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The beginning and the end of the aluminium value chain

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Abstract. Metallic aluminium does not naturally occur in nature, and it was largely unknown, virtually a mystery, until 200 years ago. The modern aluminium production using a hydrometallurgical refining process for making alumina followed by electrolysis of this mineral was first developed in 1886 and, in principle, the same technology is still used to this day. About 90% of alumina refineries in the world use the Bayer process for refining Bauxite ore. It is very efficient, but it can only be used on high quality bauxite with low content of admixtures, especially silicon. The Bayer process also generates a Bauxite Residue (BR), maybe better known as Red Mud (RM) which is a thick red-brown, high-basicity paste consisting of silicon, iron, aluminium, titanium and others. The International Institute of Aluminium estimates that since 1886 almost a billion tonnes of aluminium were produced around the world with three fourths of this amount still being in use today, of which about 35% is located in buildings and structures, 30% in electric cables and equipment and 30% in transport. Aluminium scrap is collected all over the world. In the home, it mostly consists of aluminium beverage cans. It is claimed that 1 ton of recycled empty beverage cans save 8 tons of bauxite, 4 kg of various fluorides and 14 kWh of electricity[1]. Additionally, recycling aluminium significantly reduces the negative environmental impact of ever-expanding RM landfills. As the idea of environmental responsibility is gaining more and more traction, separate household scrap recycling is becoming more and more popular around the world. How challenges related to such activity can be met will be the main topic of this paper alongside discussing new developments for alumina production without RM generation.

Keywords: materials cycle / gross energy requirement / embodied energy / global aluminium flow / aluminium use / transport sector / waste / circular materials economy / alumina production

1 Introduction

Aluminium is a fantastic metal, or element if you like, and in this paper, I try to discuss some issues I find important to focus on in order to maintain and even enhance this articulation. Although I rely heavily on various publications in the vast fields of processing, manufacturing, use and recycling, the interpretations and connotations presented are solely my own responsibility.

Being written for a SAM (Society and Materials) conference, the audience aimed at will have a varying background and I apologise for being superficial in talking about things that are outside of my own field.

Although aluminium is one of the most commonly occurring elements on Earth, it was not isolated until 1808, when H. Davy became the first person to see metallic aluminium. A small amount of the metal was produced in the following decades, but a very difficult process was required, involving heating of the ores in vacuum with pure sodium or potassium. Both these elements could only be obtained by electrolysis, which was not at all straightforward at the time [1].

As a result, pure aluminium was more valuable than gold and platinum in the 19th century. Bars of aluminium were exhibited alongside the French crown jewels at the Paris Exposition Universelle of 1855. Emperor Napoleon III of France was said to have reserved his few sets of aluminium dinner plates and eating utensils for his most honoured guests, while the others had to eat from ordinary gold plates. Also, the pyramidal cap at the tip of the Washington Monument in Washington, D.C., was made of pure aluminium which was obtained before the time of Hall and Héroult (Fig. 1). At the time of the Washington Monument's completion, metallic aluminium was as expensive as silver [2].

Modern aluminium production was invented in 1886 by American C.M. Hall and Frenchman P.L.T. Héroult. The inventors operated completely independently of each other. These two "twin" brothers were both born in 1863, invented the same process when they were in the early twenties in 1886, and both died in 1914. Besides the Hall-Héroult process, two other major inventions from the same time

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[1] Adapted from: https://www.aluminiumleader.com/production/how_aluminium_is_produced/.

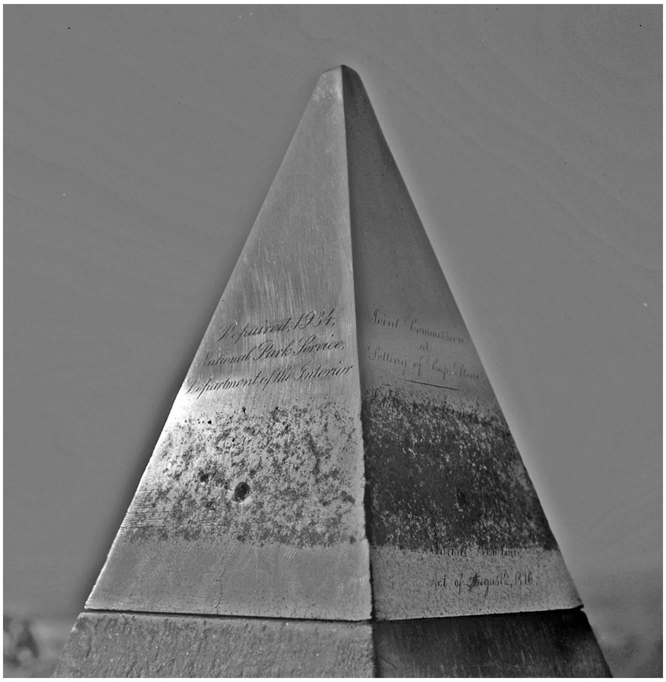

Fig. 1. The cap at the tip of the Washington Monument. Source: This image is available from the United States Library of Congress's Prints and Photographs division under the digital thc.5a48088 [1].

period led to production of aluminium on an industrial scale (and "incidentally" of magnesium) as an inexpensive commodity.

These were W. Siemens' version of the dynamo (1867) to produce electricity and K. Bayer's process for production of aluminium oxide (also called Alumina) from Bauxite (1887) to produce cheaper raw material for aluminium production. Hall and Héroult's achievements came about at the time of the great expansion in the use of electrical power in homes and factories and just in time for the development of metal airplanes. Today more than 60 million tonnes of aluminium metal are produced per year around the world using electrolysis.

Aluminium has many advocates that offer long lists of its benefits, and, as an example, the list below is randomly chosen, based on information taken from Thyssen Krupp [3]:

- Aluminium is an **extremely versatile** metal with several advantages, it is recognised for being both lightweight and flexible. It can be cast, melted, formed, machined and extruded meaning that it can be manufactured into a variety of shapes and then subsequently fabricated to suit a whole variety of uses. Due to its extreme versatility and strength, the use of Aluminium is becoming more popular, especially with the advantages it has to offer. Through the process of aluminium extrusion it can be supplied in ever more complex designs. This extrusion can be supplied in a variety of finishes including anodised, mill or painted and can then be further machined or fabricated.
- A known **lightweight metal**, it has a specific weight of approximately $2.71\,\mathrm{g/cm^3}$. It's about a third of the weight of steel, which makes it easier and cheaper to transport than most other metals. The strength of aluminium can be adapted using varying alloying elements to provide better benefits including higher strength or easier formability. Because of its lightweight nature, corrosion resistance and ease of fabrication, aluminium sheets are the firm for projects like vehicle panelling, artwork, building cladding and kitchen fitting among other applications
- Aluminium is a **corrosion resistant metal** that naturally generates a protective coating. The coating formed is extremely thin and is generated when aluminium encounters an oxidising environment. This protective aluminium oxide (Alumina) layer helps protect the surface of the metal from corrosion. Additionally, getting surface treatment such as painting or anodising can further improve the overall corrosion resistance of the metal.
- It is an **excellent conductor of heat and electricity**. Although aluminium is not as conductive as copper it is approximately a third of the weight meaning that an aluminium wire with half the weight of a copper wire would have the same amount of electrical resistance. As a result, it is the chosen material for power transmission lines. It is also an excellent conductor of heat and is used as heatsinks in a variety of applications such as LED lights, electrical products, computer motherboards, etc.
- Another benefit of Aluminium is its **reflectivity and ductility**; therefore, it serves as a good reflector. It is used in rescue blankets and light fittings because of its ability to reflect both light and heat.
- Aluminium is **odourless and impermeable**. Even with 0.007 mm thickness of aluminium foil, it is still impermeable and does not have a substance taste or smell. This is non-toxic and often used for packaging of the sensitive products including pharmaceuticals and food.
- Contrary to what most people think, aluminium is **100% recyclable** and during the recycling process, it retains all its original properties. During production, it is more cost-effective to use recycled metal than prime metal out of the ground and so, during production, as much recycled material is used as possible.

In the following we will take a closer or slightly alternative look on some of these claims, in particular number 3 and 7. Since nothing in the above list refers to how aluminium is extracted from nature, including how this, and processing and recycling of aluminium in general, might comprise some environmental issues worth consideration will also be discussed. In order to do this, we need to place this metal into the framework we usually employ for analysing extraction and processing of metals.

2 The materials cycle and some thermodynamics

Despite the danger of misleading people by introducing the concept "Materials Cycle", as this might be associated with other "articulations of sustainable development" like "Circular Economy" and "The Green Shift", it has its place here.

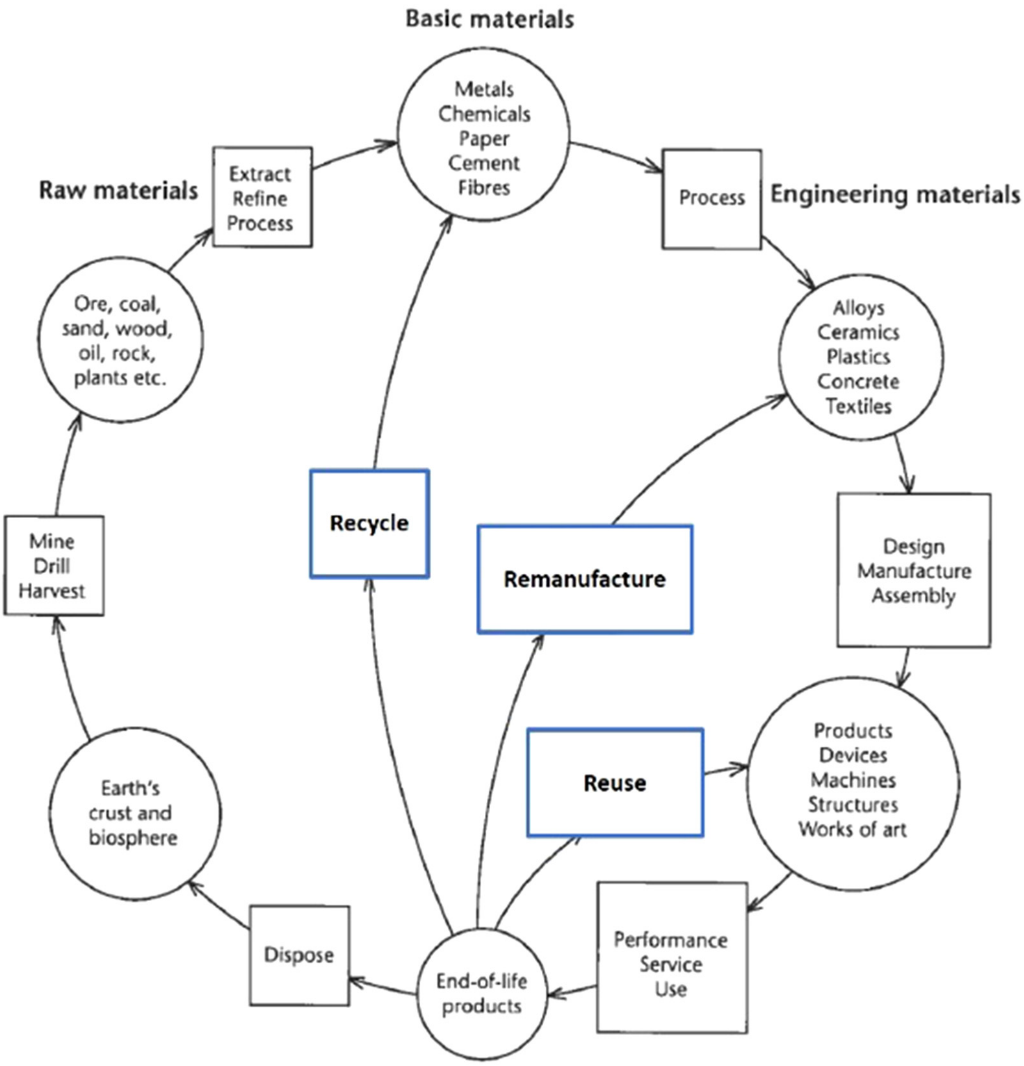

Fig. 2. The materials cycle [4].

