PBL Netherlands Environmental
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# DECARBONISATION OPTIONS FOR THE DUTCH ALUMINIUM INDUSTRY

**Henk Kortes, Ton van Dril**

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MIDDEN

Manufacturing Industry Decarbonisation Data Exchange Network

**Decarbonisation options for the Dutch aluminium industry**

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**Authors**
H. Kortes and A.W.N. van Dril

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The MIDDEN project (Manufacturing Industry Decarbonisation Data Exchange Network) was initiated and is also coordinated and funded by PBL and ECN part of TNO. The project aims to support industry, policymakers, analysts, and the energy sector in their common efforts to achieve deep decarbonisation. Correspondence regarding the project may be addressed to: K.M. Schure (PBL), Klara.Schure@pbl.nl, or A.W.N van Dril (TNO), Ton.vanDril@tno.nl.

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This report was reviewed by the companies. PBL and ECN part of TNO remain responsible for the content. The decarbonisation options and parameters are not verified by the companies.

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## Summary

In the Netherlands, three main types of activities in aluminium manufacturing can be distinguished. Primary aluminium production from aluminium oxide in the Netherlands is located at Aldel, in the Dutch city of Delfzijl. The largest secondary aluminium producers, using mostly scrap, are E-MAX in Kerkrade and Zalco in Vlissingen. Aluchemie in Rotterdam and Century in Vlissingen are the producers of prebaked carbon anodes for the primary aluminium electrolysis process.

Emissions and the production capacity of each of those sites are summarized in Table S1. The main direct $CO_2$ emissions are related to the use of carbon anodes at Aldel (process emissions), from thermal fuel use in the melting furnaces at Aldel, Zalco and E-MAX, and from thermal fuel use in the baking process of anodes at Aluchemie and Century. Indirect emissions associated with power generation for the energy-intensive electrolysis process at Aldel are not included. PFC emissions consist of organic F-gas emissions, which may substantially contribute to global warming. These emissions may occur at the anode, during the process of primary aluminium production. Aldel is currently scaling up production to its original capacity.

**Table S1 General current data per site**

| | Direct $CO_2$ emissions (EU ETS) [kt] | PFC emissions [kt$CO_2$ eq] | Thermal fuel use [PJ] | Electricity use [PJe] | Main product | Product output [kt] |
|---|---|---|---|---|---|---|
| **Aldel, Delfzijl (at projected full capacity)** | 204 | 66 | 0.5 | 6.6 | Primary and secondary aluminium | 180 |
| **Aluchemie, Rotterdam** | 144 | | 1.3 | 0.16 | Carbon anodes | 335 |
| **Century, Vlissingen** | 65 | | 0.5 | 0.08 | Carbon anodes | 145 |
| **E-Max, Kerkrade** | 20 | | 0.3–0.5 | 0.02–0.04 | Secondary aluminium | 55–60 |
| **Zalco, Vlissingen** | 16 | | 0.2–0.3 | 0.02–0.03 | Secondary aluminium | 35–40 |

On-site decarbonisation options consist of carbon-neutral fuels, such as green gas or hydrogen in the melting and anode-baking furnaces. Electric furnaces are also considered, but would require further development. At these sites, the non-fuel-process carbon emissions related to anode baking, anode consumption and melting of contaminated scrap are important sources of direct emissions, which are not so easy to avoid. As a solution, carbon capture and storage (CCS) seems not feasible on this scale. Instead of carbon anode consumption, new processes using inert anodes are now being developed. At Aldel, this could avoid the process emissions of both $CO_2$ and PFCs. If inert anodes would become the main technology, worldwide, Aluchemie and Century could decrease or terminate production, in the long run.

For Aldel, electricity-efficiency improvements and the use of renewable electricity represent important potential for reducing indirect emissions. Increasing the use of scrap to replace primary production would gradually decrease the indirect emissions from electricity generation for electrolysis.

FULL RESULTS

# Introduction

This report describes the current situation for aluminium production in the Netherlands and the options and preconditions for its decarbonisation. The study is part of the MIDDEN project (Manufacturing Industry Decarbonisation Data Exchange Network). The MIDDEN project aims to support industry, policymakers, analysts, and the energy sector in their common efforts to achieve deep decarbonisation. The MIDDEN project will update and elaborate further on options in the future, in close connection with the industry.

## Scope

This MIDDEN study addresses all the companies that are part of the Dutch aluminium industry that are registered under the EU Emissions Trading System (EU ETS). Below, Table 1 shows an overview of all the production locations that were taken into account during the project, together with their main activity and product output. Three types of main activities can be distinguished: production of primary aluminium (new aluminium) into billets and slabs (Figures 1 and 2), production of prebaked carbon anodes (Figure 3), and production of secondary aluminium (recycled aluminium) into billets and slabs. Carbon anode manufacturers were included in this study because primary aluminium is produced in electrolysis cells, requiring carbon anodes. The consumption of these anodes in the primary aluminium production process is the source of direct carbon dioxide ($CO_2$) emissions.

**Table 1 Overview of the report scope**

| Production location | Main activity | Main product output |
|---|---|---|
| **DAMCO Aluminium Delfzijl Cooperatie U.A. (Aldel)** | Production and casting of primary aluminium | (Alloyed) aluminium billets and rolling slabs |
| **Aluminium & Chemie Rotterdam B.V. (Aluchemie)** | Production of carbon anodes | Prebaked carbon anodes |
| **Century Aluminum Vlissingen B.V. (Century)** | Production of carbon anodes | Prebaked carbon anodes |
| **E-MAX Billets B.V. (E-MAX)** | Production and casting of secondary aluminium | (Alloyed) aluminium billets |
| **Zalco B.V. (Zalco)** | Production and casting of secondary aluminium | (Alloyed) aluminium billets and rolling slabs |

**Figure 1 Aluminium billets**

**Figure 2 Aluminium slabs**

**Figure 3 Prebaked carbon anodes**

## Reading guide

Chapter 1 gives a general introduction to the aluminium industry in the Netherlands. Chapter 2 addresses the current situation of aluminium production processes in the Netherlands, and Chapter 3 describes the relevant products related to these processes. Options for decarbonisation are systematically quantified and evaluated in Chapter 4.

# 1 Aluminium production in the Netherlands

Over the past few decades, the landscape of the Dutch aluminium production industry has experienced some significant changes. The following sections elaborate on these changes by giving a detailed description of the EU ETS-registered aluminium companies included in this study. The production locations are presented in Figure 4.

**Figure 4 Overview of EU ETS-registered aluminium companies in the Netherlands.**

## 1.1 Aldel

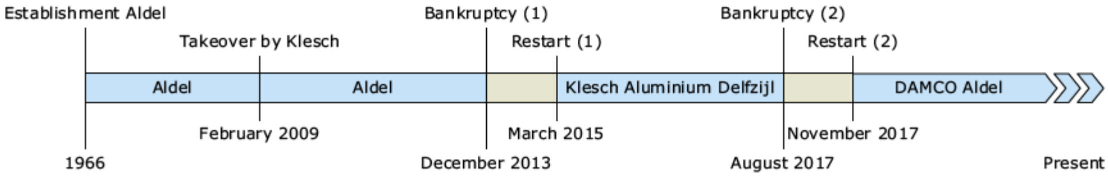
### 1.1.1 History

At the moment, Aldel (Aluminium Delfzijl) is the only manufacturer of liquid primary aluminium in the Netherlands. The company was established in 1966 by Koninklijke Hoogovens, and, as its name suggests, is based in Delfzijl, on the northern coast of the Netherlands (Aldel, 2017). This location was chosen since imported raw materials (aluminium oxide and carbon anodes) could be easily transported by ship, and because electricity prices, at the time, were low due to the nearby natural gas field in Slochteren, providing cheap electricity to local industry.

Since the opening of the factory, over time, the number of electrolysis cells (pots) expanded to 348, arranged in two electrolysis halls of 850 and 950 metres long (Colt, 1998). During a major 160 million NLG retrofit project in 1997–1998, 44 of these pots were taken out of use, the remaining 304 pots were refurbished and a new gas treatment centre (GTC) was built (Province of Groningen, 2008, p. 24).

However, approximately 5 years after the project, owner Corus (formerly Koninklijke Hoogovens) wanted to sell Aldel, because energy costs had increased significantly due to the expiration of a long-term energy contract, and the liberalisation of the Dutch energy market (Frederik, 2014). As shown in Figure 5, in 2009, Corus found a buyer for Aldel, the American investor Gary Klesch (Frederik, 2014).

**Figure 5 Developments in the ownership of Aldel, over time**



From 2009 to December 2013, the company’s name remained Aldel. After the first bankruptcy, in 2013, the name was changed to Klesch Aluminium Delfzijl in November 2014, and the production process was restarted in March 2015. Its 400 employees became part of the Basemet group (Houtekamer, 2017). This group consist of two other aluminium smelters owned by Klesch: Zalco N.V., located in the Netherlands, and Voerdal GmbH, located in Germany (Frederik, 2014). In 2011, Zalco N.V. (former Pechiney Nederland NV) closed its doors, and, in 2012 Basemet filed for bankruptcy. To save the facility in Delfzijl, Klesch decided to sell it to another holding of the Klesch Group (Wester, 2014).

Eventually, in December 2013, Klesch Aluminium Delfzijl also went bankrupt, despite of a loan of EUR 7 million that has been provided in October of that year by the Dutch Ministry of Economic Affairs and the Province of Groningen (Dutch Government, 2013). The loan was intended to provide the company with time develop a plan for the construction of a 17 km long direct power line to a nearby German power plant, to take advantage of the relatively low German electricity prices, thus avoiding the higher Dutch prices (Houtekamer, 2017). The loan was in fact an advance payment for the expected compensation for indirect $CO_2$ emissions (EUR 8 million) that was to be granted in 2014, ahead of the implementation of the regulation. In the end, the power line was never built. According to Klesch, the compensation was not sufficient to cover financial losses during construction of the line (NU.nl/ANP, 2013).

