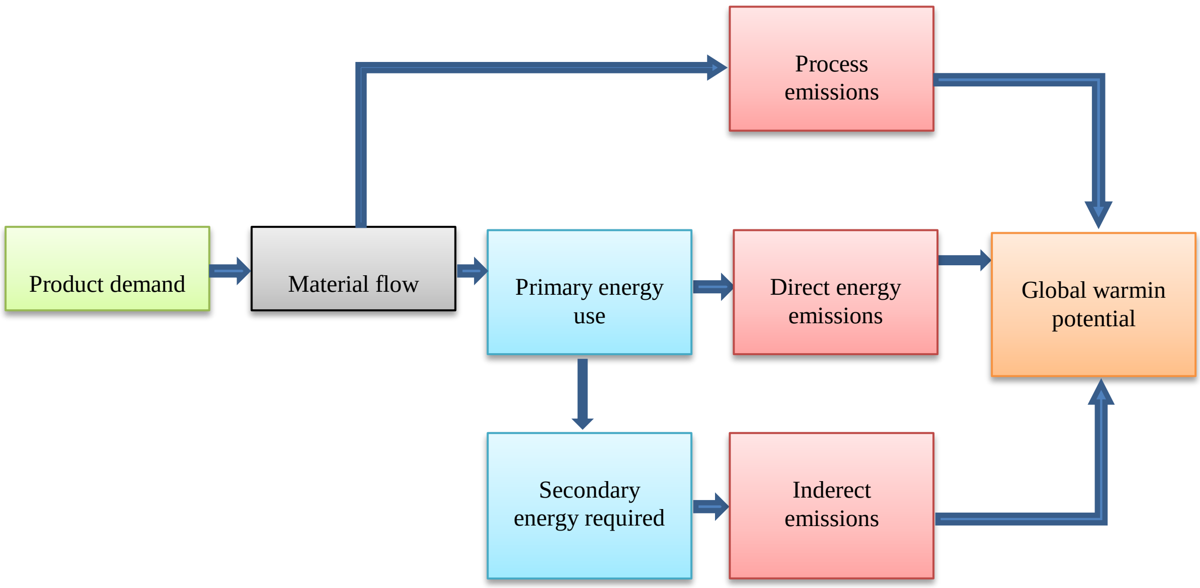


Figure 3-1 – Schematic model for illustrating of layers in the model

Colors in the schematic model represent the following:

- green colour is consumption
- grey is mass flow layer
- blue is energy use
- red is GHG emissions
- orange is climate change impact

Chain starts with the consumption generated by community in the form of demand for services. The material flow is the first layer in the model and is shown in grey. A material flow requires the transformation of aluminium through various processes within the cycle. This transformation requires use of energy and results in the emission. Primary energy consumption results into direct emissions from this energy. That happens on site in aluminium processes. Primary energy consumption also requires a secondary energy, which is defined as the energy needed for production and transportation of primary energy to the site. Indirect emissions are generated off-site, as a result of secondary energy use. The energy layer is shown in blue and GHG emissions in the red colour. Greenhouse gas emission layer directly affects the environment through global warming based on properties to specific gases. The model takes into account a number of aluminium-containing products, but also considers these products by their content of clear aluminium in the mass balances. Classification of greenhouse gas emissions is based on classification of energy use (primary and secondary) and material flow (proses). That results into three greenhouse emissions: process, direct energy and indirect energy emissions. (Colton, 2011).

The integration of all three layers (mass flow, energy use and GHG emissions) is present in the Figure 3-2. Mass flow coincides with the system depicted in the Figure 3-2, but with a clearly defined internal melting outside a semi-production. This is done to separate the energy and emission results between the two processes, but also explicitly examine the inner semi-industrial processing streams. The integration of energy and emission layers is achieved by the addition of three other processes to a global aluminium cycle (coke, pitch and anode production) energy market and energy production. These processes are outside the global aluminium cycle, but products from these processes in the cycle, they consume energy and produce. Coke, pitch and the production of anode feed electrolysis with black arrows and gets used anode butts in return. Figure 3-2 presents not only the aluminium mass flows in the system. Energy flows are shown in blue. The energy from the "Energy market" is flowing back into the "Energy production" in form of secondary energy. This represents the energy required for production and transportation of final energy. Emissions are shown by red arrows extending from the upper part of the box. The primary emissions from on-site fuel combustion are given in the upper part of each process, except of manufacturing and use processes. The process emissions are present at the top of electrolysis and anode production. (Colton, 2011)

Figure 3-2 System definition for the integrated global aluminium mass flow

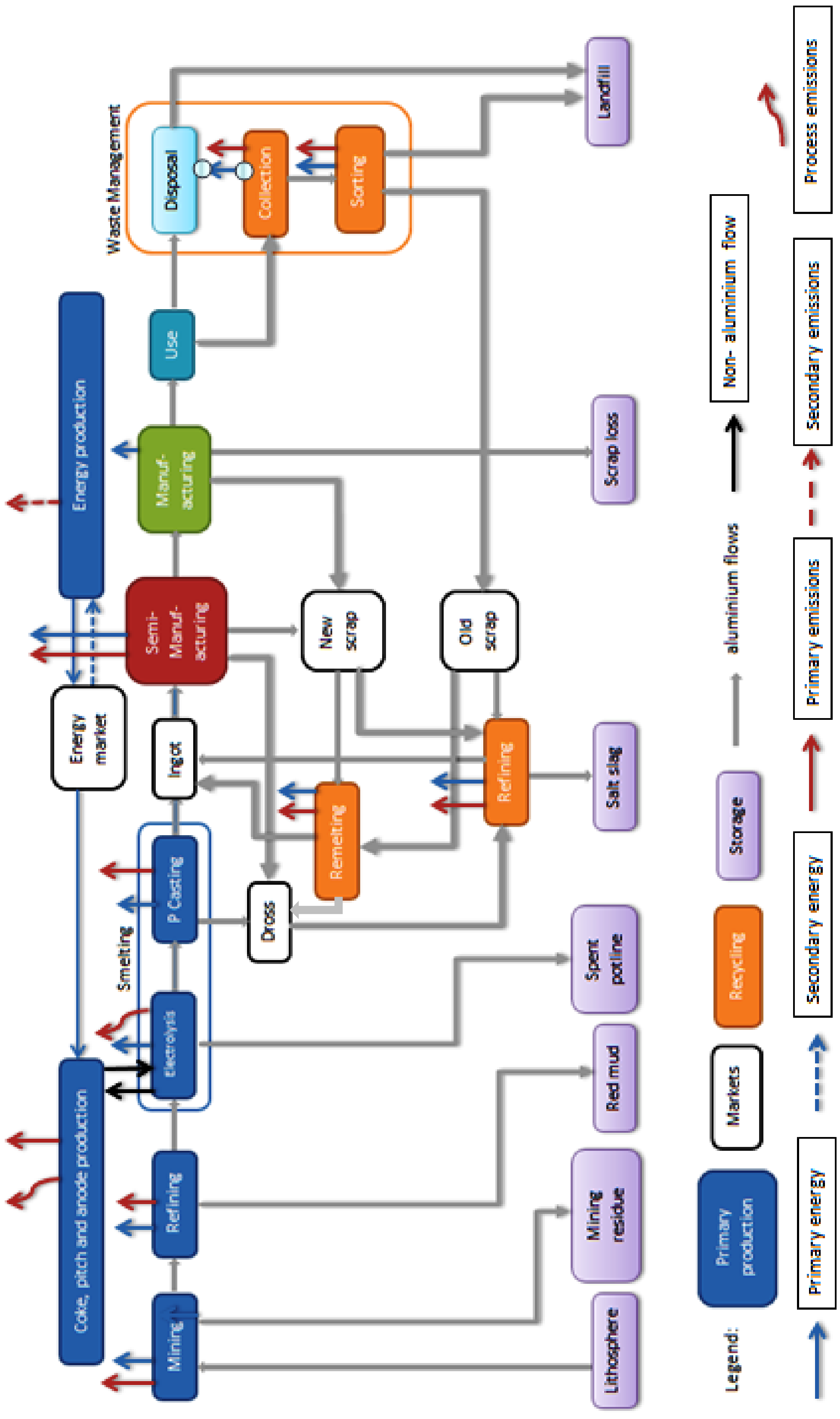


Table – System definition for the integrated global aluminium mass flow

3.1.1 Layer One: Mass

System definition for the integrated Russian aluminium mass flow model is very big in size, which makes it difficult to present in one figure. That is why, for better visualization, I divided the Russian aluminum mass flow model into several parts: primary and secondary production of aluminium, semi-manufacturing, manufacturing, use and waste management.

Based on the method described in the chapter 2 I start with calculation of primary aluminium production in Russia. Also, it is necessary to add market process for mining, refining and smelting processes. That gives a full picture of situation in Russian aluminium mass flow model for primary aluminium production. Finally, the primary production chain also requires calculations of the ratios for non-aluminium flows from anode production, which manufactures carbon anodes for electrolysis. Process mining is divided in two processes, this is due the fact that alumina in Russia is produced from both bauxite and nepheline ore. Semi-manufacturing is divided into eight groups of semi-finished products. Manufacturing is divided into seven industries. The connection between semi-manufacturing and manufacturing is not presented in the paper due possible 56 material flows between them.

Analyze of “Use” process is based on economical factor that presents aluminium consumption per capita versus gross domestic product.

Recycling of aluminium is divided on two parts: recycling from new aluminium scrap and old aluminium scrap.

3.1.2 Primary production part

The aluminium flow in the primary production chain is calculated backwards based on the figures for the required primary ingot casting production. Figure 3-3 – Material flow of primary production of 1 unit of aluminium shows ratios, normalized to one unit of aluminium in primary ingot. The chain consists of four processes that have input, output and waste flow. For calculations in this part I used two coefficients: mass transfer coefficient (blue colour) and metal content transfer coefficient (black). Those coefficients present metal concentrations of goods and historical proportionality between flows based on industry production data.