2.1 The Materials [Life] Cycle

Assuming here is a *[value]chain* of transformations which *begins* with materials being obtained from the Earth, change in various ways, then is used and finally *ends* by its return to the Earth. Figure 2[2] shows the cycle from the perspective of the useful components of raw materials obtained from the Earth. This is called the *materials cycle*. It is also referred to as the *life cycle* of a material. *Value-adding* occurs as natural resources are transformed into useful products with more value being created as the material is progressively transformed through stages in the *value chain*.

When a product, structure or other entity has reached the end of its useful life, or is no longer wanted or needed, the question arises of what to do with it. In some situations, the object may be *reusable* through repairs or modifications, or *remanufactured*. In other situations, the individual materials or components from which it is made may be able to be separated and *recycled* as secondary materials to a manufacturing process. *Reuse*, *Remanufacture*, and *Recycle* are the shortcuts in the Materials Cycle. In a way these 3 Rs are also articulations that are interpreted differently by different people. As an example: To a metallurgist a recycling process should produce metal, preferably pure, but lower grade metal is often better than none. "Recycling of a mobile phone" is not very meaningful, but recycling of the different metals in the phone is interesting.

In yet other situations it may be disposed of by burning (usually to produce useful energy) if combustible, put into landfill sites if it is deemed not to be too polluting, or put into permanent storage if it is hazardous to the environment or humans (e.g. radioactive materials). The choice depends on many factors, including available technologies for reusing and recycling, the relative costs of recovering, recycling and disposal, and government regulations.

2.2 Some Thermodynamics

The standard Gibbs energy change of formation of a compound, ΔG_f^0, is defined for the formation e.g. of oxides from one mole of oxygen at a pressure of one atmosphere.

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[2] Based on Figure 2.2 in Rankins book on materials and sustainability [4].

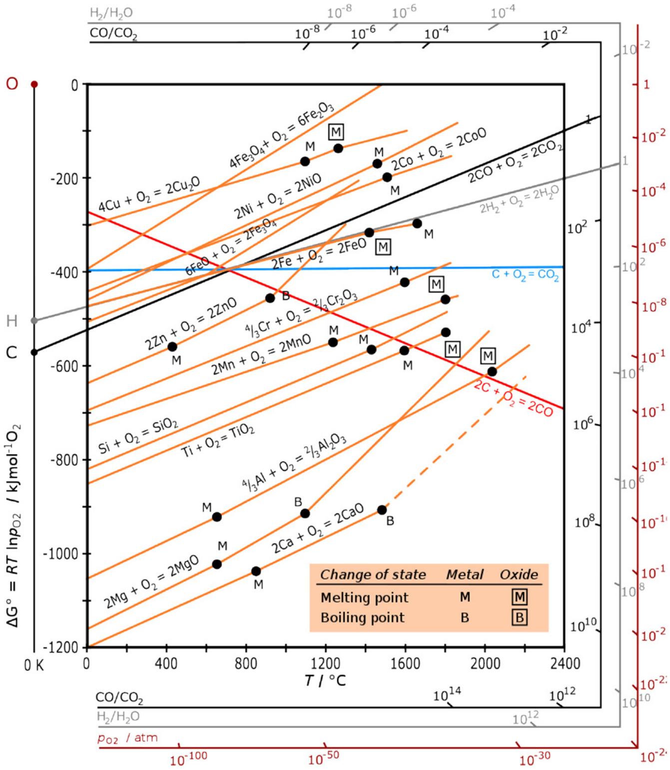

Fig. 3. Ellingham diagram based on principles described in [5].

Within temperature ranges of interest, Ellingham [5] found that the relationship between this variable and absolute temperature T [K] aligned linearly in temperature intervals without change of phase, so we have:

$$\Delta G_f^0 = A + BT, \tag{1}$$

where the B equals $-\Delta S_f^0$, the negative entropy of formation of the compound. The Ellingham diagram for metal oxide formation is shown in Figure 3. This diagram shows the Gibbs free energy of formation, of metal oxides per mole of oxygen, ΔG_f^0 as function of temperature.

Similar diagrams can also be constructed for and other metal compounds like sulphides, chlorides, carbonates, etc. In the following metal oxides are discussed, but analogous discussions can also be made for other compounds.

A very convenient property of this diagram is that it gives the stability of the various oxides at a glance: The stability of the oxides formed increases as you go downwards in the diagram. According to the diagram only CaO and MgO are more stable than Al_2O_3 at lower temperatures. This stability will facilitate formation of thin oxide films on aluminium surfaces exposed to oxygen and is the main reason for aluminium's corrosion resistance as mentioned by Thyssen Krupp. We also see that the melting point of aluminium is about 660 °C, while melting the oxide require temperatures above 2000 °C, or 2072 °C to be more exact. Accordingly, these stable aluminium films that provide corrosion resistance will not easily melt in a recycling process and may give rise to unwanted oxide inclusions.

According to the reaction for producing aluminium from Alumina:

$$2Al_2O_3 = 4Al + 3O_2(g), \tag{2}$$

we can read the ΔG_f^0-value for the *formation* of Alumina, corresponding to the bath temperature of the electrolysis process, 960 °C, and find the value of about −850 kJ/mol O_2. As seen from the reaction written on the Ellingham diagram this corresponds to the value for 4/3 moles of Al and using this and the atomic mass of aluminium which is about 27 g/mol we can calculate $\Delta G_f^0 = 23.6$ kJ/g Al for the *decomposition* of Alumina giving Al and O_2 as products according to equation (2).

This free energy value, 23.6 MJ/kg Al corresponds to 6.56 kwh/kg Al, and this is about half of the value 12–14 kwh/kg Al normally found for energy demand for electrolytic production of aluminium from pure Alumina in the industry [6]. The are many reasons for this apparent efficiency of only ~ 50%: heating of raw materials, electrode over-voltages that must be overcome and resistance losses count for most of this.

This sounds very simple, but the reality is as usual more complicated, in fact, the amounts of effort spent on developing and optimising the Al electrolysis process is enormous and far beyond the scope of this paper. Those familiar with even a fraction of this work will know that reaction in (2) above strictly speaking applies to cells with inert electrodes, and that the production of Al from Alumina is better described by the reaction:

$$2Al_2O_3 + 3C = 4Al + 3\ CO_2(g). \tag{3}$$

In the Hall-Héroult cells, carbon is consumed (~ 0.33 kg C/kg Al) and CO_2 gas (~ 1.2 kg CO_2/kg Al) is produced. The theoretical value for this reaction is much lower than the value 6.56 kwh/kg Al given above when it comes to the actual decomposition of the Alumina, but due to many other necessary considerations the power input needed for an electrolysis cell producing aluminium from Alumina will be in the range 12–14 kwh/kg Al as mentioned. Halvor Kvande and Warren Haupin [7] gives a very understandable discussion of the main factors for cell voltage distribution for Hall-Héroult Cells.

This means that we are dealing with an energy consumption of about 50 MJ/kg Al. If the electricity is generated from fossil fuels[3] with ~ 34% efficiency this would be equivalent to about 147 MJ/kg Al. In a Life Cycle (LCA) perspective additional activities like ore processing, transport/distribution of raw materials and products, handling of waste materials as well as manufacturing of process equipment must be included to obtain the total, or **Gross Energy Requirement (GER)** to produce aluminium. In the literature we can find several numbers for this, and one presumably reliable value: 212 MJ/kg Al, can be found in Rankin's book[4]. For hydroelectric power generation the Gross Energy Requirement (GER) is accordingly about 112 MJ/kg Al.

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[3] Which is the case for ~ 70% of world total Al production.

[4] Table 9.5 pp. 195 in [4].

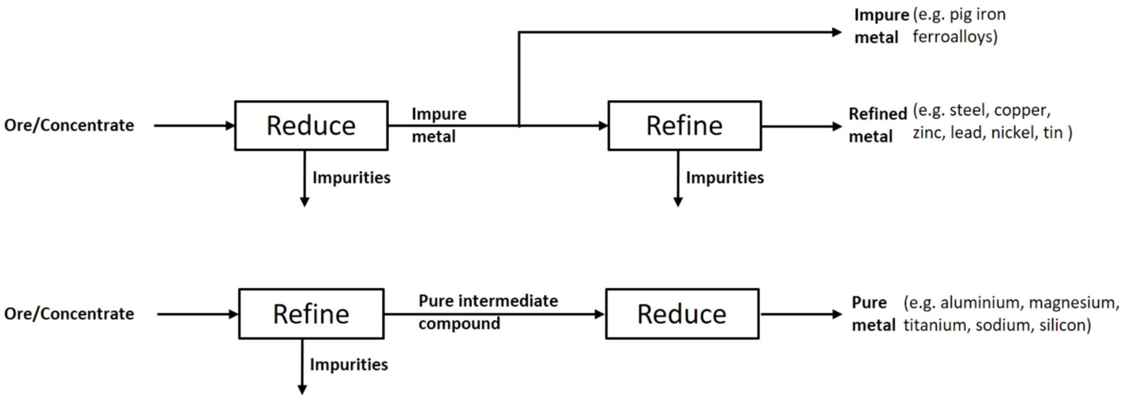


Fig. 4. Reduce and refine or the other way around. Adaption of Figure 8.4 pp. 158 in [4].

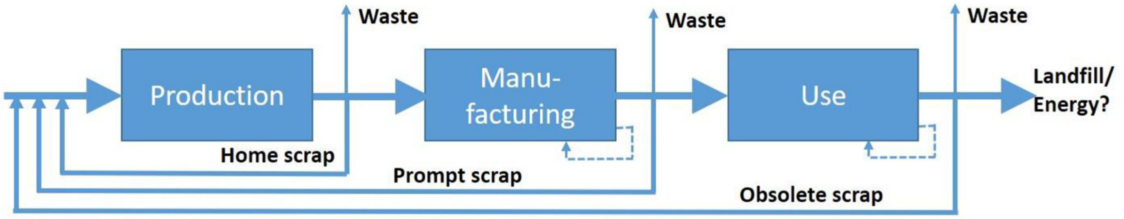


Fig. 5. The main scrap categories: Home, Prompt and Obsolete.

A very important consequence of the differences in stability of the metal oxides is that the *Extract and Refine Processing* required to obtain the sought metal differs dependant of their place in the Ellingham diagram (Fig. 3). In short, a process metallurgist mainly works *against* nature since the metals "want to" be in form of oxides, sulphides, chlorides, carbonates, etc. when exposed to normal environmental conditions.

As illustrated in Figure 4, making steel from ore after its beneficiation follows the *Reduce, and then Refine Scheme*. In order to make aluminium metal, however, you must first make a pure aluminium oxide as an intermediate compound; the *Refine and then Reduce Scheme* must be followed. This is simply because removal of contaminations from metallic aluminium is very difficult.

3 Recycling of aluminium in General

The meaning of the term "recycling" for a metallurgist is, as illustrated in Figure 2, to process "End-of-life products" such that "Basic materials", e.g. metals, are made available for new processing. Materials from recycling should accordingly be equivalent to materials coming from the *Extract and Refine Processing* which is discussed above in relation to Figure 4. In order to recycle materials available for recycling, that is materials for which there is no alternative usage, they must be taken out (collected) from the materials flow of which they are part. The most useful concepts and their most commonly used names are *Recovery Rate, Recycling Rate* and *Return Rate*. These terms are often used interchangeably, and care must be exercised to understand which term is intended:

- The *Recovery Rate* is the quantity of a secondary material that is recovered by collection systems as a percentage of the total quantity of the material available.
- The *Technical Recovery Rate* is the quantity of material recycled as a percentage of the quantity collected and is a measure of the efficiency (yield) of the technical processes used for recycling.
- The *Recycling Rate* is the quantity of a material that is recycled as a percentage of the total quantity of material available. The *Recycling Rate* is equal to the product of the *Recovery rate* and the *Technical Recovery Rate*.
- The *Return Rate* (recycled content) is the quantity of a material that is recycled for use in manufacturing as a percentage of the total quantity of the material (primary plus secondary) used for manufacturing: the *Return Rate* is the percentage of a material that is supplied from recycled sources, the balance stemming from primary sources.

Stretching the meaning of the "end-of-life products" concept, the different rates above can be applied to all of the main scrap categories: Home, Prompt and Obsolete illustrated in Figure 5. The dotted lines indicate possible internal recycling in the "Manufacturing" and "Use" phases. Also note that the concepts of "Reuse" and "Remanufacture" from Figure 2 are not shown in Figure 5.

Claim 7 in the Introduction; "... aluminium is **100% recyclable**..." is true in the meaning that the Al-atoms are generally not destroyed in any way, but the same holds for all metals since they are elements.