After having been closed for one year, in 2015, the company made a new start[1], under the name of Klesch Aluminium Delfzijl, with half of the electrolysis cells, and half the original number of employees (with a salary reduction of 25%) (Houtekamer, 2017). However, two years later, in 2017, the smelter nevertheless had to close. This time because of a conflict between Klesch and Noble, a supplier of raw materials (Houtekamer, 2017).

At the end of 2017, a new US investment company, York Capital Management (York), entered the Dutch aluminium industry. York bought the plant for EUR 19.4 million and changed the smelter's name back to 'Aldel' (DAMCO Aluminium Delfzijl Cooperatie U.A.). Currently, York is investing another EUR 80 million in the facility by renewing all the 304 electrolysis cells, with the aim for the plant to operate at full capacity by May 2019 (Van Bergen, 2018; Aldel, 2018a). Although every 5 years, the outer refractory lining and the inner carbon lining of a pot needs to be renewed, no investments in the pots' maintenance had been made by Klesch since the restart of the smelter in 2015. As a result, by 2017, only 70 of the 304 electrolysis ovens were still operational.

In addition to a change of ownership, Aldel also changed its alumina supplier. The production of primary aluminium requires a continuous supply of aluminium oxide (alumina). Alumina can be extracted from bauxite in a refinery, using the Bayer process, but the Netherlands does not have any bauxite mines or alumina refineries. Before the restart in 2017, Aldel terminated the long-term alumina supply and metal purchasing agreements it had with the global commodities group Concord Resources Limited (Aldel, 2017; Concord Resources Limited, 2017a). For the coming four years, a certain share of the raw material costs will be fixed. In return, approximately two-thirds of Aldel's aluminium products will be sold to pre-selected customers, at set prices. Only a third of the aluminium end products will be offered on the global aluminium market (Aldel, 2018a; Van Bergen, 2018).

It should be noted that Concord does not mine bauxite and refine alumina, but has a purchasing agreement with among others Noranda, a company that mines bauxite and refines alumina in Jamaica and the United States (Louisiana) respectively (Concord Resources Limited, 2017b; Concord Resources Limited, 2018). For this reason, it is likely to assume that the alumina used by Aldel is, for instance, Jamaican bauxite refined in Louisiana. From there, the alumina is exported to the port of Delfzijl, where it can be directly transferred from the ship to a silo located on Aldel's site.

### 1.1.2 Recent developments

After some recent management changes Aldel currently (summer 2018) employs 225 FTEs, but as part of York's investment plan, the workforce is expected to grow to 250 FTEs by the end of 2018 (Aldel, 2019). This will be necessary to let the facility operate on its maximum annual production capacity of 120,000 tonnes of liquid primary aluminium (304 pots), in accordance with the draft 2008 Province of Groningen permit. In the same draft permit, Aldel is allowed to produce 180,000 tonnes of aluminium per year in total, in the form of alloyed aluminium billets and rolling slabs. For this, the 120,000 tonnes of liquid aluminium is mixed with 60,000 tonnes of solid aluminium consisting of clean aluminium, and clean industrial aluminium scrap (see Chapter 2 for detailed information about the smelting and casting processes) (Aldel, 2008).

After having operated on less than a third of its capacity for the last few years, running at full capacity will have an effect on Aldel's annual $CO_2$ emissions. As shown in Figure 6 on page 11, the direct $CO_2$ emissions have significantly fluctuated over the past four years,

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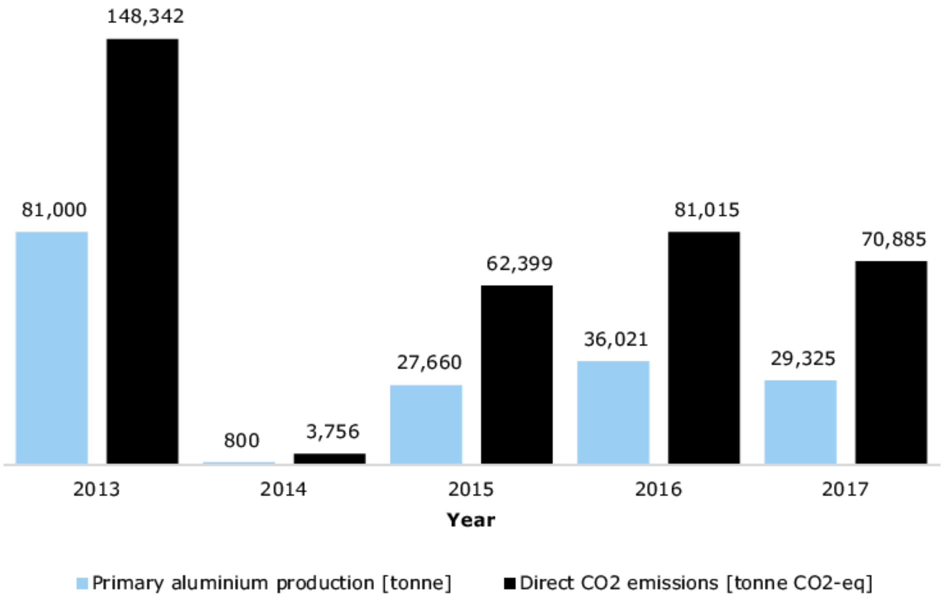
[1] Higher global aluminium prices made production in Groningen profitable again (see also Figure 17, page 43).

following the same pattern as the annual production of primary aluminium. The data about Aldel's direct annual $CO_2$ emissions are provided by the Dutch Emissions Authority (NEa), while the figures for the annual primary aluminium production are mainly obtained from the Minerals Yearbook, published by the British Geological Survey (BGS) (2018). This yearbook gives information about the production of aluminium on a national level, however, since 2012 Aldel is the only producer of aluminium in the Netherlands, it can be assumed that these figures represent Aldel's annual primary aluminium production.

According to Aldel's permit application submitted at the Province of Groningen in 2007, it is estimated that, at full capacity, Aldel will have direct emissions of around 200,000 tonnes of $CO_2$. In this, the 304 electrolysis cells are responsible for 176,500 tonnes of $CO_2$ (88%), while the remaining emissions come from casting 180,000 tonnes of aluminium into alloyed billets and rolling slabs (Aldel, 2007, p. *II.2*). For comparison, in 2017 Aldel emitted significantly less: 70,885 tonnes of $CO_2$ eq. Since Aldel is aiming to be operating at full capacity by May 2019, it is more realistic to take 200,000 tonnes of $CO_2$ as annual emission reference when analysing decarbonisation options rather than using the value of 2017.

**Figure 6: Aldel, primary aluminium production vs direct $CO_2$ emissions, period: 2013–2017 (Aldel, 2019; BGS, 2018; NEa, 2018)[2].**



While a direct annual $CO_2$ emission of 200,000 tonnes is significant, due to Aldel's electricity consumption of 1.8 TWh (6.6 PJe) per year, which is more than 1.5% of the total annual Dutch electricity consumption, the indirect $CO_2$ emissions are higher. On a global level 80% of the total GHG emissions in the aluminium industry, including indirect emissions, are electricity-related (IPCC, 2015). According to the International Aluminium Institute (IAI) (2015) primary aluminium smelters consume 14.2 MWh per tonne of aluminium of electricity on average globally.

Recently, Aldel has started to investigate how to cut its electricity consumption by applying the newest developments in power electronics. The aim is to build a pilot plant where this new technology will be tested. The new technology should enable a better control of the

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[2] Information about the share of primary aluminium in the total aluminium production is not available.

pots, thus increasing its product and energy efficiency. It is expected that 10% to 15% of energy costs could be saved.

As part of the same project, Aldel is also studying the possibilities to connect its DC supply system to an experimental Industrial Direct Current Power System. The development of this Industrial Direct Current Power System is in the hands of Groningen Seaports, the local port authority. The idea of this new DC power system is to connect generators and consumers of DC electric energy directly, thus eliminating conversion steps from AC to DC and vice versa. The elimination of these conversion steps will reduce energy losses in the power system, and could save substantial costs (Aldel, 2019).

Groningen Seaports is also initiator of various other sustainability projects in the port area. Recently, it has started the Project Zero programme where it, together with its stakeholders, will come up with a roadmap and an implementation strategy to reduce the $CO_2$ emissions from the Eemsdelta by 95%, by 2050 (Geijp, 2017).

## 1.2 Aluchemie

### 1.2.1 History

In 1966, the same year Aldel was established, the Swiss aluminium company Alusuisse opened its carbon anode plant in the port area of Rotterdam, called: “Aluchemie” (full: Aluminium & Chemie Rotterdam B.V.). By placing the factory close to the sea, various types of carbon anodes can easily be exported to primary aluminium manufacturers around the world. Also the purchase/import of raw materials (petroleum coke, coal tar pitch and anode residues) benefits from this location, since the majority of Dutch oil refineries is located in the port region. The factory started with three baking furnaces, but doubled its production to six furnaces in 1970 (Aluchemie, 2018a).

While production continues, in 1986 the Norwegian Norsk Hydro acquires a share in Aluchemie, and in 2000 also Alcan becomes stakeholder by merging with Alusuisse. Under the leadership of both companies, Aluchemie opens its seventh baking furnace in 2003 combined with a state of the art fume treatment plant, Fume Treatment Plant 5 (Aluchemie, 2018a).

A few years later, in 2007, a second shift in ownership takes place when the UK-based global mining group Rio Tinto buys Alcan for USD 44 billion (Bream and Bernard, 2007). After the takeover, Rio Tinto and Norsk Hydro invested in the two new Fume Treatment Plants 6 and 7, in 2009 and 2011 respectively, bringing the number of fume treatment plants to three. By equipping the plants with regenerative thermal oxidizers and dry scrubbers, the outlet gases could be filtered in an efficient way (Aluchemie, 2011; Aluchemie, 2013).