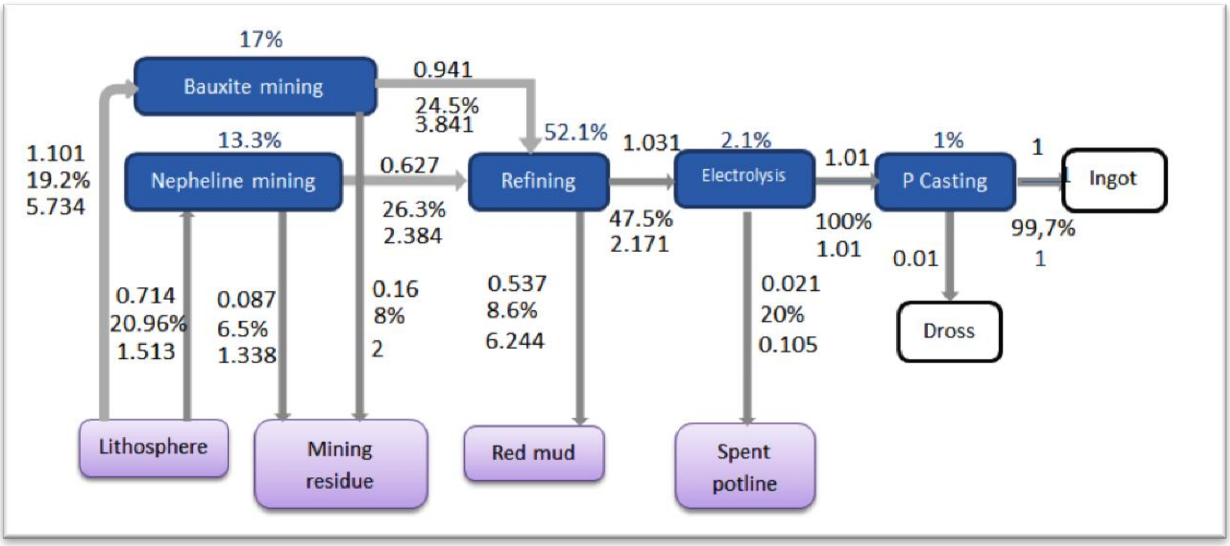


Figure 3-3 – Material flow of primary production of 1 unit of aluminium

The table above presents material flows of metal (number are presented in the flow), the aluminium content in the mass (numbers are below the flow, in %), mass flow (numbers are below the percent rate) and percent of process losses (percent is above of the process). For production of 1 unit of aluminium it is required 5.734 units of bauxite ore and 0.714 of nepheline ore. Table 3-1 – Ratios that are used for calculations of aluminium flows in the primary aluminium production presents tree types of calculation methods that are specified for each flow and flow components. C- presents content of aluminium in the goods, T-stands for transfer coefficient, MB- is mass balance.

Process	Flow	Metal content or total mass	Calculation method	Notes	Source

Primary ingot casting	Input	Metal	MB	Mass balance on metal content for primary ingot casting	
		Mass	C	Molten aluminium assumed to be 100% aluminium	
	Output	Metal		set to 1	
		Mass	C	It is gradation of types of aluminium from A0 to A999 where aluminium content ranges from 99.5% to 99.999%. Average is 99.7%	(InfoMine, 2008)
	Loss	Metal	T	Dross generation	(GARC, 2010)
Electrolysis	Input	Metal	MB	Mass balance on metal content for electrolysis	
		Mass	T	% is given for Australia	(Council, 2006)
		Mass	C	Research made by UralAluminium	(T.S. LYAPTSEVA, 2010)
	Loss	Metal	C	% is given for India	(Agrawal 2004)
		Mass	T	Assumed, that losses are the same as in Europe	(EAA, 2008)
Refining	Input	Metal	MB	Mass balance on metal content for refining	
		Mass	T		(EAA, 2008)
		Mass	C	For bauxite ore is 24.5%, for nepheline ore is 26.3%. Share of nepheline mining is 40%.	(Shepelev I.I., 2011)
	Loss	Metal	C	This information is from USSR time. Most of the aluminium refineries are not changed since. I made an assumption that middle	(Shandra, 1997)

				average is the same how it was in USSR.	
		Mass	T	Loss ratio is derived from the red mud generation rate	(IAI, 2007)
Bauxite mining	Input	Metal	MB	Mass balance on metal content for bauxite mining	
		Mass	MB	Mass balance on total mass for bauxite mining	
	Loss	Metal	C	The process of bauxite mining has not been changed since the USSR time in Russia. Therefore, the data used is from 1961.	(Encyclopedia, 1961)
		Mass	T	bauxite loss to mining residue equals to 17% in Russia	(Elia, 2009)
Nepheline mining	Input	Metal	MB	Mass balance on metal content for nepheline mining	
		Mass	MB	Mass balance on total mass for nepheline mining	
	Loss	Metal	C	Data is taken from chapter: “Nepheline mining”	
		Mass	T	Variations of loss of mass are 11.8%-14.7% (depend of concentration of H_2SO_4). Average is 13.3%	(Valyaev, 2012)

Table 3-1 – Ratios that are used for calculations of aluminium flows in the primary aluminium production

The primary ingot casting process flows are built around the 1% dross generation rate of primary ingot production. The electrolysis process is calculated based on the spent potline generation rate available for European countries. I made an assumption, that this rate is the same in Russia. There are no available rates for Russia in the free source market. The refining process is calculated using red mud generation rate and its aluminium concentration. Bauxite mining and nepheline mining are calculated through the mining waste generation rate. Those rates are presented in the Table 2-3 – Material flow of bauxite mining (OECD, 2010)

In order to complete the primary aluminium production chain it is required to calculate ratios of the non-aluminium flows from anode production that produces carbon anodes for electrolysis. World average anode requirement per ton of molten aluminium is 0.435 t / t (IAI, 2007). Carbon anode consists of 50-70% of coke (average is 60%), 15-30% of pitch (average is 20%) and 10-25% of recycled butts (average is 20%) (Karvalio, 2001). The combination of this information gives a result presented in figure below.

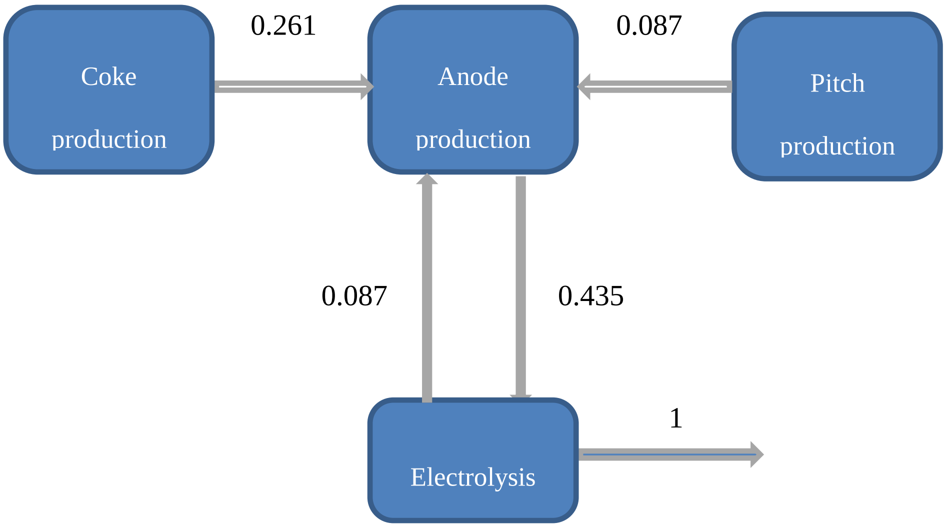


Figure 3-4 – Material flows of anode, coke, pitch production processes based on electrolysis output of molten aluminium

Primary production of aluminium in Russia in 2008 is presented in the Figure 3-5. Information that is already presented and rations that are calculated in the current chapter are used in further calculations. Figure 3-5 illustrates markets flow as a result of trade between Russia and other countries. Inflow from remelting and refining processes to primary ingot casting process is included with loss.

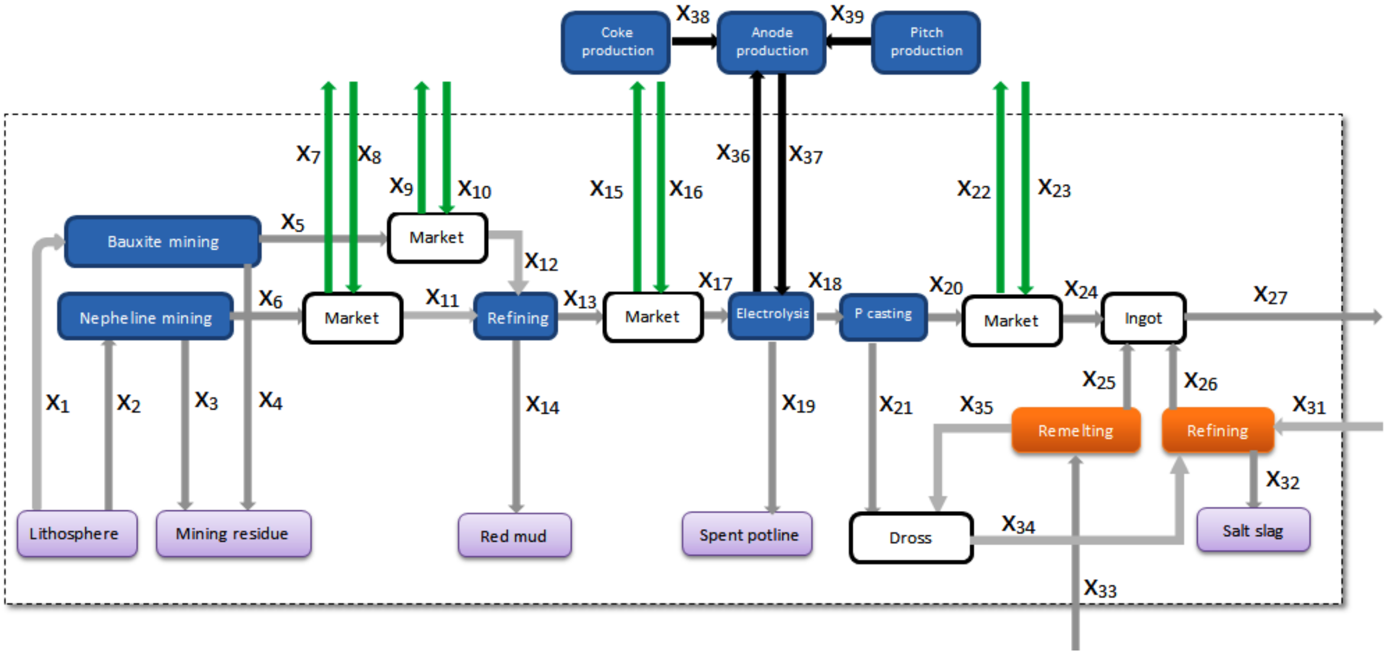


Figure 3-5 – System definition of the primary and secondary production of aluminium in Russia in 2009

In the figure above, grey arrows represent material flows, green arrows – aluminium trade, black arrows – non-aluminium flows. Blue boxes represent transformation processes, white boxes – market of aluminium between Russia and other countries, for ingot and dross – market processes, orange boxes – recycling processes, light violet – loss of aluminium, x_n – value of material flow. Each process is mass balanced.