3.1 Energy Issues in Recycling

It is often heard that the energy required for remelting aluminium is only 5–10%[5] of the energy required for primary production. This is maybe not so far from the truth, but this number must be used with care. Imagine that aluminium is produced with coal-based power supply which as mentioned above will have a Gross Energy Requirement (GER) of 212 MJ/kg Al, and this is also the **Embodied Energy (EE)** per kilogram in its first application. Imagine further that the aluminium is remelted, requiring 20 MJ/kg Al, after this first use giving a total energy input of 232 MJ/kg Al, or 116 MJ/kg Al per application, and so on. In Figure 6a the bottom curve shows the embodied energy per application of aluminium as a function of the number of times the metal has been recycled. At recycle number 10 the EE per kilogram is still about 40 MJ/kg Al which is about twice the specific remelting energy required. In a popular manner we may say that the Aluminium remembers that it once was Bauxite even after many recycles.

The example above is based on a return rate of a 100%, and as this is usually not the case, the effect of lower return rates is shown in the same figure. It is seen that the EE in a closed loop recirculation will asymptotically approach a value given by the distribution of remelted and primary material after infinite recycling, and accordingly of primary energy and remelting as given by the return rate for the loop. It is easily seen that the return rate is crucial for the energy economics of recycling.

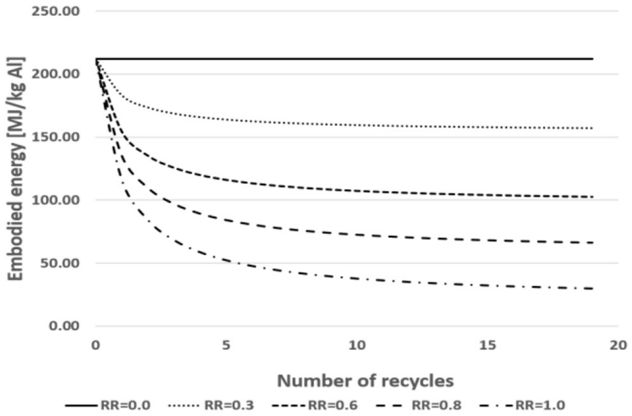
Figure 6b clearly shows the effect of changing the Gross Energy Requirement from the value for coal-based power supply (GER#1) to hydro-electric power supply (GER#2). The contribution from the remelting is of course independent of this change, and the asymptote for this per application is 12 MJ/kg Al as expected with a return rate of 60%.

What if an increase in energy used in association with the remelting is increased with a factor two in order to increase the return rate from 60% to 80%? As shown in Figure 6c this will reduce the Embodied Energy per kilogram significantly.

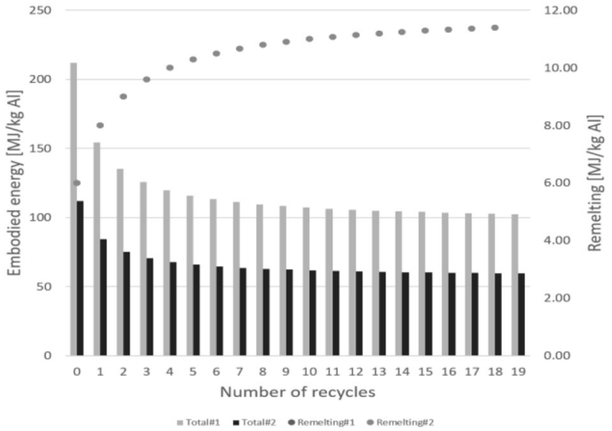
This discussion is by no means new: Reidar Huglen and Halvor Kvande [8] published a paper in TMS Light Metals more than 25 years ago; see Figure 7, but it is still unknown by the public in general.

3.2 Material quality

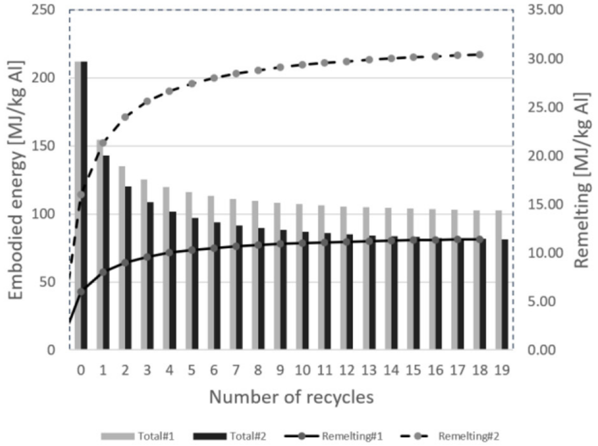
As seen above the Return Rate has significant implications on the Embodied Energy of an aluminium product, but even more important is the effect arising from the alloying and trace elements reintroduced in the metal stream through recycling in addition to those supplied with the Alumina from the refinery.



a) GER = 212 MJ/kg Al; Re-melting: 20 MJ/kg Al



b)Return rate = 60%; GER#1 = 212 MJ/kg Al; GER#2 = 112 MJ/kg Al; Re-melting: 20 MJ/kg Al.



c) GER#1 = GER#2 = 212 MJ/kg Al; Case #1: Re-melting: 20 MJ/kg Al Return rate = 60%; Case #2: Re-melting: 40 MJ/kg Al Return rate = 80%

Fig. 6. The embodied energy of aluminium: Effect of number of recycles, Return rate and GER.

An overview of the main alloying elements in wrought (low alloy) and cast aluminium alloy series is given in Table 1 based on information from Mukhopadhyay [9]. It is obvious that care must be taken when mixed scrap is remelted if the goal of the recycling is to produce alloys conforming with this system.

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[5] Table 13.3.5 pp. 279 in [4].

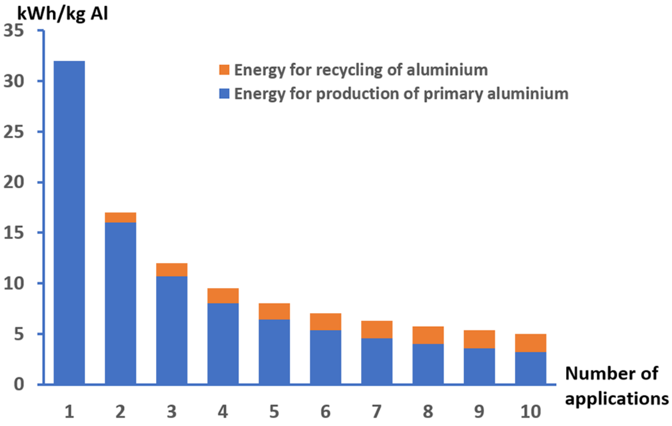

Fig. 7. Average energy consumption per number of applications of recycled aluminium. Return Rate = 100% Redrawn from Huglen and Kvande 1994 [8].

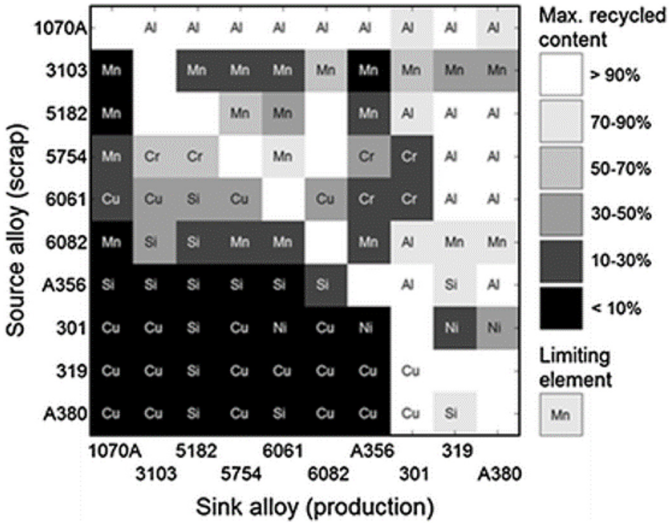

Fig. 8. Options and constraints for recycling of typical automotive aluminum alloys. Greyshades indicate the percentage of a source alloy (scrap) that could be used in production of a sink alloy. Limiting elements for recycling are indicated in each square [11].

An overview of impact of various elements on the processability and properties of some aluminium alloys given by Trond Furu et. al. [10] is partly summarized in the following list:

- Surface properties: Surface activating Pb, In, and Sn in medium strength 1000, 3000 and 6000 alloys facilitates mechanical processing, e.g. extrusion. The addition of Cu to the alloying element Si is often associated with introducing susceptibility to intergranular corrosion (IGC) of 6000-series alloys. The effect of Zn on grainy/surface appearance in extruded profiles is important in sectors where the visual aspects of products must be taken into consideration.
- Mechanical properties: Strength and ductility are reduced significantly at Ca-levels above ~500 ppm in a 6060 alloy (Al-0.40Mg-0.40Si-0.20Fe) due to the tendency of the Ca to form particles containing Si and sometimes Mg containing particles. Si and Mg are then less available to form age hardening precipitates, and thus the age hardening potential of the alloy is reduced. Relatively small amounts of Mg, Cu and Mn have a significant influence on strength due to strain hardening in 1xxx-series alloys.
- Castability: the ratio of P to Sr will influence the eutectic solidification and thus the feeding behaviour and porosity distribution of Al–Si foundry alloys. In an unmodified Al–Si melt the eutectic Si nucleates on AlP particles but adding Sr to the melt prior to casting modifies the eutectic morphology and thus improves its mechanical properties. Sr poisons the AlP particles causing an increase in the eutectic grain size. Ti and B, e.g. TiB_2, act as grain refiners and Ca can also significantly influence the porosity distribution.

To ensure that aluminium and its alloying elements are effectively recycled in the future will require the development of new robust technical and societal solutions, and close collaboration between the different players in the field is essential.

For alloys used in the automotive industries a Source-Sink diagram (Fig. 8) was developed by Modaresi and Løvik [11].

4 Global Aluminium Flow

An overview of the global aluminium flow is provided by the International Aluminium Institute [12] in the form of a publicly accessible Mass Flow Analysis (MFA) tool, and the methodology, data quality and sources for the modelling tool are described in a paper by Bertram et. al. [13].

Figure 9 shows the situation in 2007 (38.1 mill. Metric tons) and 10 years later (2017: 63.4 mill. Metric tons). It indicates how fast the global aluminium industry has increased and, more importantly, the permanency of the material fractions subject to end-of life and scrap management.

In 2013 Cullen and Allwood [14] published a Sankey diagram, Figure 10, showing the Global Aluminium Flow in 2007, where some notable features are clearly revealed:

- Two main routes: **A** Mechanical forming (Rolling, Extrusion, Wire Drawing) using primarily the “Wrought Alloys" in Table 1 and **B**: Casting using primarily the “Cast Alloys" in Table 1.
- Primary metal consumption in route **A** (29.8 mill. tons) is more than 4 times higher than in route **B** (7.1 mill. tons).
- End-of-life scrap (obsolete scrap) is mainly consumed in **B** route.
- Amount of material for End-uses (global demand for aluminium products, 45 million tonnes) is more than 5 times higher than the End-of-life scrap, 8.3 million tonnes.
- Metal products like *Drink cans* and *Packaging* are mainly made from **A**-type materials but when recycled they will follow route **B** and most likely end up in cars.

Table 1. Aluminium alloying elements series designation [9].

Wrought aluminium and its alloys		Cast aluminium and its alloys	
Designation	Main Alloying elements	Designation	Main Alloying elements
AA1XXX	Pure aluminium	AA1XX.X	Pure aluminium
AA2XXX	Copper	AA2XX.X	Copper
AA3XXX	Manganese	AA3XX.X	Silicon, with copper and/or magnesium
AA4XXX	Silicon	AA4XX.X	Silicon
AA5XXX	Magnesium	AA5XX.X	Magnesium
AA6XXX	Magnesium and silicon		
AA7XXX	Zinc	AA7XX.X	Zinc
AA8XXX	Lithium	AA8XX.X	Lithium

5 Aluminium End-USE in Society

The two sectors Transport and Packaging are used as examples to show the diversity of the way aluminium is used in society in general and also the implications on recyclability (Fig. 11).