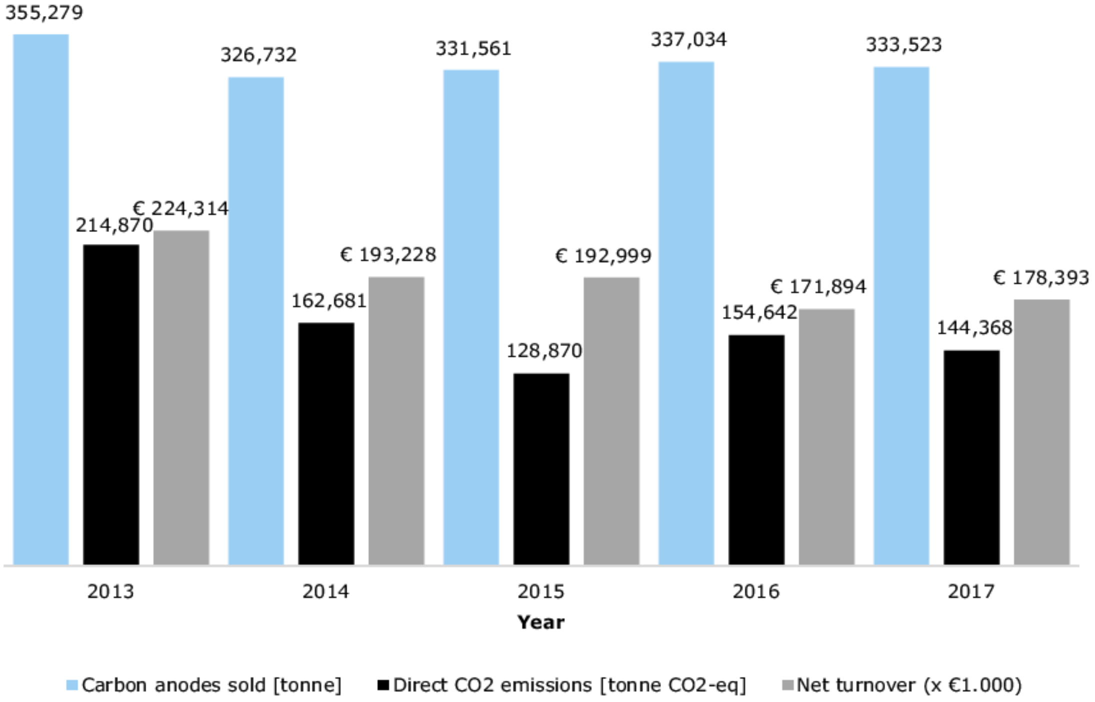
### 1.2.2 Recent developments

Last February, Norsk Hydro has made a binding offer to buy Rio Tinto’s share of 53.3% in Aluchemie, a 50% share in Swedish aluminium fluoride plant Alufluor AB, and a 100% share in Icelandic aluminium plant Rio Tinto Iceland Ltd for USD 345 million (Hydro, 2018a). Rio Tinto expects to conclude the sale in the second quarter of 2018 (Rio Tinto, 2018a). Seven months later, however, Hydro requested to terminate the transaction since the European Commission (EC) competition approval process has taken longer than anticipated (Hydro, 2018b).

At the moment Aluchemie has a workforce of 214 FTEs, together responsible for the sale of about 330,000–340,000 tonnes of carbon anodes per year, delivered by five baking furnaces (two furnaces are out of service) (Aluchemie, 2017; Aluchemie, 2018b; DCMR, 2018; Hydro, 2018a). The majority of these anodes goes to primary aluminium smelters in Norway, Canada, Iceland and Scotland (Aluchemie, 2013). By having an annual production capacity of 400,000 tonnes of anodes Aluchemie is the largest stand-alone, customer-specific anode production plant in the world (Aluchemie, 2018c). However, according to DCMR (2018) the maximum annual permitted production is lower, namely 375,000 tonnes of anodes. Last year, Aluchemie's turnover amounted to EUR 178.4 million, resulting in a net revenue of EUR 2.3 million (Aluchemie, 2017).

In 2017, according to NEa (2018), the production of prebaked carbon anodes resulted in 144,368 tonnes of direct $CO_2$ emissions, see Figure 7. In this figure, information on Aluchemie's anode production and gross sales from anodes, is combined with annual direct $CO_2$ emissions. Looking at Figure 7, a decreasing trend in $CO_2$ intensity can be noticed[3], which corresponds with Aluchemie's aim to keep improving in a sustainable way (Aluchemie, 2018d).

**Figure 7. Aluchemie: carbon anodes sold vs direct $CO_2$ emissions vs net turnover[4], period: 2013–2017 (Aluchemie, 2014; Aluchemie, 2015; Aluchemie, 2017; Aluchemie, 2018b; Hydro, 2018a; NEa, 2018).**



The port of Rotterdam is aware of the fact that for achieving deep decarbonisation in the port area by 2050, cooperation between all the companies will be needed (Port of Rotterdam, 2018a). At the moment more than regional 40 projects are running, ranging from studies focusing on hydrogen networks, to research to floating solar parks (Port of Rotterdam, 2018b).

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[3] Assuming that the annual number of anodes sold also represents the annual number of anodes produced.
[4] Gross sales of anodes corrected for guarantee costs.

## 1.3 Century Aluminium Vlissingen

### 1.3.1 History

In 1969, Pechiney Nederland N.V. started building an aluminium factory close to Vlissingen, consisting of an electrolysis department for producing primary aluminium, a foundry for casting primary aluminium into billets and rolling slabs, and a carbon anode plant (Zalco, 2018a). From the port of Vlissingen, raw materials needed for the production of aluminium and carbon anodes could efficiently be imported. In addition, by making an energy deal with a nuclear reactor located in Borssele, 3 km away, commissioned by PZEM in 1973, relatively cheap electricity could be bought for the electricity-intensive electrolysis cells (Omroep Zeeland, 2014).

To increase the energy efficiency and production capacity of the factory, in 2001, Pechiney started an investment programme of EUR 113 million to refurbish the 512 installed pots and construct a new anode baking furnace (the current baking furnace D). In 2004, the modernisation project was finished, and the production capacity expanded theoretically to 254,000 tonnes[5] of aluminium per year (PZC, 2001).

At the beginning of the same year, Pechiney, 85% owner of Zalco, became part of Alcan. However, due to higher Dutch electricity prices, in 2006, Alcan decided to sell its share even as Hunter Douglas, owning a share of 15% at that moment (Century, 2015a). The smelter is bought by Klesch & Company in 2007, and the name of the facility is changed to Zalco N.V. (Century, 2015a; PZC, 2007).

As a result of 1) a lower demand for aluminium from the automotive industry, 2) a drop in the aluminium market price, and 3) a further increase in the Dutch electricity prices, Zalco N.V. went bankrupt in 2012 (Stellinga, 2011). Leading to the demolition of its electrolysis halls, and the sale of the foundry and the anode plant, consisting of two gas-fired baking furnaces (Zalco, 2018a).

In 2012, Century Aluminum purchased the stand-alone anode plant from Zalco N.V., and changed the name to Century Aluminum Vlissingen B.V.[6] (Century, 2018a). Century Aluminum is a manufacturer of primary aluminium listed in the U.S. (NASDAQ), employing 1,500 people worldwide (Century, 2018a). The company has three primary smelters located in the U.S., and owns one Icelandic smelter (controlled by subsidiary Norðurál), together having a  total annual production capacity of 972,000 tonnes of aluminium (Century, 2018b). In addition, Century Aluminum holds a 40% interest in Baise Haohai Carbon Co., Ltd. (BHH), a Chinese anode and cathode plant. Both BHH and the plant in Vlissingen supply carbon anodes to the subsidiary primary smelter in Iceland located in Grundartangi (Century, 2018c).

### 1.3.2 Recent developments

After maintenance on baking furnace D and the installation of a new fume treatment plant (regenerative thermal oxidizers), Century started producing anodes in the end of 2013. One year later, investments were made to start building a new baking furnace C, doubling the annual production capacity to 150,000 tonnes of anodes. Until now, Century has invested more than EUR 100 million in maintenance, installations and modernisations (Century, 2015b; Century 2016a; Century, 2017a).

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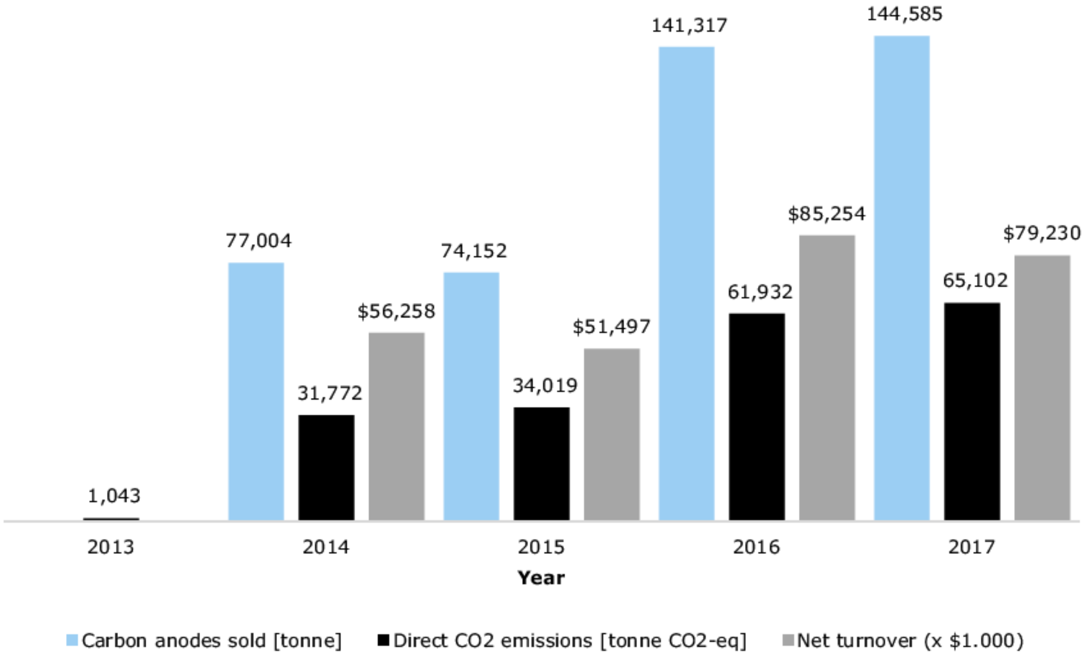
[5] In practise 230,000 tonnes of aluminium were produced (De Bruyn, Koopman, Van Lieshout, Croezen, & Smit, 2014).