Primary production of aluminium starts from mining of bauxite and nepheline ore (flows x_1, x_2) from lithosphere. Processes bauxite mining and nepheline mining have losses in the form of mining residue (flows x_3, x_4). Flows x_{11} and x_{12} show amount of material that goes to refining process after market of bauxite and nepheline (flows x_7, x_8, x_9, x_{10}) with other countries. Loss from refining process is red mud for bauxite mining and soda, potash, silica for nepheline mining(x_{14}). Alumina (flow$_{13}$) together with alumina market (flows x_{15}, x_{16}) comes to electrolysis process. The production of carbon anodes (flow x_{37}) from coke (flow x_{38}), pitch (flow x_{39}) and recycled anode butts (flow x_{36}) is the most important non-aluminium raw material production process in the aluminium cycle. Aluminium (flow x_{24}) together with aluminium market (flows x_{22}, x_{23}) goes to ingot market, which adds recycled aluminium from remelting (flow x_{25}), and refining processes (flow$_{26}$) that have dross (flow x_{35}) and salt slag (flow x_{32}) loss . Electrolysis and primary ingot casting processes have losses in form of spent potline (flow x19) and dross (flow x_{21}) respectively. Inflows for remelting (flow x_{33}) and refining (flow x_{31}) processes are flows from new scrap and old scrap, that is located outside of this system definition. Finally, total amount of aluminium (flow$_{27}$) is sum of primary production of aluminium (flow x_{24}) and inflows from remelting and refining processes (flows x_{25}, x_{26}).

Nº	Name of flow	Value, Mt	Comments	Source
X_1	Bauxite mining	2206		(METALResearch, 2010)
X_2	Nepheline mining	1099		(Federation, 2010)
X_3	Loss from nepheline mining process	177	Mass balance of nepheline mining process	
X_4	Loss from bauxite mining process	321	Mass balance of bauxite mining process	
X_5	Bauxite	1885	Mass balance of bauxite market process	
X_6	Nepheline	922	Equal to "Total nepheline"	
X_7	Export of nepheline		Numbers are unknown. I assumed, that Russia has no export/import market for nepheline ore. "Alumina production from the nepheline ore exists only in Russia and Iran, and both countries are self-supporting."	(Zheng Luo, 2007)
X_8	Import of nepheline			
X_9	Export of bauxite	1		(METALResearch, 2010)
X_{10}	Import of bauxite	14		(METALResearch, 2010)
X_{11}	Total nepheline	922	Value present in Table	
X_{12}	Total bauxite	1872	Value present in Table	
X_{13}	Alumina	1816		(Federation, 2010)
x_{14}	Losses from mining	978	Mass balance of refining process	
X_{15}	Export of alumina	2299		(Federation, 2010)
X_{16}	Import of alumina	4608	Value presented in the Table 3-3	
X_{17}	Total alumina	4125	Mass balance of alumina market process	
X_{18}	Molten aluminium	4040	Calculated with the help of mass transfer coefficient from the Table 3-3	
X_{19}	Spent potline	85	Mass balance of electrolysis process	

X_{20}	Aluminium ingot	4000		(METALResearch, 2010)
X_{21}	Dross	40	Mass balance of primary ingot casting process	
X_{22}	Export of ingot	3312	Unwrought, unalloyed aluminium	(METALResearch, 2010)
X_{23}	Import of ingot	44	Unwrought, unalloyed aluminium	(METALResearch, 2010)
X_{24}	Total ingot	732	Mass balance of aluminium market process	
X_{25}	Recycled aluminium from remelting process	320	Mass balance of remelting process	
X_{26}	Recycled aluminium from refining process	297	Mass balance of refining process	
X_{27}	Total aluminium	1349	Mass balance of ingot market	
X_{31}	Input from scrap to refining process	255		(Grishayev S.I., 2009)
X_{32}	Salt slag	33	Assumption from the source materials is that loss of material from alumina refining is 10%	(Grishayev S.I., 2009)
X_{33}	Input from scrap to remelting process	355		(Grishayev S.I., 2009)
X_{34}	Dross for refining	75	Mass balance of dross market	
X_{35}	Loss from remelting	35	Assumption from the source materials is that loss from remelting is 10%	(Grishayev S.I., 2009)
X_{36}	Recycled butts	351	Calculated from the Figure 3-4 – Material flows of anode, coke, pitch production processes based on electrolysis output of molten aluminium	
X_{37}	Carbon anode	1756	Calculated from the Figure 3-4	
X_{38}	Coke	1054	Calculated from the Figure	

			3-4	
X_{39}	Pitch	351	Calculated from the Figure 3-4	

Table 3-2Flow values integrated model

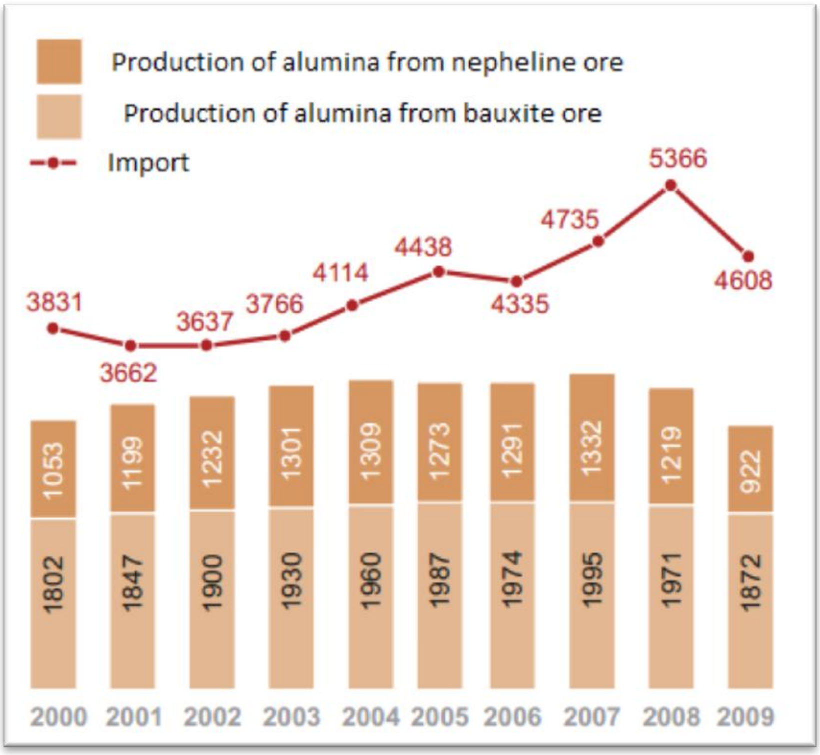


Table 3-3 – Dynamic of production and import of alumina in 2001-2009 in Russia, Mt (Federation, 2010)

The table above presents amount of bauxite and nepheline ore, which were used for production of alumina. Numbers are represented by aluminium content in ore. There is some decrease in numbers for 2009 due economic creases in the Western word and lower demand for products.

Visualization of primary and secondary production of aluminium in Russia with values of the material flows is presented in the figure below.

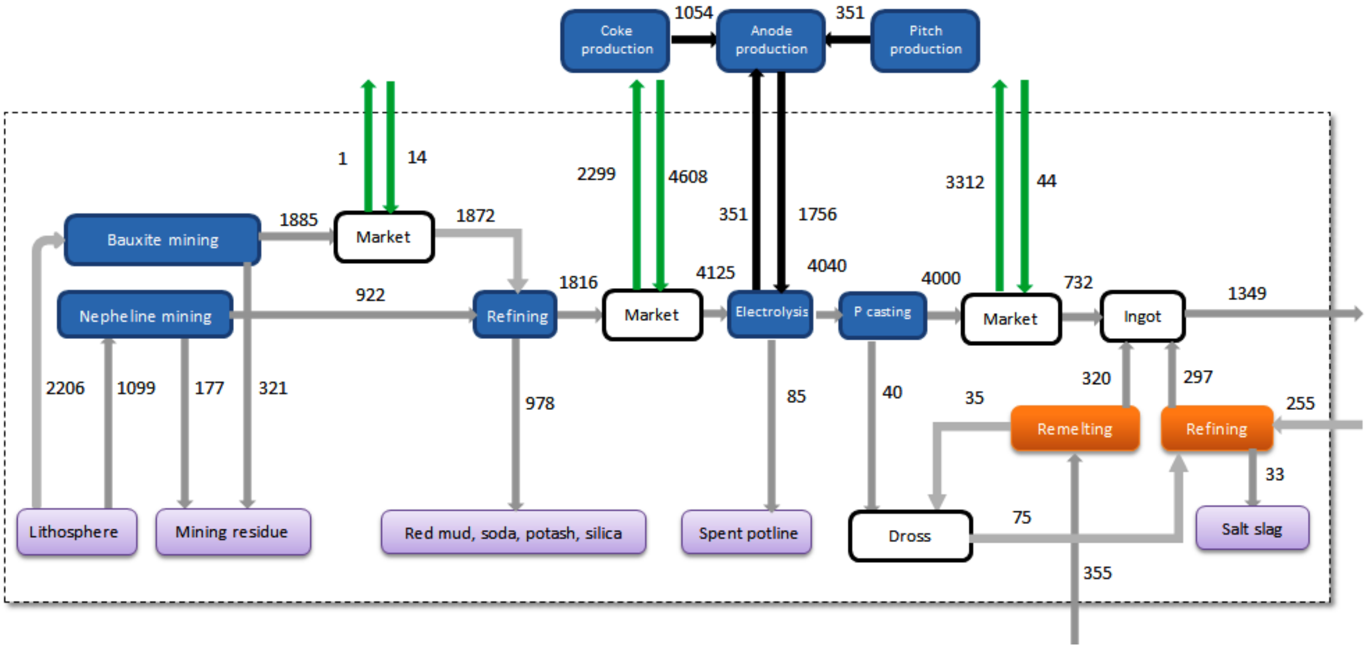


Figure 3-6 - System definition for the primary and secondary production of aluminium in Russia in 2009.Values are in thousand tons.