5.1 Transport

A large number of papers and reports are published addressing global aluminium flow and in particular the implications in and from the developments in the automotive sector [11,15–20] and, although different issues are in focus, most of these papers clearly show that this sector serves as the sink for virtually all obsolete (post-consumer) aluminium scrap, mainly in the form of cast engine blocks for internal combustion engines. A substantial amount of aluminium will be used in the automotive industry in the future, but the Cast Alloys share of this will be reduced since the electric cars have no engine blocks. It seems inevitable that the anticipated relatively fast transition to electric drive chains for passenger cars will relatively soon create a situation where it will be difficult to absorb an increasing amount of post-consumer scrap. Further information pertaining to this is given later in this paper.

Material Economics (ME) is a Swedish company describing themselves as "...team consists of former consultants of top-tier management consultancies who are passionate about sustainability", and they have conducted a project "Retaining value in the Swedish materials system" [19] together with the recycling industries in Sweden and some people from academia as part of an Innovation Program: "RE:Source". They have partly used global data [14], but also national data, especially on economy and consequences for society and people in general.

According to ME the present distribution of aluminium used in cars is 34% wrought alloys and 66% cast alloys, and, looking closer at the cast alloy use, they find that 46.4 of those 66% are found in components (drive line, engine bloc and head, etc.) that do not exist in fully electric, battery based cars; BEVs – Battery Electric Vehicles. The remaining 19.6% of the total will probably be made from cast alloys in the future. We can only assume what strategies for maintaining the use of aluminium in the automotive sector will be. Some people mention battery casings or containers as a future market, and these might be cast products.

The question of consequences from the seemingly inevitable change from Internal Combustion Engines (ICEs) toward New Energy Vehicles (NEVs) has recently also been investigated by CM Business Consulting in a recent report for the International Aluminium Institute on Aluminium usage in China's automobile industry [21]. CM describes a development for use of aluminium in passenger cars as shown in Figure 12.

For traditional ICEs, the aluminium casting is widely used to manufacture engines, roughly taking up to 70% of the total usage. For BEVs, Al casting only takes up ~ 50% of the usage in 2018, followed by Al sheets as more sheets are used to manufacture the battery pack case.

In the future, with the development of BEVs, aluminium casting, although it remains a dominant form, is forecast to take a lower proportion, while the proportion of Al rolled product is estimated to increase.

Considering that a possible development in the future will shift towards public transport systems, it is interesting to investigate the future use of aluminium in buses. The CM Group has also investigated this, and their analysis is that wrought aluminium will dominate over castings for this product group as well, as shown in Figure 13.

What is driving the development of aluminium alloys, manufacturing technologies and their use in the automotive sector is highly complex, and there are many players here: First we have the actual *metal (alloy) producers*, who may or may not rely on suppliers of Alumina. Then there are *the automakers* themselves who are experts in other fields than alloy development and metallurgy. The automakers design and assemble the cars they sell, but the individual parts and components are made by *Original Equipment Manufacturers (OEMs)*. The fourth group of actors are the *technical consultants* who have competence in testing if equipment produced is according to specifications, but they are also able to assess results generated in academia and sometimes use this to develop commercially viable products.

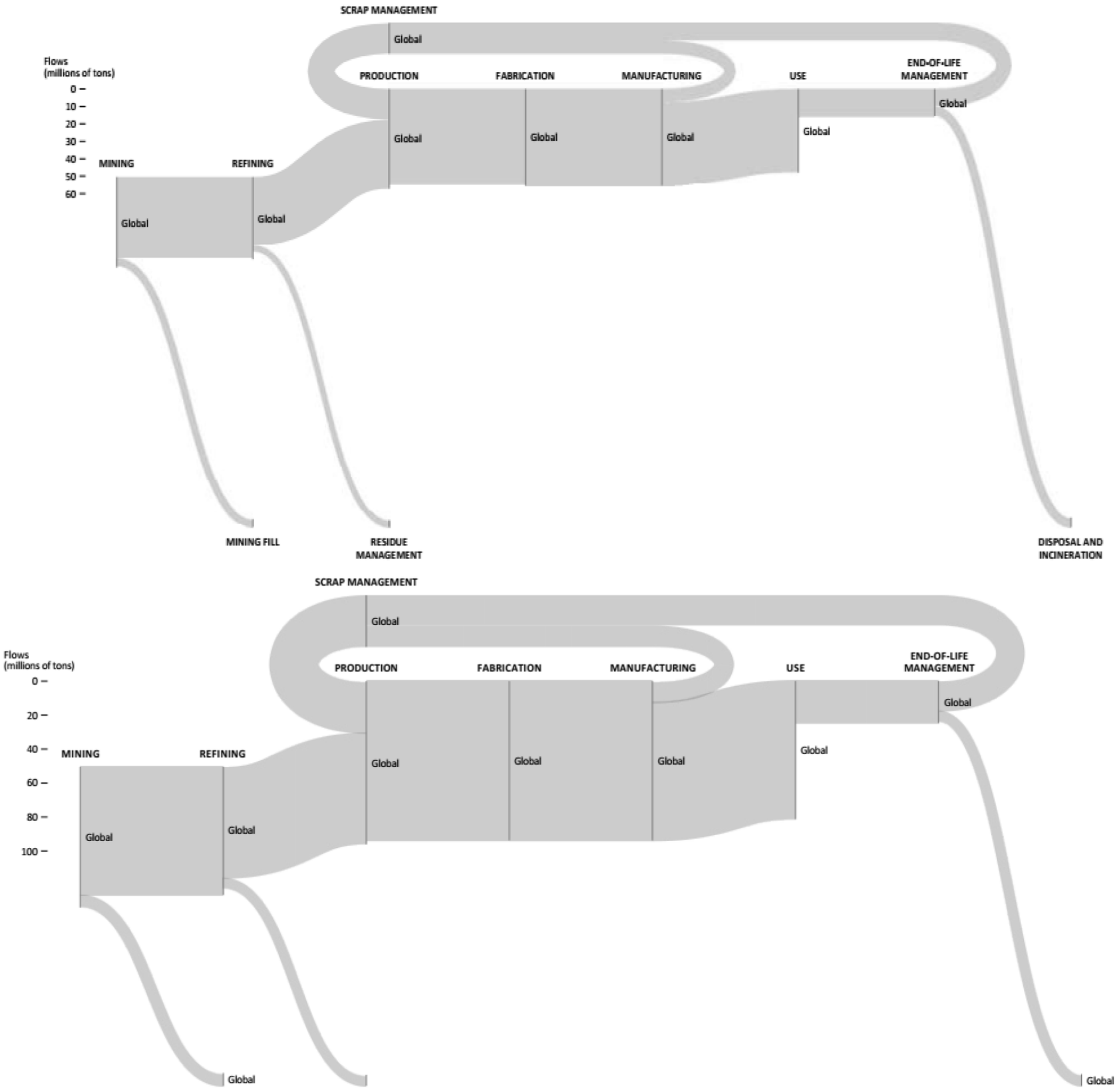

Fig. 9. Global Aluminium Flow 2007 (top) and 2017 (bottom) [12].

From Goran Djukanovic, “AluminiumInsider” [20]:

Most of the major suppliers are now developing AA7xxx automotive sheet alloys in an attempt to meet the higher expectations OEMs have for greater strength. However, the AA7xxx alloys (with additions of Zn), aside of higher cost, must overcome both corrosion and stress corrosion issues, particularly for alloys that are conventionally weldable. Consequently, the AA6xxx alloys remain the predominant materials used in automotive applications for now… The deciding trend that will dominate aluminium alloys characteristics in the future for automotive OEMs is superplastic forming. The process enables aluminium manufacturers to produce thin-walled aluminium sheet components. It is a cost-effective process that can stretch the sheet at over 200% above its original size, while maintaining or even improving tensile strength. Another trend, though not correlated to the first one, is the increasing presence of recycled scrap content in future aluminium alloys used by auto industry.

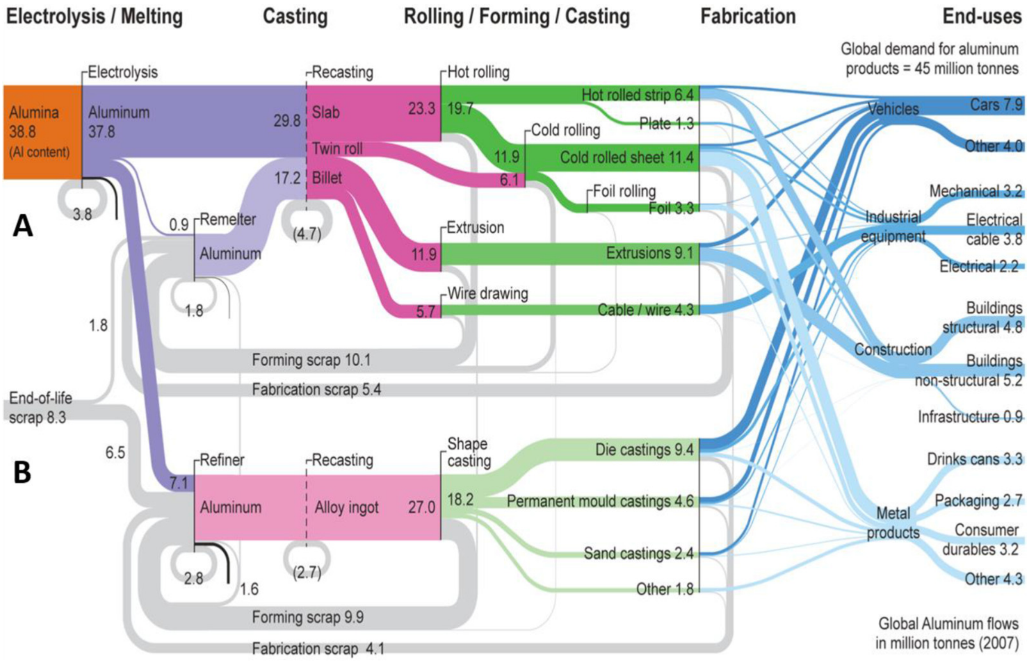

Fig. 10. Global Aluminium Flow 2007 from liquid aluminium to end-use goods [14].

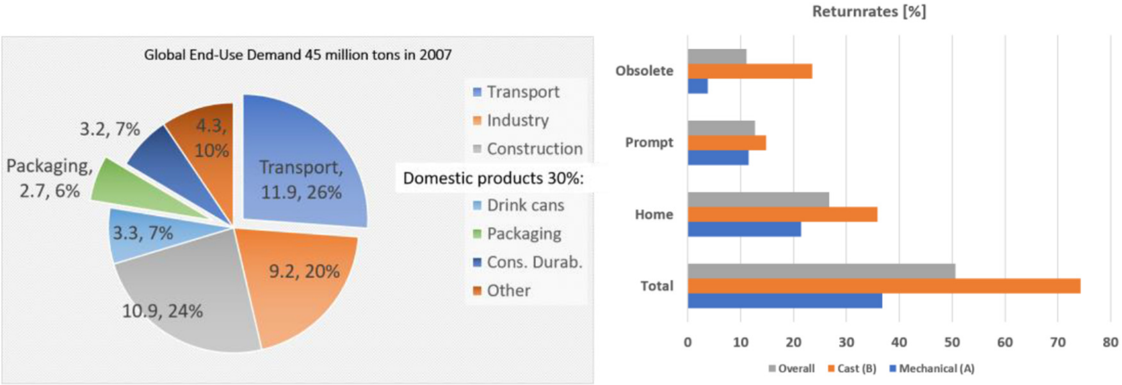

Fig. 11. Distribution of global end uses, and scrap return rates based on flows as shown in Figure 10.

In between these actors there are also commentators or “influencers” operating on the Internet. One such person is Goran Djukanovic who is running the “AluminiumInsider” [20]. He says things like:

Norsk Hydro recently introduced three new aluminium alloys (**5083**, **5456** and **7020** alloys) in order to improve the superplastic forming process by reducing the process time and rendering them more attractive to the automotive industry [20].

Generally speaking, it is in principle easy to collect the aluminium from end-of-life vehicles, and it is known what alloys the different parts of interest are made from, but on the other hand it is fairly certain that the automotive industry cannot be relied on as an unlimited sink for recycled aluminium in the future since the use of castings relatively speaking will be dramatically reduced.

5.2 Packaging

The term packaging is used mainly in connection with the food industry in the form of containers for food- and drinks packaging due to its good formability, low density and corrosion resistance. As indicated in Figure 11, drink cans and packaging for food was about 13% of the global demand for aluminium products in 2007, and according to Materials Economics [19] the European consumption for such goods was 17%.