[6] From now on mentioned as "Century".

The workforce has also experienced a rise from 44 FTEs in 2013, to 60 FTEs in 2017, following the same upward trend in production (Century, 2017a). As shown in Figure 8 on page 15, in 2017 Century produced 144,585 tonnes of anodes, resulting in a net turnover of USD 79,230,272. During the baking of anodes, 65,102 tonnes of direct $CO_2$ emissions were emitted into air. Regarding the $CO_2$ intensity of the process, over the period 2013–2017 a decrease of approximately 10% can be noticed [7].

**Figure 8. Century: carbon anodes sold vs direct $CO_2$ emissions vs net turnover[8], period: 2013–2017 (Century, 2015c; Century, 2016b; Century, 2017a; Century, 2017b; NEa, 2018)[9].**



It is expected that these trends will continue for the next coming years, since Century has announced to renew baking furnace D in 2019, making it approximately 35% more energy-efficient. In addition, its production volume will grow from 75,000 to 90,000 tonnes of anodes per year, increasing the factory's annual production capacity to 165,000 tonnes of anodes (Century, 2018d). At request of Century, the Province of Zeeland has already increased the permitted annual capacity from 150,000 to 180,000 tonnes of anodes (RUD, 2017).

For the coming years Century has the ambition to expand its anode plant even further by building a third baking furnace. Century is aiming to finish the preparations for this building project by 2020. These types of investments will be needed, since the Icelandic demand for anodes is expected to increase. In 2008, Norðurál started a greenfield project for a second aluminium production facility, located in Helguvik. Although the project is currently curtailed due to power supply issues, when completed, the smelter will produce 360,000 tonnes of aluminium per year (Century, 2018e).

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[7] Assuming that the annual number of anodes sold also represents the annual number of anodes produced.

[8] Net turnover represents amounts invoiced for goods and services supplied during the financial year reported on, net of discounts and value added taxes.

[9] Data about Century's production and net turnover in 2013 is unknown.

## 1.4 E-MAX Billets

### 1.4.1 History

E-MAX BILLETS in Kerkrade was founded in 1990 as the cast house for Alumax Europe to become the main supplier of billets for the extrusion companies from Alumax. Alumax was taken over by Alcoa in 1997 and became a part of Alcoa Netherlands with plants in Drunen, Harderwijk and Roermond. The company invested in the cast house in Kerkrade to produce high quality hard alloys for the automotive industry to supply the Alcoa extrusion companies in Europe. After selling the other Netherlands-based Alcoa companies in 2004 and 2005, the cast house was sold to E-MAX in 2007.

Approximately 20 years ago, in 1996, three entrepreneurs started a Belgium extrusion company called E-MAX, producing aluminium profiles from (alloyed) aluminium billets. Five years later, Vaessen Industries acquired the company, making it possible to invest in new extrusion equipment and to expand workforce (E-MAX, 2018a).

To ensure the supply of aluminium billets needed as input for the extrusion presses, in 2007, E-MAX took over an Dutch aluminium foundry owned by Alcoa "Alcoa Kerkrade Cast House"[10], nowadays known as "E-MAX Billets B.V.". Together with "E-MAX Profiles N.V." located in the Belgium municipality Dilsen-Stokkem, it forms the group "E-MAX sustainable aluminium" [11].

In 2011, E-MAX Sustainable Aluminium expanded its Belgium E-MAX Profiles activities by acquiring "Alex Profiles B.V.B.A.", an extrusion company located in Gullegem, followed by "BOAL Belgium N.V." in 2017, an aluminium extruder based close to Gullegem in Moorsele (Boal, 2017). This has expanded the production capacity of E-Max Sustainable to 64,000 tonnes of aluminium profiles per year (E-MAX, 2018b).

### 1.4.2 Recent developments

Currently Vaessen Industries owns three subsidiaries: Kreon, LIMEPARTS, and E-MAX Sustainable Aluminium. In total, in 2017, Vaessen Industries employed 700 workers and had a turnover of EUR 300 million (E-MAX, 2018c). In the same year, approximately 400 employees were employed by E-MAX Sustainable, yielding a turnover of approximately EUR 150 million (E-MAX, 2018d).

Looking at the situation in the Netherlands, E-MAX Billets has a workforce of 55 FTE producing 55,000 to 60,000 tonnes of (alloyed) aluminium billets per year (E-MAX, 2018b). Between 60% and 70% of these billets are transported to the extrusion facilities in Dilsen, Gullegem and Moorsele. The input material needed for manufacturing these billets, consists of on average 80% of aluminium scrap, but varies, depending on the type of alloy. A minor part of the applied aluminium scrap originates from E-MAX customers, which means that the quality and composition of the scrap is known. The major part of input materials is bought on the European scrap market and consist of industrial and end-of-life scrap (pre- and post-consumer scrap). By casting billets from remelting aluminium scrap, in potential 95% of final energy can be saved compared to the conventional process of casting billets from liquid primary aluminium, that is produced by electricity-intensive electrolysis cells (Lumley, 2011, p. 70). Compared to energy for primary production, about only 5% of energy is needed to remelt and cast recycled aluminium into billets.

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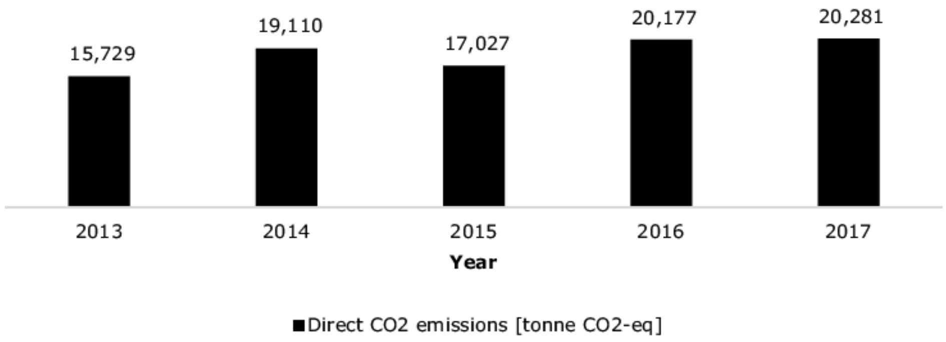
[10] Having a permitted production capacity of 95,000 tonne of casted aluminium (Alcoa, 2001).

[11] From now on the name "E-MAX" refers to the Dutch E-MAX Billets B.V.

Regarding $CO_2$ emissions, in 2017 E-MAX emitted 20,281 tonnes of $CO_2$ (see Figure 9). Between 80% and 90% of these emissions can be allocated to the gas-fired furnaces needed to remelt, cast and homogenise the recycled aluminium; 10% to 20% comes from combusting organic material enclosed in the scrap.

**Figure 9 E-MAX: direct $CO_2$ emissions (NEa, 2018)**



To reduce the $CO_2$ footprint of its aluminium profiles, in 2010 E-MAX Sustainable has developed new types of alloys, marked as "X-ECO". X-ECO alloys are made of recycled aluminium, while the properties of the alloys are equivalent to those of 100% primary aluminium (E-MAX, 2018e). It is claimed that $CO_2$ emissions will decrease to less than 2 tonnes of $CO_2$ per tonne of aluminium produced. E-MAX has announced that it will invest EUR 40 million in machinery, over the next three years, to start producing X-ECO aluminium profiles (Claes, 2017). To stimulate the company to become more sustainable, the Belgium government has provided a subsidy of EUR 956,000 (Claes, 2017).

In addition, E-MAX participates in the "Limburgs Energie Akkoord" (LEA) signed by the local energy-intensive companies, the local industry association, the municipality of Maastricht, and the Province of Limburg (Province of Limburg, 2018). The participants of this energy agreement understand that collaboration will be needed in order to achieve the national goal of 95% reduction in $CO_2$ emissions by 2050. By sharing knowledge and experiences the platform stimulates development of sustainable initiatives (LEA, 2018).

## 1.5 Zalco

### 1.5.1 History

As mentioned in Section 1.3.1, in 1969 Pechiney Nederland N.V. started building a primary aluminium factory in the Netherlands, consisting of an anode plant, an electrolysis department, and a foundry (see Figure 10).

**Figure 10 Former production site of Pechiney Nederland N.V. (1969–2006) and Zalco N.V. (2007–2011). Adapted from UTB Industry website, by UTB Industry, retrieved from https://utb.eu/projecten/zalco-aluminium.html**

In 2007 Klesch & Company bought the whole plant, and changed the name of the primary smelter to Zalco N.V. (Century, 2015a; PZC, 2007). However, Zalco N.V. had to file for bankruptcy in 2011, leading to the closure of the factory (Century, 2015a). At that time more than 600 employees worked at the factory, of which 480 in permanent employment (PZC, 2012). In 2012, the anode plant and the foundry were sold to Century Aluminium and UTB Industry respectively; the electrolysis department remained closed (Trouw, 2012). UTB Industry is part of UTB Group, a Dutch company established in 1981, specialised in industrial takeovers (UTB, 2018). During the takeover of the foundry by UTB Industry, the name of the location changed from Zalco N.V. to Zalco B.V.[12]. The demolition of the electrolysis department was finished in 2016.

## 1.5.2 Recent developments

At the moment Zalco employs 34 FTEs with a permanent employment, and 16 FTEs on temporary basis. The former production capacity of the foundry amounted to 235,000 tonnes per year, however, due to the termination of primary production not all furnaces are operational anymore. Current levels of gross production are estimated at 35,000–40,000 tonnes.