Even in Russia bauxites are the main source for the alumina production. Russia does not have big bauxite reserves comparing to major bauxite producing countries. Bauxite reserves in Russia are concentrated in over 50 smaller deposits. Russian bauxite production is only 2.2 million tons. The share of crude bauxite in alumina production is closed to 67 % and the rest is nepheline ore. It is found 15 deposits of nepheline ores in Russia and some of them are huge. External market of nepheline ore is small. Alumina production from the nepheline ore exists only in Russia and Iran, and both countries are self-supporting (Zheng Luo, 2007).

There is an acute shortage of primary aluminium, due to the lack of large deposits of high quality bauxite. Therefore, raw materials for aluminium production should not be considered without the imports of alumina. RUSAL has acquired in recent years a number of assets abroad - alumina refineries in Guinea, Jamaica, Guyana, Ireland, Italy, and Australia. Company owns Nikolaev Alumina Plant in Ukraine.

Alumina market has a tendency for frequent export and import activities. This happens due lack of raw material and better prices for some big buying countries. Russia has a second place in the world (after China) in production of aluminium, and first place in exports of aluminium-.

The rate of primary / secondary aluminium was up to 5,5:1 (in 2000). In 2009, due increasing volume of primary aluminium and deceasing demand, that rate was 7:1.

3.1.3 Semi-manufacturing part

Flows of eight different semi-manufacturing processes are connected to the seven manufacturing industries in my theses.

Semi-manufacturing processes	Manufacturing industries
Shape casting	Transportation
Flat-rolled products	Construction
Aluminium cans	Electrical
Powder and paste	Packaging
Foil rolling	Engineering
Extrusions	Consumer goods
Wire and cables	Other
Other products	

Table 3-4 – Semi-manufacturing and manufacturing industries that connect in the model

First, I consider the semi-manufacturing from aluminium with addition of market of semi-products.

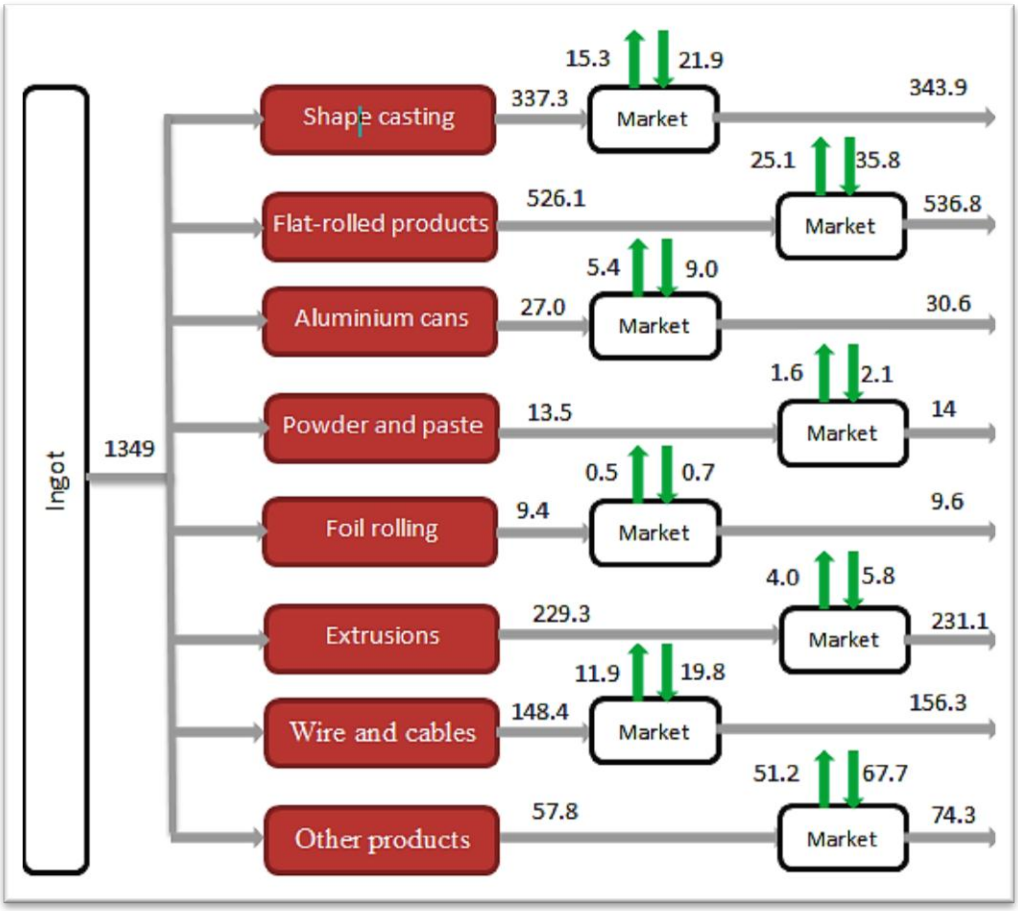


Table 3-5 – Semi-finished aluminium products.

White boxes represent market, red boxes – semi-finished product, grey arrows- flows of material, green arrows –trade of semi-finished products.

Export of semi-finished products in Russia is 115 thousand tons in 2009 (RUSAL, 2010). Please, see Appendix A for more information.

Aluminium and aluminium products stands for half of all export of non-ferrous metals. Most of this export is pure aluminium, but export of aluminium alloys have been increasing for the last years. The export share of semi-finished products and aluminium-contained products is insignificant (RUSAL, 2009).

3.1.4 Manufacturing part

The most significant areas of aluminium consumption are: transportation, construction, electrical engineering, packaging, engineering and consumer goods. Share of manufacturing industries present in Appendix A. Flows from aluminium semi-finished products to manufacturing processes have two output flows: scrap and final products. I assume that scrap which is not collected back into recycling is 2% (GARC, 2010). This number is for the world, but also representative for Russia. It is not a subject for my paper to specify where this type of scrap goes

Unified Interdepartmental statistical Information System performs import and export of manufacturing industries in Russia (System, 2012).

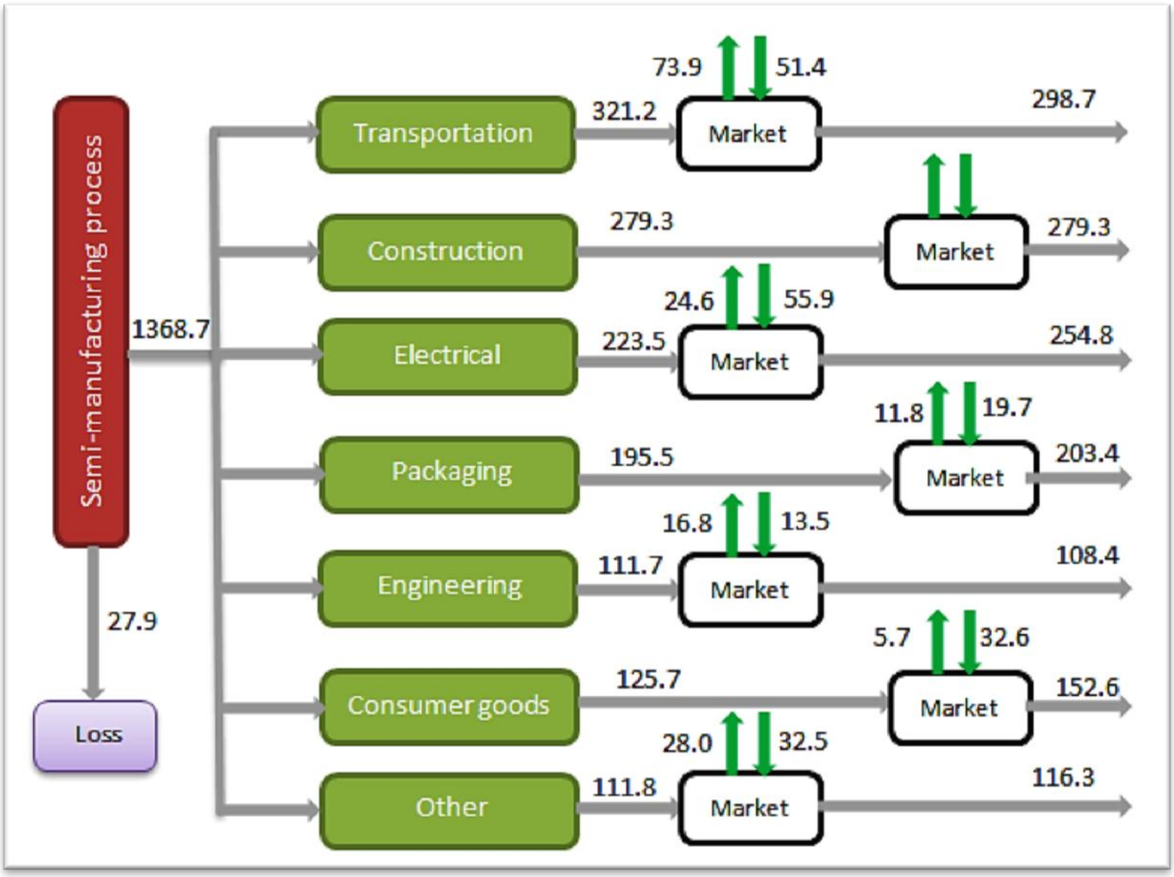


Table 3-6 – Material flows of manufacturing process.