Aluminium in consumer packaging is more challenging to recycle compared with scrap from transportation and buildings due to its small size, low mass and often complex multicomponent structure (plastics, paper, pigments, etc.). The challenge is basically twofold: *Collection* and *Recycling*. The first is in many ways a societal challenge that

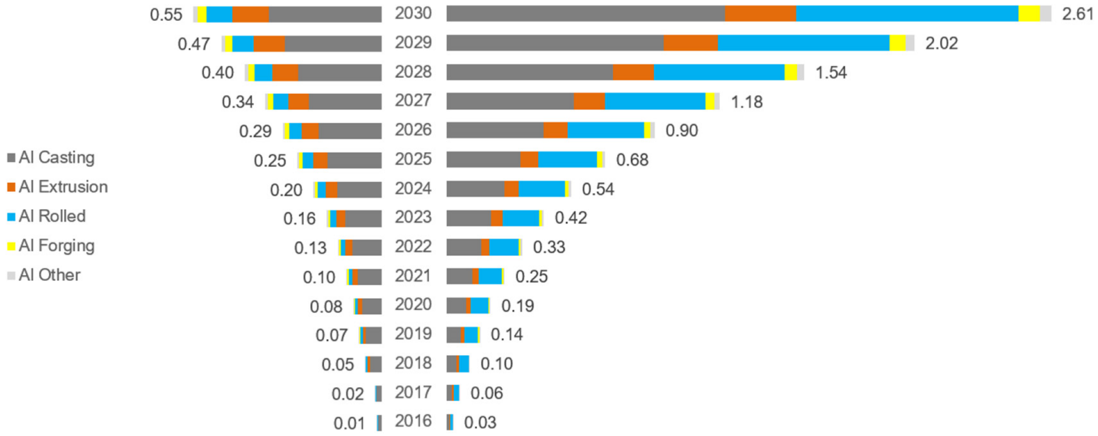

Fig. 12. Use of aluminium in million tons in Hybrid (left) and Battery Electric Vehicles (right) by forming type in China 2016–2030 [21].

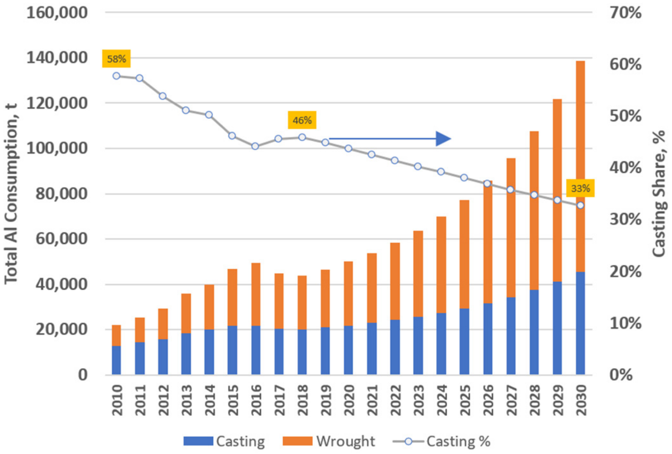

Fig. 13. Use of aluminium in million tons in buses by forming type in China 2016–2030 [21].

requires continuous effort by users of these products both as individuals, but the society in general must also provide systems that makes the collection as easy as possible for the user. Success here will increase the *Recovery Rate* of this material. As mentioned earlier this must also be combined with a sufficiently high *Technical Recovery Rate* in order to get a satisfactory *Recycling Rate*. At the Norwegian University of Science and Technology (NTNU) and the Foundation for Scientific and Industrial Research (SINTEF) in our *Centre for Research-based Innovation: SFI Metal Production*, we do research mainly on the technical aspects of recovery [22–24].

In *Project Alpakka – Circular Aluminium Packaging in Norway* [25], the aim is to increase the *Recycling Rate* of aluminium packaging waste, transforming the material into value-added products by combining innovations in return/collection systems, packaging design, and furnace operations for packaging melting/recycling operations. With *Hydro* at the forefront, and including those responsible for collection and recycling, *Norsk Metallgjenvinning, Metallco* and *Infinitum*, the food producer *Kavli*, as well as NTNU and Sintef providing research support, this will establish a circular aluminium recycling value-chain for collectors, food producers, packaging designers, and aluminium recyclers. The project will receive 1.5 million &z.euro; in support from the Research Council of Norway over three and a half years.

The mass fraction of aluminium in a packaging depends on the function aluminium plays in the item and can be categorized afterward. This categorization is useful as it coincides with how easy the item can be recycled, including sorting, pre-treatment and remelting, is decreasing with increasing category number [22]:

- *Category 1.* Structural: Sheets and foils with up to 99% aluminium by mass and thickness 50 to 250 µm. Items like cans for beverages and canned foods, trays and foils for roasting fish and chicken, aluminium tubes for cosmetics and food spreads and coffee pods. Typically contains significant amounts of organic contamination.
- *Category 2.* Functional: Smaller pieces of aluminium attached to larger pieces of other packaging materials, often designed to tear or be removed upon opening, used to seal toothpaste tubes, pill cards and many food items. Typically attached to other materials such as plastics, papers.
- *Category 3.* Laminar: Aluminium rolled into thin foil used in laminate with organics such as plastic, lacquer (which could also contain metal oxides), paper and glue. The aluminium in such foil is typically thinner than 50 µm, and very difficult to separate out.

Unprocessed aluminium household waste contains a large fraction of organics materials in the forms of foodstuffs and inherent co-materials such as plastics, coatings and lacquers. These cannot be part of a recycled metal and are typically removed thermally, whether this occurs during remelting or in a separate de-coating step. The aluminium contains significant contents of alloying elements such as magnesium, iron and silicon. These are both a challenge and an opportunity: If utilized correctly recycled materials could require lower additions of alloying elements. Sometimes these alloying elements, which are difficult to remove from the aluminium melt, must be diluted with primary aluminium.

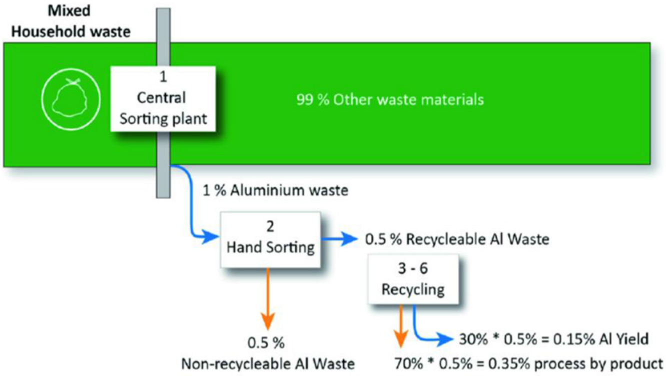

Fig. 14. Aluminium in Mixed Household Waste [22].

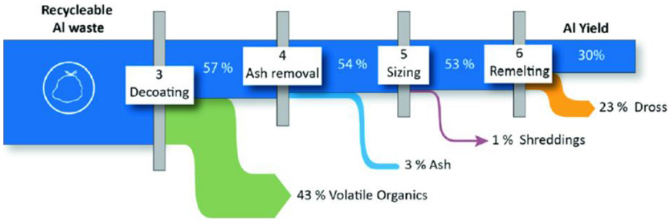

Fig. 15. Recycling process steps for Al-recovery [22].

– *Example 1 Recycling of Mixed Household Waste*

In his master project Sigvart Eggen, an NTNU student, wanted to investigate recycling of real-life waste material containing aluminium, and through visits to several companies involved in collecting and pro-cessing household waste, he obtained samples of waste material believed to contain aluminium. As shown in Figure 14, such waste is about 1% of the total mixed waste. Based on earlier experiments, material of category 3 above was sorted out as *Non-recyclable* using the procedures for recycling planned for this project.

This material is mainly multilayer packaging consisting of multiple layers of different plastics, sometimes paper, and aluminium, aluminium typically amounting to less than 20% of the total weight. The combination of these materials gives a packaging material that is lightweight and has excellent preserving qualities. Because of this unique combination of properties, the use of multilayer packaging is rapidly increasing. A drawback of multilayer packaging however is recycling. Because the different materials are in close contact, it is hard to separate and recycle them. Today most multilayers are landfilled or incinerated, causing the materials to be lost.

In addition to determining the Yield or *Technical Recovery Rate* for the procedure to 30% as shown in Figure 15, it was also found that the difference in decoating temperatures was very important for pore formation (Measured by Reduced Pressure Test, RPT), inclusion density (Measured by Porous Disk Filtration Analysis, PoDFA) and Alloy Chemistry (Fig. 16).

– *Example 2 Recycling of Sorted Household Waste*

Nespresso single-use coffee pods consist mainly of aluminium (88%). The rest are plastics (e.g. polypropylene filter), a silicone ring, lacquers and so on. Nespresso focuses on in-house recycling. They provide collection systems that bring the used pods from the customers to their own recycling facility within an established local recycling company. This ensures a pure scrap composition. The pods are collected in plastic bags. The pods and bags are shredded and pass through a sieve. Around 30% of coffee residue is separated by this sieve. The shredded scrap passes through a drying drum, the temperature depends on the water content of the coffee residue. After the drying process, the remaining coffee residue is dry enough to be separated by a second sieve. The scrap now contains only aluminium and plastic, which are separated using an eddy current system. The aluminium pods are compacted into bales ready for further processing. The aluminium is melted and used for a variety of applications, but since 2017, the company has attempted to use the recycled aluminium for new pods. The coffee residue can be converted into biogas and compost [24].

Used coffee capsules is an example of a packaging which is *Collected* at producer retail outlets. *Recycling* of collected capsules can, however, be challenging due to their high organic content (coffee residue) and an assessment of suitable recycling methodologies is hence required. An investigation [23] following the procedure sketched in Figure 17 showed that even supposedly similar units, in this case Nespresso capsules, behave differently. One illustration of this is the result of the thermal pretreatment of heating the capsules to a holding temperature of 500 °C and maintaining this for 3 h as shown in Figure 18. During this heat treatment, pyrolysis processes occurring were followed by gas analysis and confirmed that degradation of organics during pyrolysis is a complex process (Fig. 19). To define the exact formation of components can be challenging due to the multiple reactions that happen simultaneously. However, detection of the main compounds in the off gas provides some hints about the degradation mechanism that occur during the thermal process including drying, pyrolysis and melting. During the whole process, at least two periods can be identified. The first one corresponds to a dehydration and the second to a degradation process. The organic material degrades into volatile components and char. The second period correspond to a cracking step, which degrades long organic molecules into short chain hydrocarbons like methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4) and butane (C_4H_{10}). Cracking of aliphatics and aromatic bonds leads to formation of free hydrogen (H_2) and compounds from hydroxyl (–OH) group like cresols and acetic acid (CH_3COOH). From the off-gas analysis presented in [23], it can be also seen that formation of halogenated compounds are only stable in the gas phase after 300 °C.

Coffee capsules contains 86 wt.% coffee and other organic (coatings) materials, which will degrade into volatile gases and pyrolytic coke during thermal treatment. Defining metal yield relative to mass of capsules treated showed metal yield results between 74.6 and 82.3% (78.2% in av.) trials performed after emptying the coffee from the capsules.

Fig. 16. Effect of de-coating temperature. From left unprocessed material, de-coating at 300 and 550 °C [22].

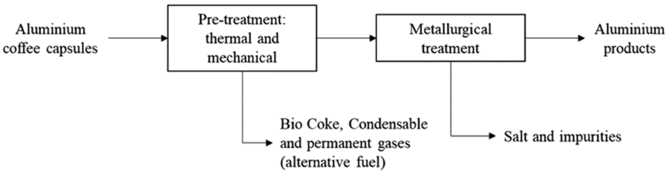

Fig. 17. Procedure for recyclability assessment of used aluminium coffee capsules.

Fig. 18. Different coffee capsules before and after holding at 500 °C for 3 h [23].

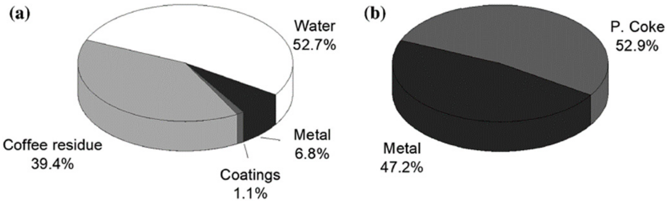

Fig. 19. Mass distribution of material components of a capsule before (a) and after pyrolysis (b) [23].