By closing and demolishing the electrolysis department, also the supply of primary aluminium ended. Nowadays, Zalco casts billets and slabs from primary aluminium and clean aluminium scrap purchased on the market. The current levels of recycling are estimated at 65% to 70%.

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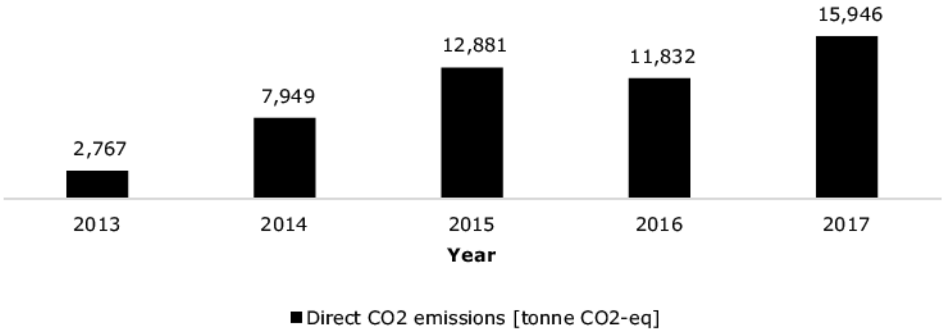
[12] 'Zalco' refers to Zalco B.V.

Regarding the $CO_2$ footprint of the foundry, 15,946 tonnes of $CO_2$ were emitted directly into air in 2017 (see Figure 11). To reduce its footprint, Zalco is studying the advantages and disadvantages of equipping its casting furnaces with oxy-fuel burners. In addition, Zalco is investigating the feasibility to generate a part of its own electricity use, by placing a wind turbine on site (Zalco, 2018b).

**Figure 11 Zalco: direct $CO_2$ emissions (NEa, 2018)**



On a regional level, several $CO_2$ reduction programmes are ongoing, initialized by the Province of Zeeland, Zeeland Seaports, and Smart Delta Resources for example. The last one is a cooperation of 11 energy- and feedstock-intensive companies to reduce their use of energy and feedstock. In March 2018, they have published a roadmap for a climate-neutral industry in the Delta region. Zalco does not participate directly in this project[13].

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[13] Neither does Century.

# 2 Aluminium processes

Looking at the main techniques that are currently used by the Dutch aluminium companies registered under the EU ETS, the following processes can be identified:

- The Hall – Héroult process used for producing primary aluminium (Section 2.1);
- The process of producing prebaked carbon anodes (Section2.2);
- The process of casting liquid primary aluminium into billets and slabs (Section 2.3);
- The recycling and casting of aluminium from industrial aluminium scrap into billets and slabs (Section 2.4).

The following sections address these processes by giving an overview of main inputs and outputs, including a comparison with relevant international literature.

## 2.1 Hall – Héroult process

Nowadays, primary aluminium is extracted from alumina (aluminium oxide $Al_2O_3$) by means of an industrial electrolysis cell, invented independently by the American chemist Charles Martin Hall, and the Frenchman Paul Héroult in 1886. While the design of an electrolysis cell has changed over years, the working principles have remained the same. Based on the process characteristics given in Table 2 and the construction of a typical electrolysis cell illustrated in Figure 12, a description of the Hall – Héroult process is given below.

**Table 2 Average characteristics of the Hall – Héroult process at Aldel in the Netherlands, compared to the European average (EAA, 2018) and the ranges given in the Best Available Technologies (BAT) Reference Document (BREF) (Cusano et al., 2017)**

| Type | Value per tonne of liquid primary aluminium | Source |
|---|---|---|
| **Raw materials** | | |
| Aluminium fluoride ($AlF_3$) | Aldel: 15–18 kg<br>EAA: 16.4 kg<br>BREF: 13–30 kg | (Aldel, 2007, p. 16)<br>(EAA, 2018, p. 32)<br>(Cusano et al., 2017, p. 398) |
| Aluminium oxide ($Al_2O_3$) | Aldel: 1.93 tonnes<br>EAA: 1.908 tonnes<br>BREF: 1.910–1.960 tonnes | (Aldel, 2008, p. 26)<br>(EAA, 2018, p. 32)<br>(Cusano et al., 2017, p. 398) |
| Prebaked carbon anodes (C) consumption (net) | Aldel: 0.43 tonnes<br>EAA: 0.413 tonnes<br>BREF: 0.41–0.45 tonnes | (Aldel, 2008, p. 26)<br>(EAA, 2018, p. 32)<br>(Cusano et al., 2017, p. 398) |
| **Energy inputs** | | |
| Electricity consumption (including rectifier loss, pollution control and auxiliary consumption) | Aldel: 15.21 MWh<br>EAA: 14.79 MWh<br>BREF: 13.6–15.7MWh | (Aldel, 2007, p. 73)<br>(EAA, 2018, p. 32)<br>(Cusano et al., 2017, p. 398) |

| Type | Value per tonne of liquid primary aluminium | Source |
|---|---|---|
| **Gas emissions** | | |
| Carbon dioxide ($CO_2$) (direct) | Aldel: 1.58 tonnes<br>BREF: 1.4–1.7 tonnes | Based on anode consumption.<br>(Cusano et al., 2017, p. 404) |
| (non GHG) fluoride emissions (F) | Aldel: 0.67 kg (0.4 kg HF)<br>EAA: 0.45 kg<br>BAT: ≤ 0.6 kg | (Aldel, 2008, p. 21)<br>(EAA, 2018, p. 32)<br>(Cusano et al., 2017, p. 1030) |
| (GHG) perfluorinated compounds (PFCs) ($CF_4$ & $C_2F_6$)[14] | Aldel: 0.07 kg (551 kg $CO_2$ eq)<br>EAA: 0.02 kg (157 kg $CO_2$ eq)<br>BREF: 0.01–0.1 kg (79 kg $CO_2$ eq–787 kg $CO_2$ eq) | (Aldel, 2007, p. 96)<br>(EAA, 2018, p. 32)<br>(Cusano et al., 2017, p. 401) |

### 2.1.1 General process

As presented in Figure 12, the Hall – Héroult process can be imaged as feeding alumina into a 8 m x 4 m steel cell, made up of carbon anodes hanging in a bath of molten cryolite ($Na_3AlF_6$) enclosed by a crust of mixed alumina, broken solid bath material, frozen cryolite, and a carbon lining (anthracite/graphite) that acts as a cathode (Aldel, 2007, p. 16). In practice, the bath temperature ranges between 960–970 °C, and the anode-to-cathode distance amounts to 4 to 5 cm. The bath (electrolyte) consists for 83% to 87% of cryolite ($Na_3AlF_6$), for 8% to 12% of aluminium fluoride ($AlF_3$), and for 5% to 6% of fluorite ($CaF_2$) (Aldel, 2007, p. 16). According to Aldel (2007, p. 19), the carbon and refractory lining of the cell have to be renewed after approximately 2,100 days, which corresponds to the technical pot lifetime of 5 to 8 years given in literature (Breault, Poirier, Hamel, and Pucci, 2011; Cusano et al., 2017, 2017, p. 398). According to Basemet's annual report of 2010, the economic lifetime of the cells is 4 years for Aldel and the former Zalco primary smelter (p. 26). Liquid aluminium is tapped daily by removing the pot cover panels and sucking up 1,100 kg of liquid aluminium from the bottom of each cell. Subsequently the liquid aluminium is poured over into a pan and transported in liquid condition to Aldel's casting department (Aldel, 2007).

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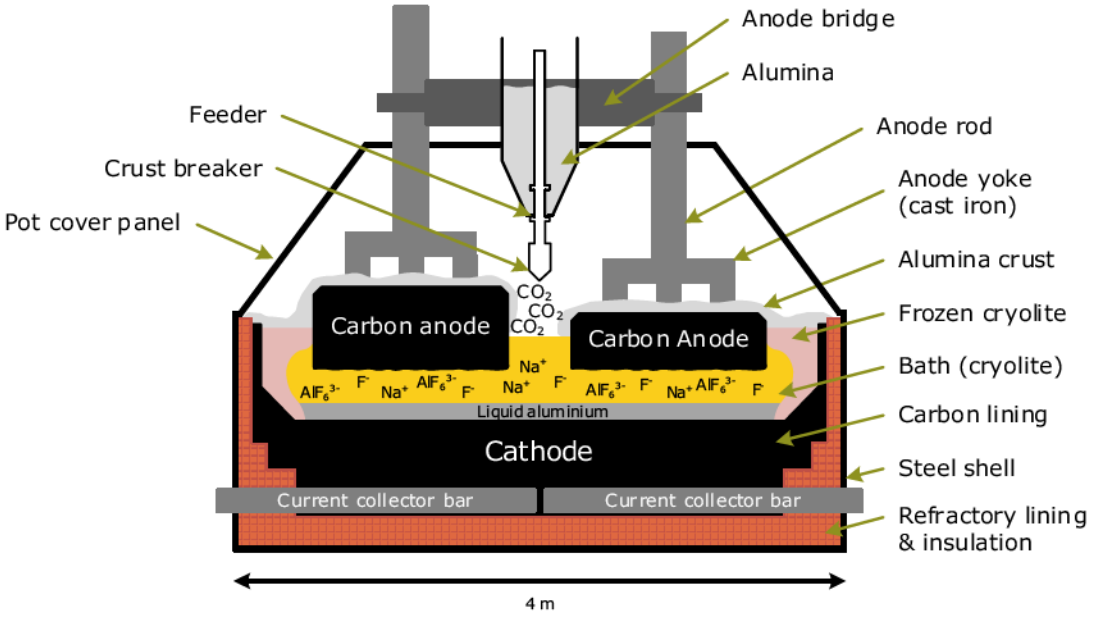
[14] $CO_2$ equivalents are calculated by assuming a ratio $CF_4$ : $C_2F_6$ of 9 : 1, and global warming potentials of 7,390 and 12,200 times higher than that of $CO_2$ respectively (EAA, 2018, p. 32; IPCC, 2016).