Green boxes represent industries, white boxes represent market, red boxes – semi-finished product, grey arrows - flows of material, green arrows –trade of semi-finished products and light violet – loss from semi-manufacturing process.

Simple assumption here is that loss from manufacturing process to market of new scrap and scrap loss equals to 20% (273.7 Mt) (G.T. Armisheva, 2010)

3.1.5 Use part

Analyze here is based on the economical rate that represents aluminium consumption per capita versus gross domestic product (GDP) per capita in present year and 2050. Formula that presents dependence between those two factors is used. Please, see chapter 2.1.2.

GDP refers to the market value of all final goods and services produced within a country in a given period. (Guardian, 2009) Economic growth is enabled by increased productivity, which minimizes inputs (labour, capital, material, energy, etc.) for a given amount of output. Lowered cost makes products and services more attractive and lead to increased demand. Economic growth is also the result of population growth and the introduction of new products and services (Kendrick, 1979).

My assumption here is that increase in economy leads to increasing in aluminium consumption per capita. Table 8-1 – Economics' grow of gross domestic product by countries from 2010 to 2050 (Appendix B) represents' growth of gross domestic product from 2010 to 2050. This growth will lead to increase in consumption of aluminium per capita. Formula is used for calculation of aluminium consumption per capita that presented in Appendix B. Parameters are presented in the Table 8-2.

Material flow of aluminium equals 1686 Mt in 2009. This number has possible inconsistency due to the fact that the average consumption of aluminium is for Europe.

3.1.6 Recycling part

Recycling of aluminium is divided into two parts: recycling from new aluminium scrap and old aluminium scrap. There are two inflows of new aluminium scrap. First one is coming from manufacturing industries. New scrap market split this material flow into two: where 57% goes to refining process, 43% goes to remelting process. Second is received from semi-manufacturing process, where 48% goes to refining process, 52% goes to remelting process after new scrap market process. Old scrap market receives aluminium waste from use process through waste management process. In the same time, waste management is divided into disposal, collection and sorting processes.

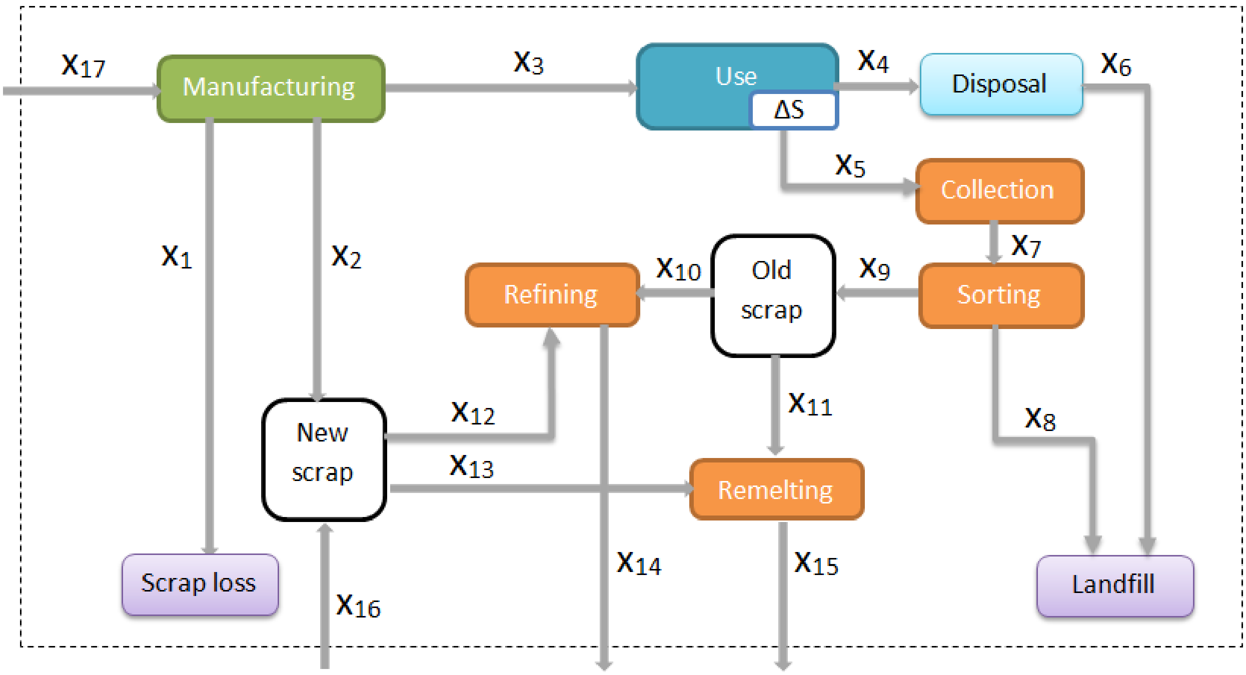


Table 3-7 – System definition for recycling of aluminium in Russia.

Values of mentioned above material flows are presented in the table below.

Nº	Name of flow	Value, Mt	Comments	Source
X_1	Loss from manufacturing process	68.4	Assumed 5%.	See chapter “Manufacturing part”
X_2	New scrap from manufacturing process	205.3	Assumed 15%. 57% goes to refining process, 43% goes to remelting process	See chapter “Manufacturing part”, Appendix C
X_3	Output from manufacturing process	1139.8	Mass balance of manufacturing process	
X_4	Losses of old scrap to	183.3		(Finnimore, 2006)

	disposal			
X_5	Old scrap for collection	550	Mass balance of collection process	
X_6	Losses of old scrap to landfill	183.3	Mass balance of disposal process	
X_7	Collected aluminium scrap	550		(EnergyResearch, 2005)
X_8	Loss of old aluminium scrap from sorting	173.2	Mass balance of sorting process	
X_9	Old aluminium scrap for recycling	376.8	Mass balance of old scrap market	
X_{10}	Old aluminium scrap for refining process	124.6	Mass balance of refining process	
X_{11}	Old aluminium scrap for remelting process	252.2	Mass balance of remelting process	
X_{12}	New aluminium scrap to refining process	130.4	117 Mt from manufacturing process and 13.4 Mt from semi-manufacturing process	Appendix C
X_{13}	New aluminium scrap to remelting process	102.8	88.3 Mt from manufacturing process and 14.5 Mt from semi-manufacturing process	Appendix C
x_{14}	Recycled aluminium from refining process	255		Table 3-2
X_{15}	Recycled aluminium from remelting process	355		Table 3-2
X_{16}	New scrap from semi-manufacturing process	27.9	48% goes to refining process, 52% goes to remelting process	See chapter 2.2.3, and Appendix C
X_{17}	Inflow to manufacturing	1413.5		Table 3-6
ΔS	Change of stock of products	406.5	Mass balance of process of use	

Table 3-8 – Description of material flows with values

Market of new scrap has two outputs: material flows to refining and remelting processes. Calculation of values for these material flows is based on a percentage rate of new scrap of manufacturing industries and semi-manufacturing categories.

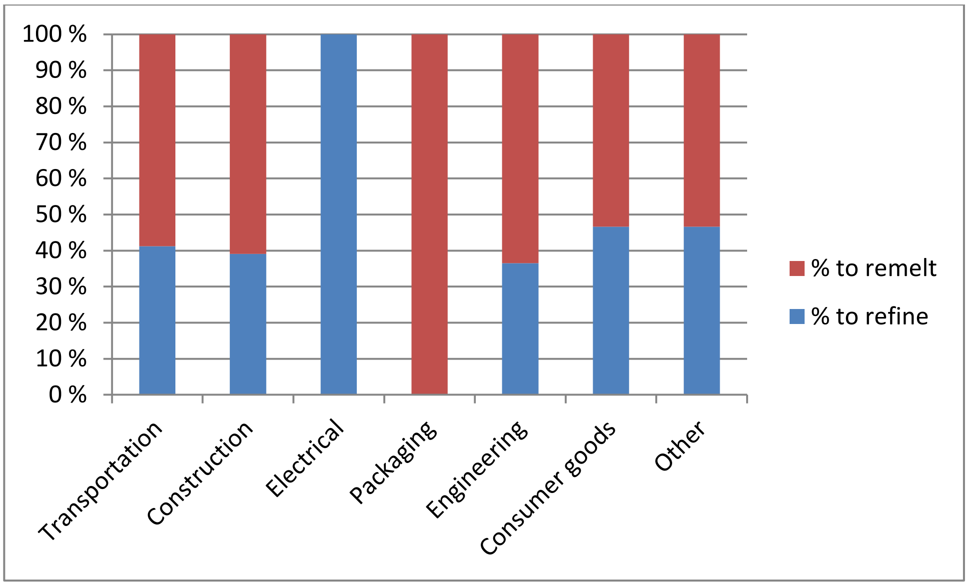


Figure 3-7 – Percent rate of new scrap for refining and remelting processes from manufacturing industries (Appendix C)

Similar method is used for calculation of output from new scrap market process for semi-manufacturing categories. Table below represents rate in percent, new scrap for refining and remelting processes.