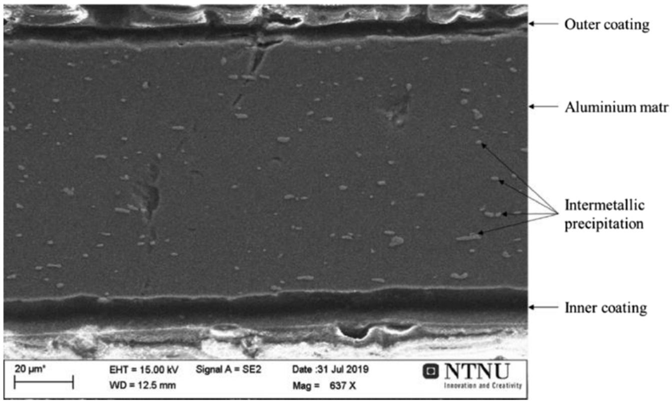

Fig. 20. Cross sectioned wall of a coffee capsule. The total wall thickness was measured to 100 µm consisting of 13 µm of inner and 6 µm of outer coating. Intermetallic Al–Fe–Si precipitates are present in the matrix [23].

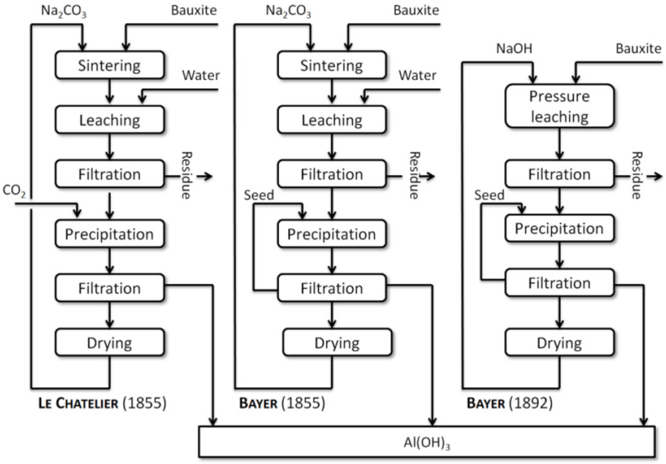

Fig. 21. Bauxite refining [33].

Remelting capsules with all (100%) coffee residue still present gave a metal yield of zero, removing half of the coffee residue (50%) gave 2.9% metal yield, while remelting capsules retaining 10% of the original amount of coffee residue gave a metal yield of 10.2%. The water content and the degradation of organics still present after pre-treatment has an important influence on the metal yield since produced gases react with aluminium to produce aluminium oxides and/or carbides, which cannot be recovered during the remelting in salt.

The remelted aluminium had the purity of ~ 99 wt% Al. Main minor/alloying elements are Fe and Si (Fig. 20). Na and K concentrations are high due to the recycling process under a chloride based salt flux which can be removed by fluxing with either pure chlorine or chlorine/inert gas mixtures.

For later handling it is of great importance that the recovered metal is in the form of larger pieces – coalescence efficiency was measured and varied from 0 to 100%. The efficiency was in average 83.8% for the used capsules and 95.3% for the unused ones.

6 From bauxite to alumina

The bauxite ore was discovered in 1821 by Pierre Berthier (1782–1861), a professor at the School of Mines in Paris, while he was sourcing iron ores in a southern part of France [26]. Berthier thought it was an iron ore as the dark reddish-brown color exhibited by bauxite ore is relatively similar to the color of iron ore. However, it was observed

Table 2. Mineralogical compositions of lateritic and karst bauxites [31].

Constituent	Lateritic bauxite	Karst bauxite
Al_2O_3	Gibbsite, Boehmite	Boehmite, Diaspore
SiO_2	Kaolinite, Quartz	Kaolinite, Quartz, Chamosite, Illite
Fe_2O_3	Goethite, Hematite	Hematite, Goethite, Maghemite, Magnetite
TiO_2	Anatase, Rutile	Anatase, Rutile, Ilmenite
CaO	Calcite, Apatite, Crandallite	Calcite, Apatite, Crandallite

that the ore has a high content of Alumina. The name of bauxite is derived after the village of Les Baux where he discovered the ore. In the literature [27], bauxite is regarded as an ore that is produced from parent rocks containing Al–Fe–Si with the exception that the Al content is relatively high, up to 60 wt.%. Bauxite deposits are primarily divided into two groups according to their host rock, which are laterite and karst bauxites. Lateritic bauxite is mostly found in equatorial regions and is formed by laterization/weathering under intense wet and warm condition of silicate rocks, e.g., granite and gneiss, and mafic rocks that are rich in magnesium and iron oxides [28]. On the other hand, karst bauxites are formed by a weathering process that occurs upon carbonate rocks such as limestone and dolomite [29], where the deposit occurrence is known preferentially in Europe and Northern Asia [30–32]. These two bauxite types, however, have different mineralogical compositions that eventually affect the efficacy of alumina recovery after a digestion treatment. Lateritic bauxite is dominated by gibbsite, which is considerably easier to digest in the Bayer process (Fig. 21), whereas karst bauxite has a high amount of boehmite, and diaspore, which are more difficult to digest [30,33]. Table 2 shows an approximate mineralogical composition of lateritic and karst bauxites as reported by Smith [31].

In alumina production by the Bayer process, the digestion of bauxite is one of the most energy consuming steps compared to the other parts. The digestion effectiveness of bauxite in this process mainly depends on its mineralogy (e.g., gibbsite, boehmite, or diaspore) knowing that different Al_2O_3-containing minerals require different digestion conditions. Monohydrates (γ-AlOOH and α-AlOOH) are less reactive than the trihydrates (γ-Al $(OH)_3$), which need a higher temperature and alkali concentration for their digestion. Nevertheless, all three minerals need considerable high pressure and temperature to yield metallurgical grade alumina. It is also known that the pre-desilication process at elevated temperature [31] and the bauxite residue (Red Mud) of this process have severe problems with the environment [34–36], which need attentive regulation concerning its disposal and storage.

6.1 The Pedersen process – EnsureAl

Harald Pedersen had proven in 1927 [37] that it is viable to yield alumina at low pressure and temperature-leaching of calcium-aluminate slags that is produced from smelting-reduction of bauxite. An overall illustration of the process is shown in Figure 22. This process was run commercially in Høyanger, Norway, from 1928 to 1969 with 17 000 ton of annual production before closing. During that period, other researchers had adapted the patent for utilizing ferruginous bauxite in Albany, and a pilot-plant of alumina production from non-bauxitic source (clay) in Tennessee. Years later, preliminary studies on an alumina refinery plant with 200 000 tons of annual production, was also made based on the same process. The process does not produce red mud as the iron oxides of the bauxite is 99.9% reduced during the smelting. Furthermore, the CO_2 gas produced from the smelting-reduction process can be utilized in its later process (precipitation), and the sodium carbonate used in the leaching treatment could be recovered from the leachate during the precipitation. Therefore, the Pedersen process can be a good alternative for alumina recovery with lower environmental impact than the Bayer process.

> *Letter by George B. Kauffman to the editor of Journal of Chemical Education [38]:*
>
> *The "chemically feasible" but "commercially unlikely" reprecipitation of hydrated aluminum hydroxide from a sodium aluminate solution by carbon dioxide cited in the "Textbook Forum" feature by Colin H. L. Kennard [1989, 66, 313] is indeed not a step in the Bayer process for the extraction of alumina from bauxite. However, it is a step in the older Le Chatelier process (1855), developed by Louis Le Chatelier (1815–1873), a French mining engineer who was the French Inspector General of Mines and the father of the chemist Henri Le Chatelier (1850–1936) of Le Chatelier's principle fame. Charles Martin Hall's (1863–1914) Pittsburgh Reduction Company, which became the Aluminum Company of America in 1907, continued to use the Le Chatelier process until 1911, when Karl Josef Bayer's (1847–1904) U.S. patent, issued in 1894, expired. Alcoa thereafter used the more economical Bayer process.*

The Pedersen process ideas are the backbone of the research and development work conducted in the EU-project ENSUREAL [39]. The project consortium spans across 8 European countries (7 EU member states and 1 associated country-Norway) bringing together a variety of expertise and know-how. 7 large enterprises, 3 SMEs, 2 Universities and 1 Research & Technology organisation constitute the consortium. NTNU is one of the universities

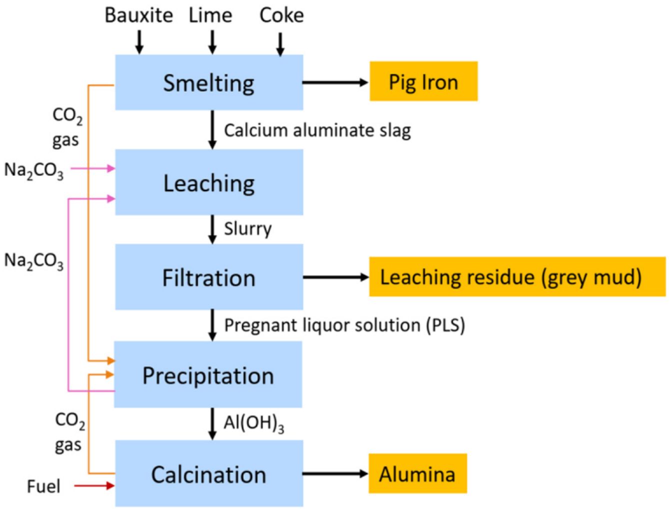

Fig. 22. The Pedersen Process [40].

and working closely together with SINTEF, the R&D organization mentioned, and the National Technical University of Athens (NTUA), as well as personnel from the other partners are proceeding towards ambitious objectives. At NTNU two PhD students are engaged: *Fabian Imanasa Azof* who defended his thesis [40] May 8, 2020, and *Adamantia Lazou* who still has about one year left of her research period. Several MSc students, project students and summer internship students have also been involved.

The Pedersen process is based on the combination of pyro- and hydrometallurgical processes and can be divided into several steps. First, bauxite is smelted with lime and coke, and subsequently, the generated slag is leached in a Na_2CO_3 solution, and, afterward, an $Al(OH)_3$ is precipitated out of the solution by the introduction of CO_2 gas. Finally, a pure Al_2O_3 is obtained after the calcination treatment. A simplified process flow of the Pedersen process is shown in Figure 22. In addition to the operation at Høyanger, Norway, the process was implemented in other parts of the world including the USSR (now Russia), China, Manchuria (now Northern China), Japan, and Sweden. The process was also economically interesting for the German industrial group, Nordag, so that they planned to build a similar alumina plant based on the Pedersen process at Sauda, Norway, during the second world war. The plant was planned with an annual capacity of 50 000 tonnes Al_2O_3 and it was being commissioned when the war ended [40].

Much of the work done in Ensureal is not published yet, but a sort of impression of the ongoings is shown in the published papers [34–36,40–45] included here.

The main principle of the Pedersen process is to produce calcium-aluminate slags and pig iron by smelting reduction of high iron- and silica-containing bauxites. Coke and limestone are used to reduce the iron oxide and adjust the basicity of slag during smelting. There is evidence that complete iron separation from bauxite is feasible through the smelting-reduction process, and up to 99.9% of the iron can be eliminated. Moreover, it is shown that the partial separation of silicon, titanium, and other elements from the Al_2O_3-containing slag occurs. The phase compositions and the distribution of elements between the metal and slag phases provide information about the high-temperature behaviour of the bauxite components during smelting reduction. Employing electron microscopy analysis, it is indicated that the morphologies of $CaO.Al_2O_3$, $12CaO.7Al_2O_3$, $2CaO.Al_2O_3.SiO_2$, and $CaO.Al_2O_3.SiO_2$ phases in the slag, as well as the complex oxides of Ca–Al–Si–Ti in the slag behave differently as the mass ratio of $Al_2O_3/(Fe_2O_3 + SiO_2)$ in the bauxite changes. It is also shown that the phases of slag produced from smelting-reduction below 5 K s1 of cooling rate are proper for further leaching process.