**Figure 12 Construction of a typical electrolysis cell used for producing liquid primary aluminium at Aldel (front view)**



## 2.1.2 Raw materials

### *Alumina and aluminium fluoride consumption*

As shown below in Eq. 1 and Eq. 2, in theory two molecules of $Al_2O_3$ (1.89 kg) and three molecules of C (0.33 kg) are needed to produce four molecules (1 kg) of liquid primary aluminium, emitting three molecules (1.22 kg) of $CO_2$ (Hauping, 1995, p. 5). However, in practice, the consumption of alumina and carbon anodes is higher, and accordingly the $CO_2$ emissions (Table 2) (Eq. 3). As stated in literature, due to carbon anode oxidation with oxygen from air, the consumption of carbon ranges between 0.40 and 0.45 kg, resulting in $CO_2$ emissions between 1.47 and 1.65 kg (Lumley, 2011, p. 50; Obaidat, Al-Ghandoor, Phelan, Villalobos, and Alkhalidi, 2018; U.S. Department of Energy's Office of EREE, 2007, p. 20).

$$2\ Al_2O_3\ (bath) \quad + \quad 3\ C\ (s) \quad -> \quad 4\ Al\ (l) \quad + \quad 3\ CO_2\ (g) \qquad \text{Eq. 1}$$

$$1.89\ kg \quad + \quad 0.33\ kg \quad -> \quad 1\ kg \quad + \quad 1.22\ kg \qquad \text{Eq. 2}$$

$$1.93\ kg \quad + \quad 0.40–0.45\ kg \quad -> \quad 1\ kg \quad + \quad 1.47–1.65\ kg \qquad \text{Eq. 3}$$

To maximise the productivity of a pot during its lifetime, the composition of its bath is controlled by means of an automatic central point feeder, adding $AlF_3$ periodically. This is needed, because when adding $Al_2O_3$ to the bath, $AlF_3$ starts reacting with the soda impurity ($Na_2O$, 0.4%–0.7%) enclosed in the feed $Al_2O_3$, forming cryolite and alumina (Eq. 4). Also, calcium impurities lead to formation of $CaF_2$. Cryolite is essential in the Hall – Héroult process, since it lowers the melting point of alumina from 2,072 °C to ≈950 °C by dissolving it into aluminium ions ($Al^{3+}$) and oxides ($O^{2-}$).

$$3\ Na_2O\ (bath) \quad + \quad 4\ AlF_3\ (s) \quad -> \quad 2\ Na_3AlF_6\ (l) \quad + \quad Al_2O_3\ (l) \qquad \text{Eq. 4}$$

Guidelines prescribe that the weight ratio between sodium fluoride (NaF) and aluminium fluoride ($AlF_3$), indicated as the bath acidity, should range between 1 and 1.5, also expressed as 10% to 12% $AlF_3$ excess. The concentration of alumina in the bath should vary between 1% and 3%, below 1% unwanted anode effects occur (see Section 2.1.4).

***Carbon anode consumption***

At Aldel each reduction cell is equipped with 24 anodes, and consumes 0.43 tonnes of carbon anode per tonne of aluminium produced (Aldel, 2008, p. 26). Since the anodes hang in the bath, the consumption of carbon molecules takes place at the bottom of the anodes, enlarging the anode to cathode distance. To maintain an optimal anode to cathode distance, the anodes are automatically lowered down over time. Carbon anodes cannot be consumed entirely, since the iron yoke is not allowed to make contact with the bath. Therefore the gross consumption of carbon anodes amounts to 0.547 tonnes per tonne of aluminium (Aldel, 2007, p. 52). On average the anodes have a lifetime of 25–28 days depending on current intensity, so on average one is renewed daily (Aldel, 2007, p. 19). To lift the used anodes out of the bath, the alumina crust is broken, after which the new anode is placed and the alumina crust is restored. Anodes residues (butts) are send back to, and recycled at, the anode supplier.

### 2.1.3 Energy input

***Electricity***

The required energy to run the electrolysis of $Al_2O_3$ is coming from an underground 220 kV power connection. By means of transformers and rectifiers the 220 $kV_{AC}$ is converted to approximately 1,000 $V_{DC}$. From there the power is supplied to the reduction cells, which are connected in series (Aldel, 2008).

By applying the energy conservation principles of the first law of thermodynamics, the minimum energy requirement for producing one tonne of aluminium is 6.23 MWh (Obaidat et al., 2018, p. 6). Moreover, according to Faraday's law, producing 1 kg of aluminium requires a current of 2,980 Ah; implying a minimum voltage of 2.1 V (U.S. Department of Energy's Office of EREE, 2007, p. 28).

In practise, however, cell voltages are almost twice as high, due to several voltage barriers. At Aldel, the reduction cells operate on a voltage of 4.5 V (Stam, Taylor, Chen, Mulder and Rodrigo, 2009). In addition, Aldel's current efficiency ranges between 92% and 95% (Aldel, 2007, p. 16). For this reason, Aldel has a specific electricity consumption of 14.17 MWh (Stam et al., 2009). When including rectifier losses and energy needed for the gas treatment centre, the specific energy consumption amounts to 15.21 MWh, resulting in an annual electricity usage of approximately 1,820 GWh (Aldel, 2007, p. *V*.2).

### 2.1.4 Gas emissions

***$CO_2$ emissions***

In theory, the specific direct $CO_2$ emissions would be 1.22 tonnes (Eq. 2), however, in practise, based on a carbon consumption of 0.43 tonnes, Aldel emits 1.58 tonnes[15] of $CO_2$. The higher $CO_2$ emissions are a result of carbon oxidizing from the high-temperature anode surfaces (Obaidat et al., 2018). To minimize this effect, the anodes are covered with a mix of alumina and broken solid bath material forming a crust (see Figure 12).

Not all of the carbon is directly emitted as $CO_2$. As stated in Aldel's environmental permit application (2007, p. 96), $CO_2$ emissions amount to 1.47 tonnes per tonne of aluminium, corresponding with a specific carbon consumption of 0.40 tonnes. The remaining carbon

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[15] Assuming that all C molecules (eventually) oxidize into $CO_2$ : 0.43 tonne · (44/12) = 1.58 tonnes of $CO_2$ per tonne of liquid aluminium.

(0.03 tonnes per tonne of aluminium) is emitted as carbon monoxide (CO) into the atmosphere. However, after two months this CO will be converted into $CO_2$ by reacting with other atmospheric compounds (ATSDR, 2012).

As mentioned in Section 1.1.2, it is likely to assume that the alumina needed for the Hall – Héroult process is refined from bauxite mined for instance in Jamaica. Considering the average fuels needed for bauxite mining and alumina refining (Bayer process), as given in the life cycle report of the Aluminium Association (AA) (2013, p.30), the total average/indicative amount of direct $CO_2$ emissions for producing one tonne of aluminium becomes respectively: 1.58 (electrolysis) + 0.044 (mining) + 1.37 (alumina refining) = 2.99 tonnes of $CO_2$[16].

### *$SO_2$ emissions*

Besides $CO_2$ emissions (Eq. 1), using carbon anodes also results in sulfur dioxide ($SO_2$) emissions, since the petroleum coke used for making anodes may consist of 0.9% to 3.5% sulfur. Aldel uses anodes with less than 1.5% sulfur to limit emissions. Per tonne of aluminium, 13.75 kg of $SO_2$ is emitted into air (BAT: <15 kg) and further desulfurization is not required according to BREF (Aldel, 2008, p. 26).

### *F emissions (inorganic, non GHG)*

In addition to $CO_2$ emissions, the Hall – Héroult process also produces a significant amount of inorganic fluoride gases. These F-gases are mainly produced by the evaporation of electrolyte, and the formation of hydrogen fluoride (HF) by hydrolysis of $AlF_3$ due to moisture (Lumley, 2011, p. 54). To avoid that all these inorganic gases end up in the atmosphere, at Aldel 98% of the inorganic F-gases are captured by a Gas Treatment Centre (GTC)[17] having a total extraction capacity of 1,520,000 $Nm^3$ per hour (Aldel, 2008, p. 22; Folkers, De Weerdt, Klut, Dupon and Engel, 2014). In short, this dry scrubber system (= BAT) captures inorganic F-gases by using (primary) alumina as adsorbent. The (secondary) alumina, containing adsorbed fluoride, can be reused up to 20 times before the full adsorption capacity is reached, and it is fed to a cell's bath (Aldel, 2007, p. 29). The part of the cell gases that are not treated by the GTC (2%), consist of inorganic F-gases escaped from pots when opening pot covers needed to replace carbon anodes. These gases are emitted into the atmosphere by natural roof ventilation (<20,000,000 $Nm^3$ per hour). This ventilation is driven by the heating of ambient air by the electrolysis cells: approximately two-thirds of the electrical energy input is transferred as heat to the environment, corresponding with 120 MW in total (Aldel, 2007, p. 22). As a result, per tonne of aluminium 0.67 kg of inorganic F-gases (0.4 kg HF) are emitted (Aldel, 2008, p. 21).

An option to reduce the amount of F-gases leaving the pots during anode replacements, is to change the configuration of the pots from "end to end" to "side by side". According to Aldel (2007, p. *IX*.3) such a change in setup is only possible when constructing new electrolysis halls, requiring an investment of EUR 500 million.

### *PFC emissions (organic, GHG)*

Another type of F-gases emissions, are organic F-gases, powerful greenhouse gases such as $CF_4$ and $C_2F_6$. These gases are classified as PFCs and have a global warming potentials 7,390 and 12,200 times higher than that of $CO_2$ respectively (IPCC, 2016). Both gases are produced during so-called anode effects, where bath gases accumulate under the anode, forming a layer of gas. As a result cell voltages increase rapidly to 30 V, causing an electric arc in which $CF_4$ and $C_2F_6$ (and $NO_x$) are produced. Anode effects occur when the bath

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[16] Using the specific fuel emission factors given in the EAA report (2018, Table 2, p. 15), and excluding emissions of generation of the electric power used.