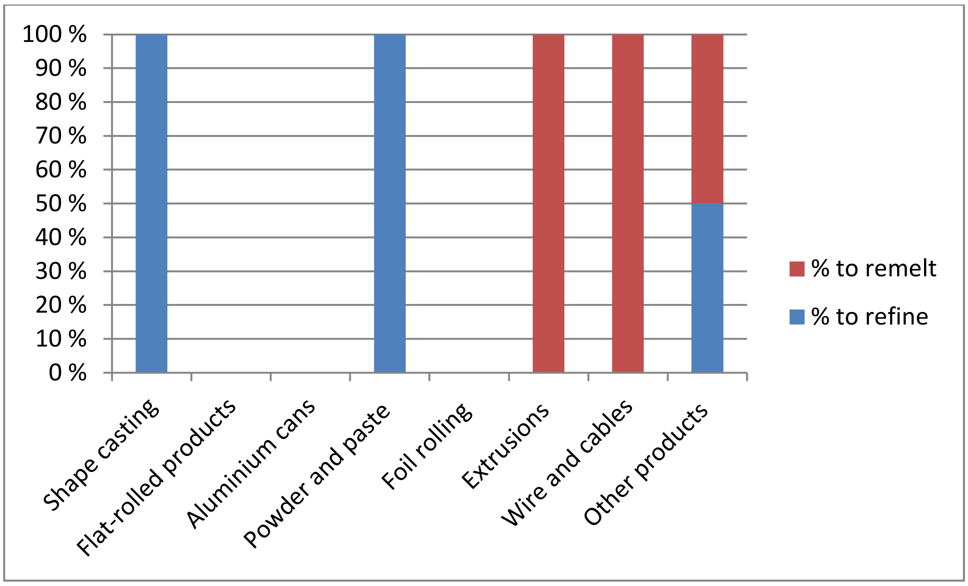


Figure 3-8 – Percent rate of old scrap for refining and remelting processes (Appendix C)

Flat-rolled products, aluminium cans and foil rollings are recycled internally. Assumption here is, that other products have percent rate 50/50.

Flows X_{12}, X_{13} are calculated by multiplying output from manufacturing industries and semi-manufacturing categories on percent rate that is present in the table above.

3.2 LAYER 2: ENERGY

IPCC report recommends cutting emissions by 50-80% within year 2050. Energy is important factor for my analyze. Russian industry consumes around 125 Mtoe of energy per year where 5% goes to primary aluminium production (Agency I. E., 2011).

3.2.1 Primary Energy

Primary energy coefficient is taken from different literature sources (Appendix D). Due the small amount of energy consumption I did not took into account powder and paste, foil rolling, wire and cables, and semi-finished products. Those products are not playing big role in aluminium cycle of aluminium. Assumed, that recycled aluminium ingot is refinery of aluminium scrap. Collection and sorting processes were integrated in one process. Coke production, pitch production and collection together with sorting processes have only value of total output without share of energy. Transfer coefficient between MJ and kWh is 1 MJ=0.28 kWh.

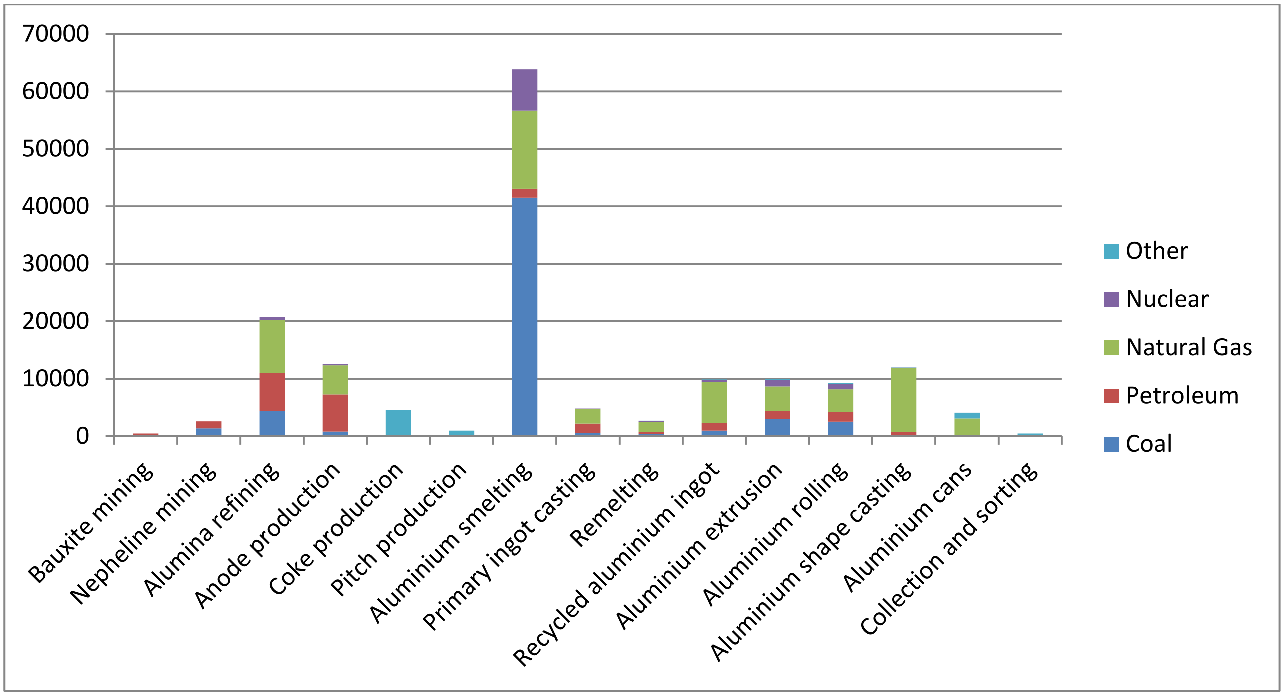


Figure 3-9 – Primary energy intensity of processes, units: MJ/t

Total amount of energy consumption of aluminium cycle in Russia is calculated by using ep = Ep * F (Formula 2-10), where primary energy use (MJ) equals to primary energy intensity (MJ/t) multiplied with material flow (t).

3.2.2 Secondary energy

Secondary energy is energy that is used for production of energy that requires for process energy and for transport of this energy. Different types of energy are compared in the table below.

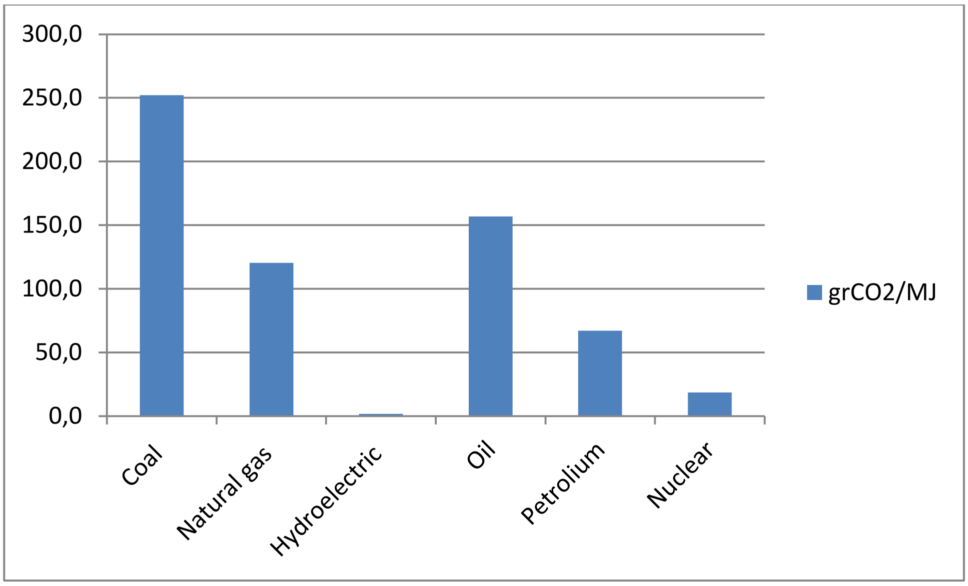


Table 3-9 – Carbon dioxide emissions versus MJ of energy (Appendix D)

Production of energy from the coal has the biggest amount of CO2 emission. Energy from the natural gas is 2.1 times lower, than energy from the coal. The same number for energy from oil is 1.6 time less. Hydropower stations produce 0.6% of CO2 emission compare to energy production from coal. Nuclear energy is a little higher than hydro.

3.3 LAYER 3: EMISSION

Emissions in the aluminium chain are divided into process, electricity, fossil fuel, transport, ancillary and PFC eq. emissions. Numbers for those emissions are presented in Appendix E.

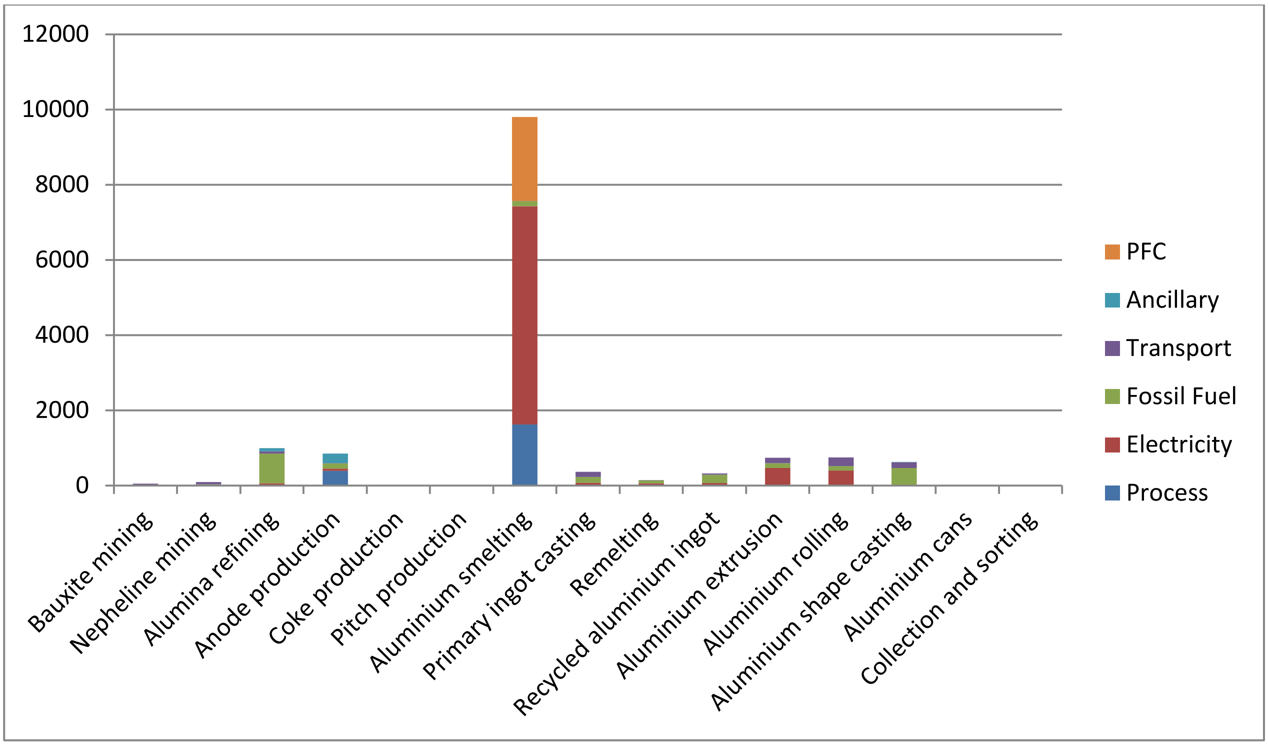


Table 3-10 – CO2-eq emissions by process of aluminium cycle. Values are shown in kg of CO2 equivalents per 1000 kg of process output.