On the hydrometallurgical part, the leaching characteristics and mechanism of synthetic $CaO–Al_2O_3$ slags in alkaline solution at atmospheric pressure have been studied experimentally. The purpose of the study is to have a better understanding of the leaching part of the Pedersen process since the solvent used is different from the Bayer process, but in agreement with the Le Chatelier process. The crystalline slags contain $CaO \cdot Al_2O_3$, $3CaO \cdot Al_2O_3$, $CaO \cdot 2Al_2O_3$, and $12CaO \cdot 7Al_2O_3$ phases, and leaching residues (predominantly $CaCO_3$) are characterized by XRD and semi-quantitative analysis. In a solution containing 120 g/L Na_2CO_3, the slag with the highest amount of $12CaO \cdot 7Al_2O_3$ phase is the most leachable one in the $CaO–Al_2O_3$ system with about 95% of alumina extraction. The leaching extent is confirmed by employing Inductively Coupled Plasma-High Resolution-Mass Spectrometer (ICP-HR-MS) analysis, and it decreases by 0.4% for every percent of the bayerite ($Al(OH)_3$) formation during leaching.

High concentration of aluminium (high recovery) is obtained from pregnant liquid solution (PLS) that uses solvent which consists 100–120 g/L Na_2CO_3. On the other hand, lower concentrations of aluminum (low recovery) are produced from solutions with a mixed $Na_2CO_3–NaOH$ at any studied temperatures. The addition of NaOH in the solution decreases the aluminum dissolution of the slag, while it increases the silicon dissolution into the PLS. Furthermore, the higher the aluminum concentration of the solution is, the higher the concentration of silicon.

The main differences between Bayer and Pedersen processes are summarized as follows:

- Inclusion of a pyrometallurgical process step, in which there are mainly three phases: Metal, Slag and Gas. The metal is mainly iron, and we might think that Pedersen had the idea: *“Why not remove the iron before it becomes an environmental problem?”*, but this is rather doubtful, one 100 years ago. Considering that bauxite was discovered in geological prospecting for iron ores, it is more probable that the underlying idea was to utilize the iron contained in the bauxite as well. The aluminium is contained in the slag in combination mainly with calcium oxide and other stable oxides that might be in the ore, see Figure 3. In its original design this process step was an electric smelting furnace, but it is possible to proceed this with a prereduction process as in the Titania slag production at TTI in Tyssedal, Norway [46,47].

Table 3. Main differences between grey and red mud [40].

Parameter	Grey mud	Red mud
Main components	$CaCO_3$, CaO, SiO_2	Fe-oxides, Al_2O_3
Al_2O_3 losses	8% (low)	15% (moderate)
Na_2O losses	2%	5%
Mud/Alumina mass ratio*	1.5–2 : 1	1–1.2 : 1
Alkalinity	Low	High

*Depending on the bauxite compositions.

Table 4. Comparison of the Bayer and Pedersen process [40].

Parameter	Bayer Process	Pedersen Process
Overall process characteristic	Hydrometallurgical	Pyrometallurgical Hydrometallurgical
Ore type	High Al_2O_3:Fe_2O_3 ratio	Low Al_2O_3:Fe_2O_3 ratio
Main byproducts	Red mud (not consumable)	Pig iron (consumable) Grey mud (consumable)
Leaching conditions	Digestion by NaOH 150–250 °C High pressure	Digestion by Na_2CO_3 40–80 °C Atmospheric pressure
$Al(OH)_3$ precipitation	45–80 °C; 48–70 h	70–80 °C; 6–10 h
Electric energy consumption	Reference process	10% higher
Using ores rich in TiO_2 and SiO_2	Reference process	More flexible
Raw materials costs	Reference process	Higher (∼ 40% in average)
Process costs per unit mass of Alumina	Reference process	30–50% lower[6]

- Reduction of iron oxides can be done with coal as presently at TTI, but TTI are developing hydrogen based prereduction in their operation, and naturally the same option is considered in the Ensureal work where also charcoal is looked at. This pyrometallurgical processing is indeed twofold: reduction and smelting, and the splitting into two sub-steps allows optimizing of both. Overall the pyrometallurgical processing makes the "New" Pedersen process very versatile both regarding raw materials where low-grade bauxites, Red Mud and even bottom ash from municipal waste incinerators (MWIBA) can be handled to produce a slag with consistent quality, that is rich in easily leached constituents.
- Slag leaching with Na_2CO_3 solution is carried out at low temperature and ambient pressure and this has considerable advantages regarding both investment and operation. No Red Mud is produced, and the leaching residue here is Grey Mud, see details in Table 3.

Grey Mud can be used in cement, fertilizer, or lime and CO_2 source industries due to its high content of $CaCO_3$, and also potentially reused as lime source in the smelter stage. Like Red Mud, Grey Mud can be a source of inorganic polymers, refractory metals, rare earth elements (REE) and other potential valorisations.

An overall comparison between Bayer and Pedersen processes is given in Table 4.

It is also worth mentioning that the combination of pyro- and hydrometallurgical processes can be utilised in complex recycling operations in general. One example is the recycling of electronic materials including mobile phones and computers (WEEE) etc. Separation of the "raw materials" into clearly defined phases (metal, slag/sulphide, gas) using proper additives and controlling oxygen potential and temperature in a pyrometallurgical processing step will generally facilitate better yields in subsequent hydrometallurgical and electrolysis processing steps.

Aluminium containing waste material (dross and metal waste) can be added to the Pedersen charge mix and depending on the aluminium content this will also reduce the amount of carbon needed for the reduction of iron oxides in the smelting process. The aluminium fraction will of course be oxidized to alumina ready for a new tour in the material life cycle.

7 The big picture

The concept "Material Cycle" is, as indicated at the beginning of this paper, somewhat misleading as it might lead people to think that it is possible to follow all material along one single route from beginning to end. It is fairly obvious that in reality there are many such cycles, and they

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[6] Operation at lower pressures and temperatures significantly reduce Investment/Capital/operation costs even if pyrometallurgical processing is added; commercially valuable by-products are produced; reduction of environmental costs.

are interlinked, often in ways that create difficulties in the effort to reach e.g. a Circular Economy. In previous sections, a few details from the materials cycles relevant to aluminium processes and products are presented, and even if the landscape seems cluttered, I think there is some sort of hope that the aluminium community might eventually reach a situation with considerably more balanced loops or cycles than is the case today.

Central topics relevant to discussions on Materials and Environment are *Economic Efficiency* and *Environmental Effectiveness* were discussed in an OECD workshop in 1998. The next couple of paragraphs are based on a discussion of these topics [48].

A general distinction between efficiency and effectiveness is obtained from Webster's Dictionary [49]:

a. *Effectiveness = causing or capable of causing a desired or decisive result*

b. *Efficiency = the degree of effectiveness with which something is done*

An example of the differences between these terms, is the present article. The finished product, the article, may be consistent with the initial objectives, and may thus contribute to a better understanding for example of extended producer responsibility. If so, it has an effect and the effectiveness may be high. The effectiveness is, thus, describing the relation between intended goals and obtained results. However, it is difficult to predict the efficiency under which this article is produced. It may have taken years and consumed a lot of resources to finish. In that case the system has been effective, but not very efficient.

In Nature, processes are very effective, but not necessarily efficient because the rates of reactions are often slow. On the contrary, in industrial processes the focus is on efficiency, emphasising high rates and throughputs. Talking from an environmental point of view, the effectiveness of these processes is often ignored. What the intended objectives really are, should, however, become crucial in this discussion.

Both effectiveness and efficiency are measures used to describe a system irrespective of how the system is defined. They differ from each other by effectiveness being an *extensive* measure and efficiency an *intensive* measure. Effectiveness is dependent on both quantity (volume, weight, energy and entropy) and quality (exergy and renewable/non-renewable). These may be added up to show the total amount of the property or resource in question. Hence, effectiveness can be related to an external point of reference. Quantitatively speaking, effectiveness traces the relation between input, output *and* the loss of a system, and, in more qualitative and general terms, effectiveness concerns the relation between intended objectives and obtained results. In contrast, efficiency, being an intensive measure, cannot be added up. Efficiency refers to the property *per unit* and is thereby dimensionless. Efficiency is thus *only* describing the system, and not the interaction between the system and its surroundings.

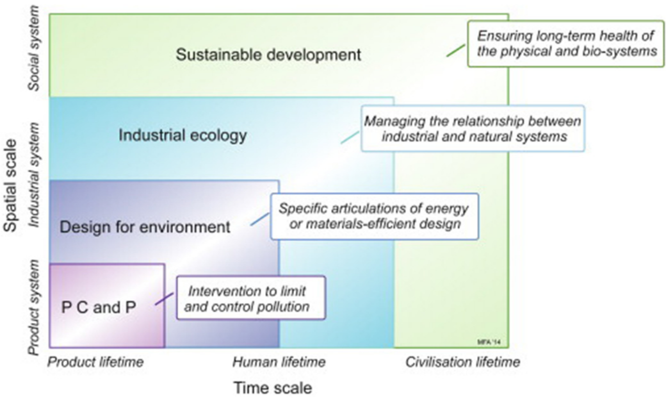

Fig. 23. Scale of vision [50].

It will be necessary to address many issues on different *scales* simultaneously and in a coordinated manner. To have any hope of handling household waste and other forms of obsolete scrap it will be necessary to integrate the users of the many products consumed domestically in a responsible manner – they must become *stakeholders* in the value chain whether it is linear or circular. A third issue has the nature of a paradigm shift (Green shift) that may be labelled *stewardship or responsible manufacturing.* And the final question is : will *waste* disappear, or at least be sufficiently reduced if a *Circular Materials Economy* precipitates?

7.1 Scale of vision [adapted from Ashby [50]

Ashby introduces differing scales of thinking about the relationship of technology and the environment. A horizontal axis describes the time scale, ranging from that of the life of a product to that of the span of a civilization. A vertical axis describes the spatial scale, again ranging from that of the product to that of society. It has four nested boxes, expanding outward in a conceptual scale, each representing an approach to thinking about the environment (Fig. 23).

Pollution Control and Prevention (PC and P). This is intervention on the scale and lifetime of a single product and is frequently a clean-up measure.

Design for the environment. Here the time and spatial scales include the entire design process; the strategy is to foresee and minimize the environmental impact of product families at the design stage, balancing them against the conflicting objectives of performance, reliability, quality and cost.

Industrial ecology derives from the perception of human activities as part of the global eco-system. Here the idea is that the processes and balances that have evolved in nature might suggest ways to reconcile the imbalance between the industrial and the natural systems, an idea known as the ecological metaphor.

Sustainable development requires thinking on a truly grand scale. Here is one (of many) formulation of what that will involve – A set of operating principles for true sustainable development:

- The rate of use of renewable resources (air, water, biomass) must be no greater than the rate of regeneration.

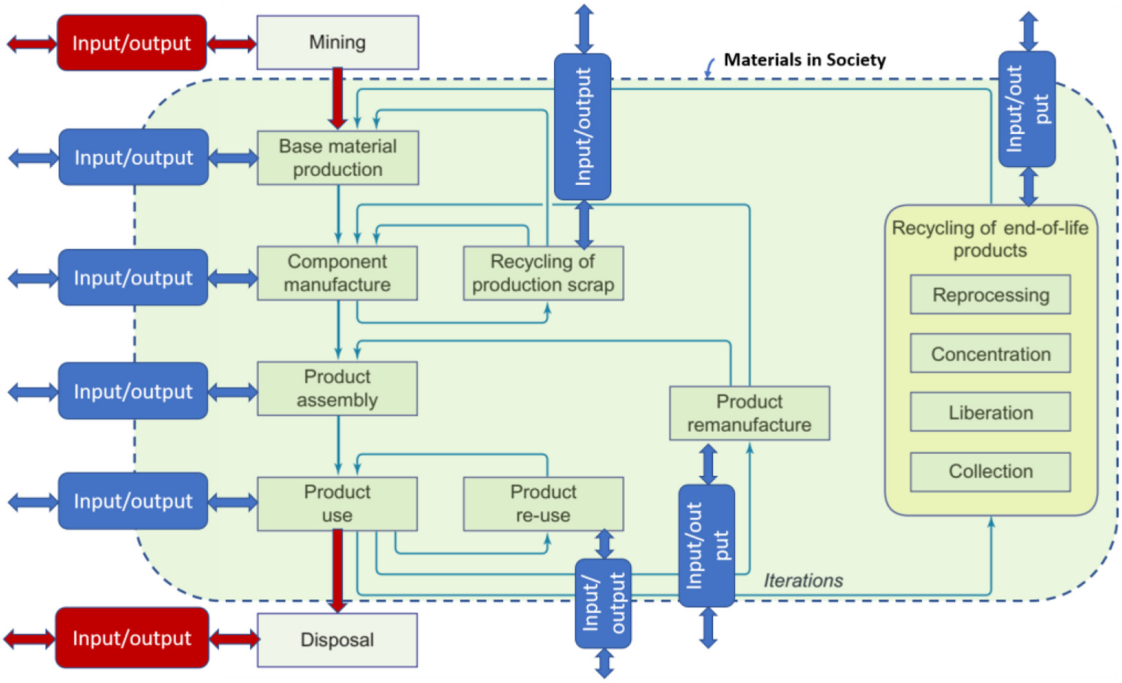

Fig. 24. The life cycle of a material – e.g. Aluminium. Adapted from [51].