[17] Built during the Retrofit project in 1998, costs: 20 million NLG (Aldel, 1997, p. 19).

concentration of alumina drops below 1%, or when turning the cells on or off (Aldel, 2007, p. 18).

To limit the number of anode effects, monitoring of the alumina concentration is essential. In 1998, Aldel switched from side-feeding alumina manually a few times a day, to feeding alumina continuously and automatically by means of a central point feeder (= BAT) (Alsema, 2000). As a result, the average number of anode effects dropped from 1 per cell, per day, in 1998, to 0.05 per cell, per day, in 2006 (Aldel, 2008, p. 20). Once Aldel is operating at full capacity in 2019, it is expected that the total PFC emissions amount to 70 g per tonne of primary aluminium produced, better than the EAA average in 2005 (see Table 2). For comparison, currently European smelters emit per tonne on average 17.9 g ($CF_4$) + 2.05 g ($C_2F_6$) = 19.95 g (EAA, 2018, p. 32). Aldel did not yet establish a site-specific emission factor which may be part of the difference with today's European mean value.

## 2.2 Production of prebaked carbon anodes

As shown in Figure 12, carbon anodes play an essential role in the current production of primary aluminium. There are two EU ETS companies that produce these carbon anodes in the Netherlands: Aluchemie and Century. Before going into detail on how these anodes are manufactured, first Table 3 gives an overview of main inputs and outputs involved.

### 2.2.1 General process

Overall, the process of manufacturing carbon anodes can be divided into two major steps: the production of green anodes, and the baking of green anodes, see Figure 13. During the first step, petroleum coke and anode residues are pulverized individually, and preheated up to 160 °C. Subsequently, the two materials are mixed together with pitch, and formed into green anodes by using a vibro-compactor (Century, 2018d).

In the second step, batches of uncalcined anodes are transported to open ring furnaces to be baked at maximum fluewall temperatures ranging from 1,190 to 1,200 °C. To reduce energy consumption, a part of the heat enclosed in flue gases is reused for preheating the next batches of green anodes up to 600–650 °C. During the calcination of the green anodes, the pitch is carbonised and volatized, losing one third of its weight. A small portion of the volatile organic compounds (VOCs) will end up in the flue gases leaving the furnaces. Before the flue gases are emitted into air, they are first treated by a fume treatment system, consisting of regenerative thermal oxidizers, and in the case of Century, also of a wet scrubber (see Section 2.2.4) (Aluchemie, 2018e; Century, 2018d).

**Table 3 Average characteristics of the carbon anode production process at Aluchemie and Century, compared to the European average (EAA, 2018) and the ranges given in the BREF (Cusano et al., 2017)**

| Type | Value per tonne of prebaked carbon anode | Source |
|---|---|---|
| **Raw materials**[18] | | |
| Petroleum coke | Aluchemie: 755.7 kg (71.8%)<br>Century: 635.9 kg (62.3%)<br>EAA: 692 kg (68.1%) | (Aluchemie, 2012, p.7)<br>(Century, 2017a, p.11)<br>(EAA, 2018, p. 29) |
| Anode residues | Aluchemie: 141.2 kg (13.4%)<br>Century: 247.4 kg (24.2%) | (Aluchemie, 2012, p.7)<br>(Century, 2017a, p.11) |

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[18] The import of green anodes, as mentioned in the EAA report, is excluded.

| Type | Value per tonne of prebaked carbon anode | Source |
|---|---|---|
| | EAA: 164 kg (16.1%) | (EAA, 2018, p. 29) |
| Coal tar pitch | Aluchemie: 155.5 kg (14.8%)<br>Century: 137.8 kg (13.5%)<br>EAA: 160 kg (15.7%)<br>BREF: 13%–18% | (Aluchemie, 2012, p.7)<br>(Century, 2017a, p.11)<br>(EAA, 2018, p. 29)<br>(Cusano et al., 2017, p. 380) |
| Losses due to pitch combustion | Aluchemie: 52.4 kg (5.2%)<br>Century: ~50 kg (5%)<br>EAA: 16–76 kg (~2%–7%)<br>BREF: 5%–10 % | (Aluchemie, 2012, p.7)<br>(Century, 2018d)<br>(EAA, 2018, p. 29)<br>(Cusano et al., 2017, p. 381) |
| **Energy inputs** | | |
| Electricity consumption | Aluchemie: 131 kWh (0.47 GJ)<br>Century: 145 kWh (0.52 GJ)<br>EAA: 89 kWh (0.32 GJ) | (Aluchemie, 2012, p.7)<br>(Century, 2018d)<br>(EAA, 2018, p. 29) |
| Thermal energy consumption | Aluchemie: 121.3 $Nm^3$ natural gas (3.83 GJ); Century: 110.7 $Nm^3$ natural gas (3.50 GJ)<br>EAA: 2.40 GJ[19] (baking only) | (Aluchemie, 2012, p.7)<br>(Century, 2018d)<br>(EAA, 2018, p. 29) |
| **Gas emissions** | | |
| Carbon dioxide ($CO_2$) (direct) | Aluchemie: 540 kg[20]<br>Century: 450 kg | (Aluchemie, 2012, p.7)<br>(Century, 2017a, p.11)<br>(NEa, 2018) |
| (non GHG) fluoride emissions (F) | Aluchemie: 0.01 kg<br>Century: <0.6 mg<br>EAA: 0.03 kg<br>BREF: 0.01–0.1 kg | (Aluchemie, 2012, p.7)<br>(Hagen, Schrinker and Deinlein, 2015) (Century, 2015b)<br>(EAA, 2018, p. 30)<br>(Cusano et al., 2017, p. 395) |

### 2.2.2 Raw materials

#### *Petroleum coke*

As shown in Table 3, petroleum coke (pet coke) is the leading raw material used in the anode production process. Coke is a residue from the distillation of crude oils, making oil refineries the main supplier of coke. Before coke can be used as input in green anode production, it needs to be calcinated to remove contaminations, such as metals and sulfur compounds (Cusano et al., 2017, p. 381). The share of sulfur embodied in petroleum coke determines not only the amount of $SO_2$ emitted at the anode plant, but also the $SO_2$ emissions at the primary aluminium facility.

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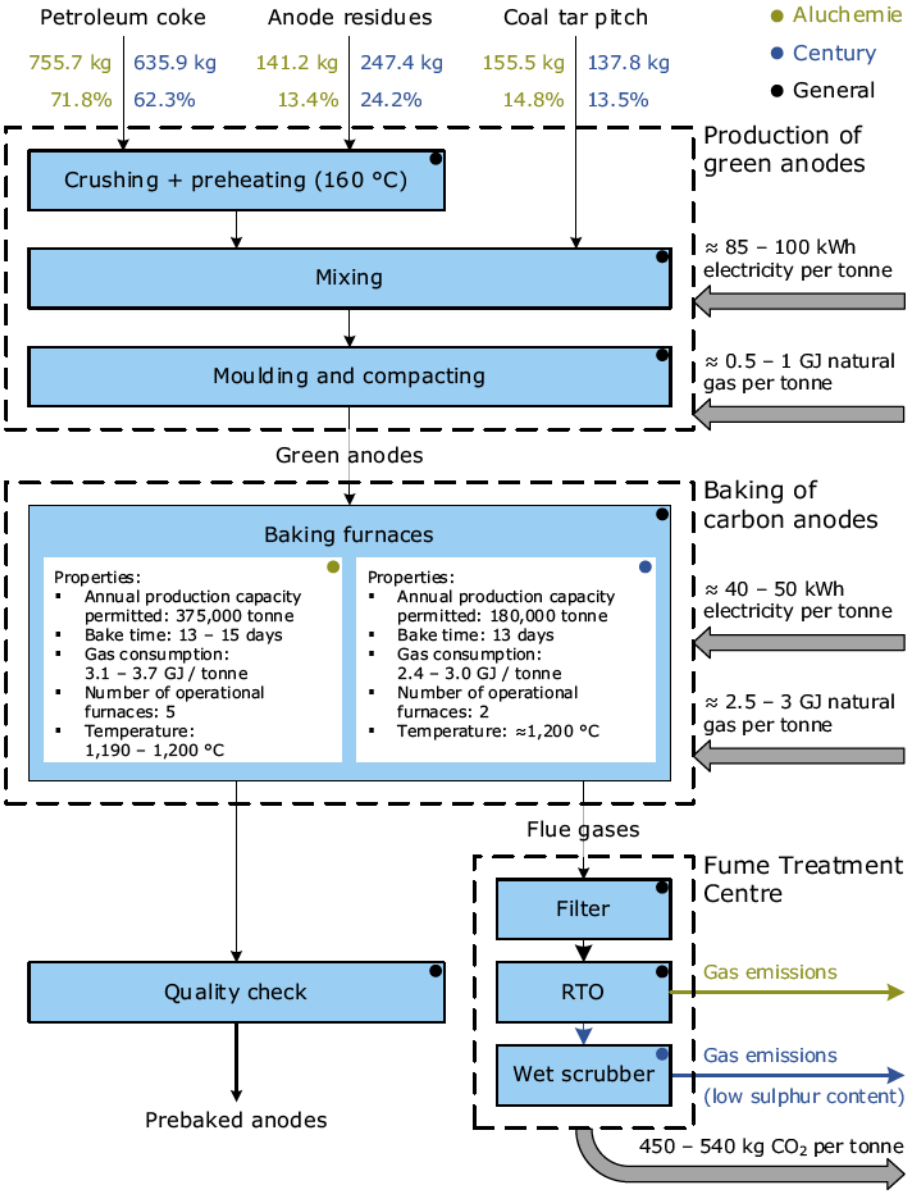
[19] Composed of 1,791 MJ natural gas, and 609 MJ heavy oil.

[20] Recent data on the production of anodes and emission of direct $CO_2$, suggest that Aluchemie's $CO_2$ intensity has dropped from 540 kg to 433 kg (Aluchemie, 2018b; NEa, 2018).