Result of analyze is quantified greenhouse gas emissions that is generated by different processes, from electricity or fossil fuel consumption, by transportation, ancillaries or perfluorocarbons.

Process emissions (kg CO2-eq) are calculated by multiplying process emission intensity (kg CO2-eq/t) on material flow (t). ip = Ip * ep (Formula 2-12) is described in the chapter of this paper.

Secondary emissions (kg CO2-eq) are calculated by multiplying secondary emissions intensity (kg CO2-eq/MJ) on primary energy use (MJ). Formula is described in the chapter 2.1.1of this paper.

4 SCENARIOS

Calculations in this paper are based on percent rate of total greenhouse gas emissions and total energy use.

Process	**Share of total GHG emissions, %**	**Share of total energy use, %**
Bauxite mining	0.3	0.3
Nepheline mining	0.6	1.6
Alumina refining	6.0	13.1
Anode production	5.1	7.9
Coke production	3.4	2.9
Pitch production	6.4	0.6
Aluminium smelting	59.1	40.2
Primary ingot casting	2.2	3.0
Remelting	0.8	1.7
Recycled aluminium ingot	1.9	6.2
Aluminium extrusion	4.5	6.3
Aluminium rolling	4.5	5.8
Aluminium shape casting	3.8	7.5
Aluminium cans	0.7	2.6
Collection and sorting	0.7	0.3

Table 4-1 - % rate of total greenhouse gas emissions and total energy consumption

The highest share rate of gas emission and total energy consumption has aluminium smelting, anode production (with addition of coke and pitch productions) and alumina refining. Those 3 processes are taken into account in order to meet the level that IPCC has set to industries for emissions reduction within year 2050.

The following scenarios are relevant:

1. GHG emissions for inert anodes within “Anode, coke and pith production” are reduced by 41% (See chapter “Electrolysis” 2.2.2.5). That will result in total GHG emissions for aluminium production in Russia by 6.1%.

2. Wetted cathode technology is responsible for nearly 21% of GHG emissions from electrolysis process (See chapter “Electrolysis” 2.2.2.5). That will result in total GHG emissions for aluminium production in Russia by 12.4%.

3. Inert anode and wetted cathode technology in combination will stand for 22% reduction of total energy consumption within aluminium production in Russia (See chapter “Electrolysis” 2.2.2.5).

4. Production change to the best available smelting technology (PFPB) will result to 3.8% reduction of total GHG emissions for aluminium production in Russia (See chapter “Electrolysis”).

5. Electrolysis process has minimum energy consumption (7.32 kWh/kg (26.1 MJ/kg)). Total energy consumption in aluminium production in Russia is decreased by 16.4%.

6. It is possible to reduce emissions by substitution of energy sources. Most environmentally friendly energy is hydro and nuclear (Appendix D). If we substitute 10% energy not clear energy to nuclear power, then the total emissions within aluminium production process in Russia will decrease by 23.9 gCO_2/MJ.

5 CONCLUSION

If all scenarios are implemented then the decrease of total GHG emissions in aluminium production in Russia will equal to 22.3% and decrease in the total energy consumption will equal to 38,4%.

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7 APPENDIX A

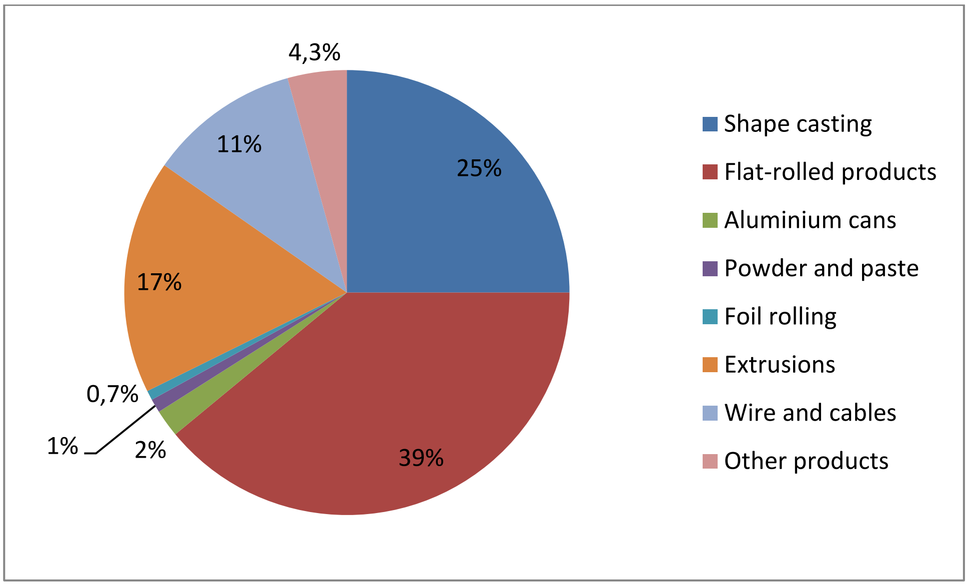
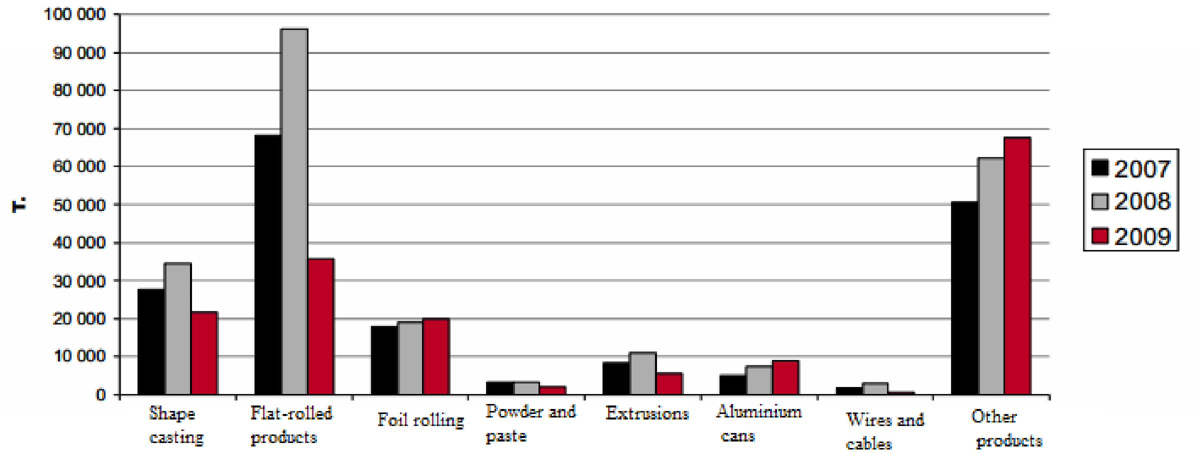


Table 7-1- Share of semi-finished products from aluminium (RUSAL, 2010) (Kupikaeto, 2009)



Products	2007	2008	2009
Shape casting (SC)	27 813	34 617	21 859
Flat-rolled products (FRP)	68 068	96 073	35 813
Foil rolling (FR)	17 995	19 172	19 837
Powder and paste (PP)	3 250	3 182	2 108
Extrusions (E)	8 202	10 883	5 796
Aluminium cans (AC)	5 191	7 456	9 006
Wire and cables (WC)	1 775	3 015	671
Other products (O)	50 485	62 171	67 674
Total	**182 779**	**236 569**	**162 765**

Table 7-2– Import of semi-products by categories (RUSAL, 2010)

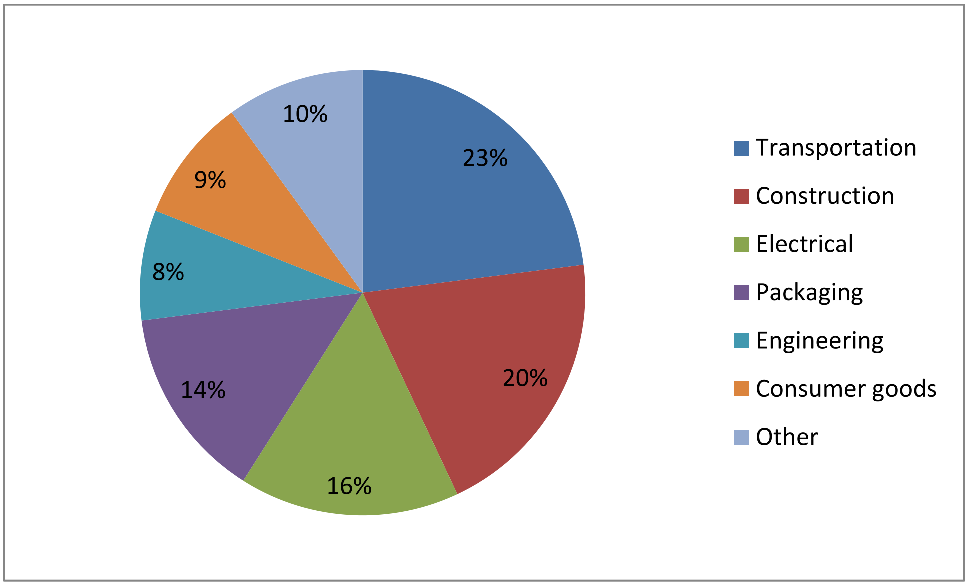


Table 7-3 – Share of manufacturing industries in Russia (Ministry, 2011).