- The rate of use of non-renewable resources (high quality minerals, fossil fuel) must be no greater than the rate at which renewable resources, used sustainably, can be substituted for them.
- The rate of emission of pollutants (gas, liquid and solid emissions) must be no greater than the rate at which they can be recycled, assimilated or degraded by the environment.
- People are not subject to conditions that undermine their ability to meet their own needs.

Principles such as these require changes in the way we use materials that appear, today, to be unachievable. But they remain an ideal, something sustainability measures might be judged against.

Material efficiency means providing more material services with less material production. Remember that material *production* is not the same as material *consumption*. Consumption is greater than production because of the contributions of *material recycling* and *reuse*, and this is one way the requirement above concerning rate of use of non-renewable resources can be fulfilled. The second possible way this can be done is to improve or enhance the properties of the materials used such that less materials is required for the same function.

Put another way, material efficiency means maintaining enough material in the Materials in Society box of Figure 24 to provide the services we need while minimizing new material flowing in from the outside and thus achieving *balance,* such that the system is in a state of *equilibrium*. In contrast the most characteristic feature of the industrial system in general today, and including the aluminium system, is its basis on *growth*. If the equilibrium state is reached, the materials that are conserved in the Materials in Society box will become a renewable resource.

The input/output boxes crossing the border of in the Materials in Society box indicate that in general an input of typically energy and materials will be needed, and there will also be a possible output of by-products and emissions/wastes not utilized within the box.

7.2 Actors/Stakeholders

Stakeholder analysis means identifying the interested parties – the stakeholders – and their concerns, their influence and the ways they interact. The three key stakeholder questions are:
- Who are they?
- What do they want?
- How will they try to get it?

Failure to identify, respect and involve stakeholders in a project is likely to generate opposition that may obstruct or defeat the purpose of the project itself. I think it will also be important to “educate” present users of e.g. aluminium to become stakeholders so that they find it meaningful to put in the extra effort needed to maintain a sound industry. Making conceptual choices is notoriously difficult, even if it just deals with choosing one of several optional technical solutions to a problem. The technology must be embedded in complicated social systems, and thus problems may start if the actors/stakeholders who will come under influence of this are unprepared mentally or knowledge wise.

7.3 Stewardship

Stewardship is defined as the care and management of something throughout its life cycle – we might even say taking the responsibility of that "something".

Three main aspects of stewardship:
- What is being entrusted to care?
- To whom is it being entrusted?
- How will it be taken care of?

Three types of stewardship exist [4]: (a) *Resource stewardship*, (b) *Material stewardship* and (c) *Product stewardship*. The first two are sometimes lumped together into Process stewardship incorporating exploration, mining, processing, smelting and refining, and the main objective is sustainability issues pertaining to resource use and processing, and naturally the mining and metallurgical industry is involved in these issues. Product stewardship is at the same time simpler and more complex as it relates to more stakeholders from design, engineering, manufacturing, use, recycling, and must address several questions and choices. The main question for aluminium could be whether it will be possible still in the future to sell and buy aluminium for different uses, or will the manufacturers have to rent the aluminium they need to make their products, and when these products reach an end-of-life stage the aluminium must be returned to the "steward".

The used Nespresso coffee capsules, a packaging which is collected at producer retail outlets for subsequent recycling, is an example of an emerging trend we are familiar with under the label "leasing". In this way you do not buy the product, only its function.

The Aluminium Stewardship Initiative (ASI)[7] is a global non-profit standard setting and certification organization inviting producers, users and stakeholders in the aluminium value chain with a commitment to maximize the contribution of aluminium to a sustainable society. This organization aims to collaboratively foster responsible production, sourcing and stewardship of aluminium through the objectives:
- To define globally applicable standards for sustainability performance and material chain-of-custody for the aluminium value chain
- To promote measurable and continual improvements in the key environmental, social and governance impacts of aluminium production, use and recycling
- To develop a credible assurance and certification system that both mitigates the risks of non-conformity with ASI standards and minimises barriers to broad scale implementation
- To become and remain a globally valued organisation advancing programs for sustainability in the aluminium value chain, which is financially self-sustaining and inclusive of stakeholder interests.

This looks good but spans wider than most definitions of "stewardship", and maybe without being clear on the aspects listed above.

The main aluminium companies operating in Norway, Alcoa[8] and Hydro[9], are both members of this organization

7.4 Waste and Circular Materials Economy

The main idea in the Circular Economy is to prevent the generation of waste and everybody should think thoroughly on what they consider waste. For materials, waste is related to what it is, how it is treated, its value/price, its availability and so on... But as someone said: A waste is not a waste until we waste it.

Waste: The concept of "waste" has two different meanings, depending on the context: for environmentalists, waste is the material that leaves the human system for final dispersion or discharge into the environment or landfills; for lawmakers, industry and consumers, waste is the material that an economic actor gets rid of, whether it is eventually dispersed or recycled in the economy. For instance, according to European regulations, waste means "*any substance or object which the holder discards or intends or is required to discard*" (Directive 2008/98/EC on waste).

The circular economy means more than just efficient recycling. Taken literally, it means relying on renewable energy, tracking materials through the economy so that their location is known and using them in designs that allow their reuse with as little reprocessing as possible. The concept goes beyond the mechanics of production and consumption of goods, moving from the idea of *consuming* of materials to one of *using* them, somewhat in the way properly managed land is used for agriculture without consuming it. This implies a different approach to design, one that retains or regenerates materials during several manufacturing cycles and reduces demand on the use of critical materials. It is an important part of a resource-efficient, low-carbon economy, reducing costs and supply risks, and generating value.

In the literature we may find an enormous amount of publications addressing Circular Economy, or Circular Materials Economy, and this has also become almost a magic formula for politicians when they speak about "The green Shift" or "Sustainability". Very few, however, have really gone into the core of the matter and looked at what is necessary in order to establish this concept in a real world. A few exceptions exist though, and one of them is Markus Reuter who in 2016 received TMS EPD Distinguished Lecture Award and a paper was published in December the same year [52].

This paper must be read in detail to really understand the impact it will have on the development if the pointers and suggestions presented are followed. Reuter is quite clear on the fact that a Circular Economy must rest on a fully developed "*metallurgical Internet of Things (m-IoT). This is the digitalized Web of Metals (WoM) or, in other words, the system integrated material production (SIMP). Its digitalization provides the real-time detail that quantifies*

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[7] https://aluminium-stewardship.org/.

[8] https://news.alcoa.com/press-release/alcoa-gains-approval-market-sustainably-produced-products-aluminium-stewardship.

[9] https://www.hydro.com/en/media/when-experts-unite/the-recycling/.

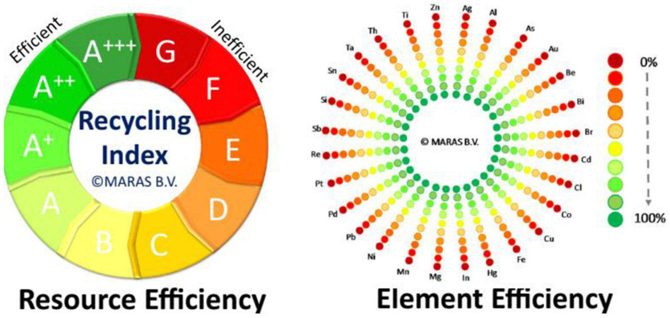

Fig. 25. m-IoT permits the optimization of both Element Efficiency and Resource Efficiency [52].

the three pillars of sustainability: social, environmental, and economical. This is termed "circular economy engineering" (CEE), i.e., the digitalization of the CE, using among others the theory and technology of minerals processing, metallurgy, recycling, computer-aided engineering (CAE), and product design.

This provides the basis for the estimation of the metrics of resource efficiency (RE) and, hence, provides a direction for innovation and also enables the m-IoT"[10].

In this paper Reuter also presents a number of ideas of how society in general may be involved in this process by providing information as shown in Figure 25, as well as actors and stakeholders from industry and the associated research communities.

8 Concluding remarks

Going back to the aluminium benefits as expressed by Thyssen Krupp [3] and listed in the introduction of this paper:

- *extremely versatile* – this also means that it is easily combined very intimately with many other materials e.g. other metals, but also paper and plastics;
- *lightweight metal* – sometimes this is an advantage, but in other cases it means that a lot of material on the basis of volume is needed to obtain the intended purpose;
- *corrosion resistant metal* – the main meaning of this is that all aluminium surfaces are immediately oxidized when exposed to oxygen and this also gives unwanted effects in processing and recycling;
- *excellent conductor of heat and electricity* – this is of course a positive property when a conductor of heat or electricity is needed, but when using aluminium in construction, e.g. window frames, then barriers for heat loss must be included;
- *reflectivity and ductility* – usually positive properties;
- *odourless and impermeable* – positive, usually, but when combined with paper (e.g. Tetra pack) or plastic (e.g. bags for potato chips) the advantage is for the consumer, and not for the recycler;
- *100% recyclable* – yes, it is a metal (or an element if you like), but because of its tendency to mix well/react with other elements, especially oxygen, forming stable compounds, it is one of the most difficult elements to recycle.

True balance, e.g. in the form of a Circular Materials Economy encompassing the complex area of *aluminium production, use and recycling* will not occur until some sort of equilibrium or at least steady state situation is established including the relations to external activities illustrated in Figure 24. In the long run it will be necessary to improve the communication on Aluminium's Recylability.

By reading various webpages produced by various stakeholders the impression is that Recycling of aluminium is so easy, and so good for the environment that it is done close to 100%. This might easily be interpreted by decision makers in society that new products or applications of aluminium are easily obtained on basis of recycled material only, and then the energy (exergy) consumption is reduced drastically as well. It ought to be said very clearly that this is not the case presently. Remelting of any scrap metal will in general require that in order to obtain a material of wanted quality the concentrations of some contaminations (tramp elements) must be reduced relative to levels in the scrap. This is mainly due to insufficient sorting of various waste materials available. This reduction of contamination levels can either be done by *diluting* with pure (e.g. primary) metal, or by *metal refining*. The first of these options is easily done but leads to lower Return Rate as already seen. The second option is difficult for aluminium, and as discussed in relation to Figures 3 and 4 really means to fight the forces of nature.

In my opinion the time has now arrived to look seriously at alternatives to the Bayer process for Alumina production. Viable alternatives should be able to process a range of feedstock materials containing aluminium and also produce by-products of commercial interest rather than environmentally challenging waste. Some variant of the Pedersen process will probably be a serious candidate here. In this connection it will also be natural to evaluate the possibility to recycle problematic household waste via the slag-making stage in that process. Similar concepts have been applied to the more general problematic waste problem called Waste Electrical & Electronic Equipment (WEEE). Making concept choices is notoriously difficult, even if it just deals with choosing one of several optional technical solutions to a problem. The technology must be embedded in complicated social systems, and thus the new problems may be generated, and I believe that the application of stewardship thinking applied in a balanced manner on the different scales of vision will be a fruitful approach. It is quite possible that business models adhering to the PSS (Product Service System) development [53] over recent years will lead to the sought-after integration between business practice and societal needs regarding the intriguing element Aluminium.

It should, however, always be remembered that Earth is a closed system with respect to matter – Al-atoms will not disappear, but unless something is done, they might be

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[10] Cited from Markus A. Reuter "Digitalizing the Circular Economy – Circular Economy Engineering Defined by the Metallurgical Internet of Things" [52].

harder (and more expensive) to get the best use of in the future. On the other hand, Earth is an open system with respect to energy (exergy) and as we know, this resource can do wonders if applied wisely.

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