8 APPENDIX B

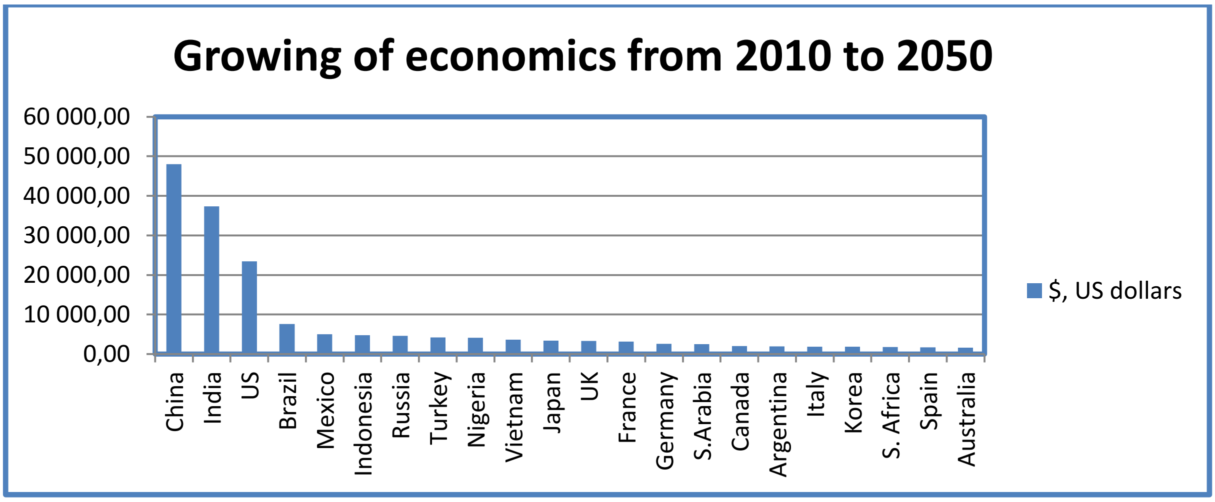


Table 8-1 – Economics' grow of gross domestic product by countries from 2010 to 2050 (Goldman, 2007)

$\frac{Al}{c} = 29.41/(1+e^{(-0.00021*(\frac{GDP}{c}-17000)})$ **(Formula 8-1)** where

Al/c – aluminium consumption per capita;

GDP/c- gross domestic product for a present year per capita;

Parameter	Value	Unit	Source
GDP/c in 2009	15300	$	(Agency, 2012)
GDP/c in 2050	72569	$	(Goldman, 2007)
Population in 2009	139,390	Thousand people	(People, 2012)
Population in 2050	118,233	Thousand people	(People, 2012)
Aluminium consumption in 2009	12.1	Kg per capita	Calculated from Formula
Aluminium consumption per capita in 2050	29.4	Kg per capita	Calculated from Formula
Amount of aluminium in 2009	1686	Mt	Calculated by multiplying aluminium consumption by population
Amount of aluminium in 2050	3476	Mt	Calculated by multiplying aluminium consumption by population

Table 8-2 – Parameters that used for calculation of aluminium amount in 2009 and 2050.

9 APPENDIX C

		Refiner			Remelter (tolled, purchased)		Remelter (internal)	
Life Cycle Stage	Product	kt/y	Standard #	Furnace[a]	kt/y	Standard #	kt/y	Category
Production	Dross[b]	77	16	b, c	0	16	0	16
Fabrication	Extrusion scrap	0	5		489	5	572	4
	Rolling scrap	0	5		0	5	1,144	4
	Foil scrap[c]	0	5		0	5	439	4
	Wire and cable	0	3		39	3	0	3
	Foundry scrap	195	7	c	0	7	0	7
	Dross[b] (foundry)	162	16	b, c	0	16	0	16
	Turnings[d] (extrusion and rolling)	191	13	a, c	0	13	315	12
	Turnings[d] (foil)	26	12	a, c	0	12	52	12
	Turnings[d] (foundry)	297	13	a, c	0	13	0	12
Manufacturing	Building	86	6	a	134	5		
	Transportation	196	6	a	280	6		
	Consumer durables	35	6	a	40	6		
	Cans and rigid packaging	0	6	a	156	15		
	Foil	11	15	c	0	15		
	Cable and wire	45	3	a	0	3		
	Engineering	80	6	a	139	6		
	Other	35	6	a	40	6		
	Turnings[d,e]	99	13	a, c	0	13		
End-of-Life	Building	95	6	a	92	6		
	Automotive	759	9	c	36	6		
	Other transport	60	6	a	58	6		
	Cans and rigid packaging	45	10	c	179	10		
	Foil	60	14	a	0	14		
	Engineering	278	9	c	27	6		
	Consumer durables	95	9	c	0	9		
	Other	37	9	c	0	9		
Trade[f]	New scrap	74	6	a	0	6		
	Dross[b]	−16	16	b, c	0	9		
	Old scrap	−136	9	c	0	16		
Total		2.886			1.709		2.522	

[a]Presumable mode of melting. a – Flux-free melting furnace, b – tiltable rotary furnace, c – fixed-axle rotary furnace.
[b]Also known as skimmings.
[c]Foil fabrication includes rolling into foil stock and final foil.
[d]Representative for turnings, chips, and cuttings.
[e]Turnings generated during manufacturing of various products.
[f]Net imports of aluminium scrap to the EU.

Table 9-1 - Scrap recycling model data for remelting and refining destination (Bertram, 2005)

Manufacturing industries	Refine, kt/y	Remelt, kt/y	% to refine	% to remelt
Transportation	196	280	41.2	58.8
Construction	86	134	39.1	60.9
Electrical	45	0	100.0	0.0
Packaging	0	156	0.0	100.0
Engineering	80	139	36.5	63.5
Consumer goods	35	40	46.7	53.3
Other	35	40	46.7	53.3

Table 9-2 – Data of percent rate of old scrap for remelting and refining processes

Semi-manufacturing categories	Refine, kt/y	Remelt, kt/y	% to refine	% to remelt
Shape casting	195	0	100	0
Flat-rolled products	0	0	0	0
Aluminium cans	0	0	0	0
Powder and paste	77	0	100	0
Foil rolling	0	0	0	0
Extrusions	0	489	0	100
Wire and cables	0	39	0	100
Other products	50	50	50	50

Table 9-3 – Data of percent rate of new scrap for remelting and refining processes. Zeros for refining and remelting processes mean internal recycling of new scrap.

10 APPENDIX D

	Coal	Petroleum	Natural Gas	Nuclear	Other
Bauxite mining	2	478	0	0	0
Nepheline mining	1368	1212	0	0	0
Alumina refining	4,342	6,626	9,279	496	0
Anode production	779	6489	5079	194	0
Coke production	0	0	0	0	4568
Pitch production	0	0	0	0	980
Aluminium smelting	41,515	1,543	13,618	7,143	0
Primary ingot casting	549	1,620	2,552	95	0
Remelting	378	294	1,799	169	18
Recycled aluminium ingot	937	1,319	7,151	419	44
Aluminium extrusion	2,977	1,464	4,219	1,139	118
Aluminium rolling	2,549	1,654	3,928	975	101
Aluminium shape casting	59	669	11,147	26	1
Aluminium cans	0	0	3,077	0	1025
Collection and sorting	0	0	0	0	450
Primary aluminium ingot	50,807	21,268	36,335	8,282	0

Table 10-1 – Values of energy use for aluminium processes.

Values are in MJ. Values for bauxite mining, alumina refining, anode production, coke production, pitch production, aluminium smelting, primary ingot casting, remelting, recycled aluminium ingot, aluminium extrusion, aluminium rolling and aluminium shape casting is taken from (GARC, 2010); nepheline mining from (Dvoinikov, 2011); aluminium cans from (Americas, 2010); collection and sorting from (Quinkertz, 2001)

	grCO2/MJ
Coal	252.1
Natural gas	120.4
Hydroelectric	1.7
Oil	156.9
Petrolium	67.2
Nuclear	18.5

Table 10-2 –Carbon dioxide emissions per MJ of energy from different types of fuel (BOURDIER, 2000), (ToolBox), (Beerten, 2009)

11 APPENDIX E

	Process	**Electricity**	**Fossil Fuel**	**Transport**	**Ancillary**	**PFC**	**Total**
Bauxite mining	0	0	16	32	0	0	48
Nepheline mining	0	0	32	64	0	0	96
Alumina refining	0	58	789	61	84	0	991
Anode production	388	63	135	8	255	0	849
Coke production	0	0	0	0	0	0	560
Pitch production	0	0	0	0	0	0	1057
Aluminium smelting	1,626	5,801	133	4	0	2,226	9,789
Primary ingot casting	0	77	155	136	0	0	368
Remelting	0	57	81	2	0	0	140
Recycled aluminium ingot	0	70	222	28	0	0	320

Aluminium extrusion	0	471	128	141	0	0	740
Aluminium rolling	0	403	114	235	0	0	752
Aluminium shape casting	0	3	461	157	3	0	624
Aluminium cans	0	0	0	0	0	0	122
Collection and sorting	0	0	0	0	0	0	113

Table 11-1 – Values of GHG emissions for processes of aluminium cycle.

Values are shown in kg of CO2 equivalents per 1000 kg of process output.

Values for bauxite mining, alumina refining, anode production, aluminium smelting, primary ingot casting, remelting, recycled aluminium ingot, aluminium extrusion, aluminium rolling and aluminium shape casting is taken from (GARC, 2010); nepheline mining from (Karnachev, 2011); coke production from (Inventories, 2006); pitch production from (IAI, 2003); aluminium cans from (Americas, 2010); collection and sorting from (ArrowEcology, 2010)