**Figure 13 Simplified overview of the production process of prebaked carbon anodes at Aluchemie and Century, numbers are per average tonne of anode (Aluchemie, 2012, p.7; Aluchemie, 2018e; Century, 2017a, p.11; Century, 2018d)[21]**



Properties:
- Annual production capacity permitted: 375,000 tonne
- Bake time: 13 – 15 days
- Gas consumption: 3.1 – 3.7 GJ / tonne
- Number of operational furnaces: 5
- Temperature: 1,190 – 1,200 °C

Properties:
- Annual production capacity permitted: 180,000 tonne
- Bake time: 13 days
- Gas consumption: 2.4 – 3.0 GJ / tonne
- Number of operational furnaces: 2
- Temperature: ≈1,200 °C

In addition to petroleum coke, packing coke is used in order to separate the anodes and prevent them from oxidising. However, during the baking process a part of the coke ignites, resulting in a packing coke consumption of 12–18 kg (Cusano et al., 2017, p. 393).

### *Anode residues*

To reduce waste streams, a part of the input materials consists of anode residues, coming from primary aluminium factories. Century, for example, transports anodes to its parent company in Iceland. In return, shipping containers filled with anode residues are sent back to Vlissingen in order to be reused. Since the butts have already been cleaned from bath

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[21] The properties of Aluchemie's baking furnaces are based on information provided by Aluchemie (2018b). Other data in this figure is based on Aluchemie's social report (2012).

material ($Al_2O_3$ and $AlF_3$) in Iceland, and the composition of the residues is known, they can be used directly in the production of green anodes (Century, 2018d).

### *Coal tar pitch*

To bind crushed pet coke and anode residues, anode plants make use of preheated pitch. During the baking of anodes, the pitch is converted into coke (carbonisation), making the anodes electrically conductive. Due to its carbonisation, the pitch loses one-third of its weight, resulting in an overall anode material loss of around 5%. The combustion of packing coke and pitch can be considered as the main material loss during the anode production process (U.S. Department of Energy's Office of EREE, 2007, p. 22).

## 2.2.3 Energy input

### *Electricity*

As illustrated in Figure 13, electricity is mainly consumed (67%) during the production of green anodes, when preheating the raw materials for instance. Table 3 shows that the total electricity consumption of the two Dutch production plants ranges between 130 and 150 kWh per tonne of anode, which is slightly above the average of 124.2 kWh consumed by North American anode plants (AA, 2013, p. 35). Looking at the electricity consumed in the green anode department, the Dutch companies perform in line with the European average: $130 \cdot 67\% = 87$ kWh, and $150 \cdot 67\% = 101$ kWh, compared to 89 kWh[22] (EAA, 2018, p. 29).

### *Thermal energy*

Looking at the thermal energy requirements, Aluchemie and Century need 3.83 GJ and 3.50 GJ to produce one tonne of anodes respectively, which matches with the average specific thermal energy consumption of 3.585 GJ given in the AA report (2013, p. 35). When focusing on the amount of energy consumed by the baking furnaces, European anode plants consume on average 2.4 GJ per tonne of anode, while for the Dutch baking furnaces this figure ranges between 2.4 GJ–3.7 GJ (Table 3 and Figure 13).

According to the U.S. Department of Energy's Office of EREE (2007, p.22), the minimum theoretical energy requirement for baking anodes amounts to 0.75 kWh (2.7 GJ) per tonne of anode. In theory, this energy could be completely delivered by the energy released during the carbonisation and volatilisation of the coal tar pitch, making the use of additional fuels unnecessary. However, in practice, this is limited by the oven design. As shown in Table 4, volatiles deliver only ≈30% of the required energy, the remaining energy comes mainly from preheated air (≈25%) and additional firing of natural gas (≈30%). Moreover, only 20% of the input energy goes into heating the anodes (Lin, Gao, Tang and Li, 2012). To understand where the remaining 80% of the energy goes, Figure 14 demonstrates the design of a general open anode baking ring furnace.

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[22] Assuming that the EAA only addresses electricity consumed during the production of green anodes.

**Table 4 Heat balance of a typical anode baking furnace, ranges are indicative (Lin et al., 2012)**

| Heat input | | Heat output | |
|---|---|---|---|
| Natural gas combustion heat | 30%–35% | Anodes heating | 15%–25% |
| Packing coke combustion heat | 7%–12% | Packing coke heating | 5%–10% |
| Volatile combustion heat | 25%–30% | Energy loss through fumes | 35%–45% |
| Existing furnace heat storage | 3%–4% | Heat loss from top of furnace | 5%–10% |
| Preheated air heat storage | 20%–30% | Furnace heat storage | 25%–30% |

As shown in Figure 14, an anode baking furnace can be divided into a number of sections/chambers (in this case, for example 32), separated by head walls. Each section can be further split into a number of pits, separated by (hollow) refractory flue walls. Depending on the dimensions of a section, the pits are typically loaded with 12 to 21 green anodes, covered in packing coke (see Figure 15). Energy needed to bake the anodes is provided by gas-fired burner ramps. During a baking cycle the ramps are shifted along the sections, the anodes stay in the same section. Figure 15 illustrates how zones in a baking furnace are defined. By shifting the ramps to the next section (in this case to the left) the section zones move along, creating a continuous process cycle.

**Figure 14 Design of a general open top anode baking furnace. Adapted from *Riedhammer* website, by Riedhammer, 2010, retrieved from http://www.riedhammer.de/System/00/00/95/9565/ed_deDE/Internetversion.pdf**

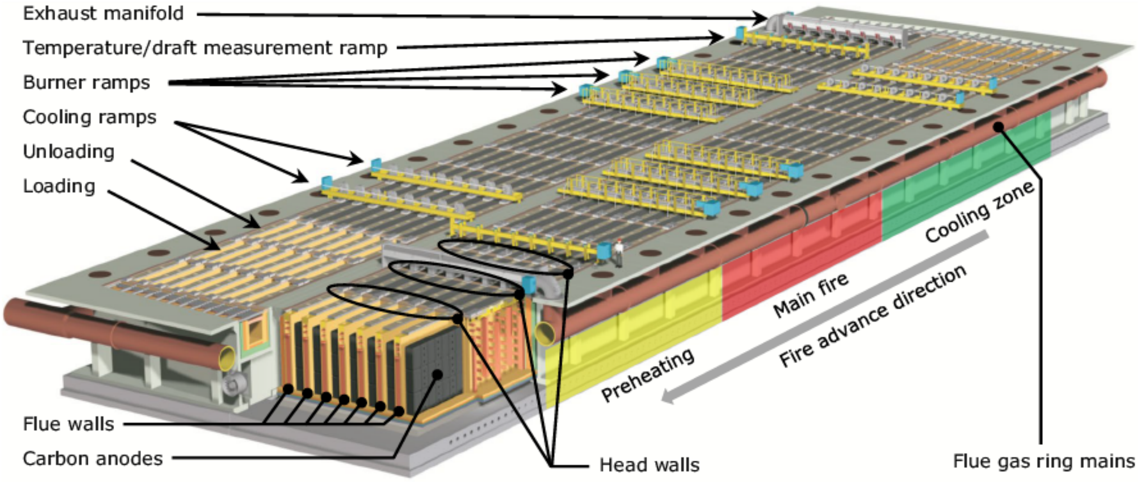
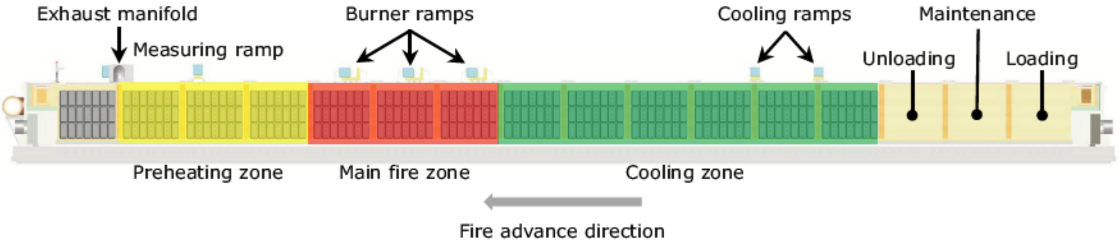
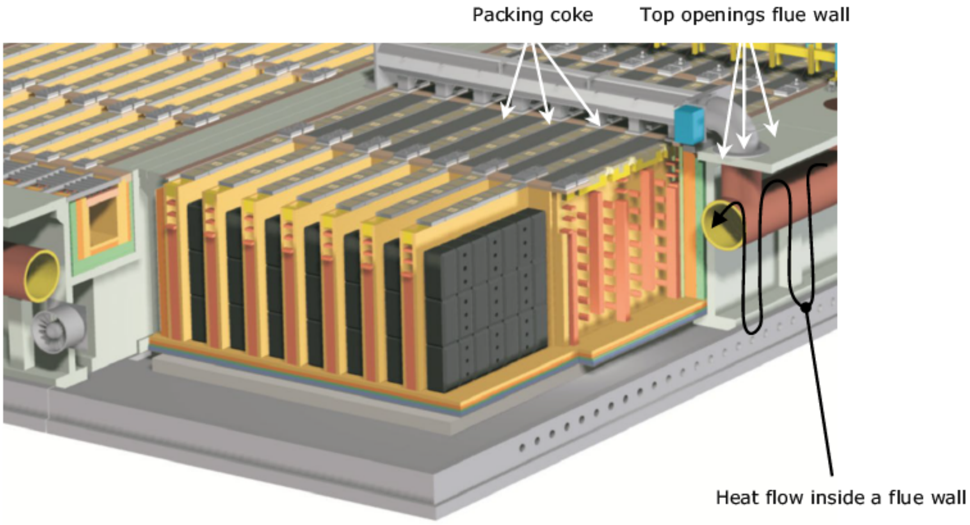


**Figure 15 Side view of anode baking furnace. Adapted from *Riedhammer* website, by Riedhammer, 2010, retrieved from http://www.riedhammer.de/System/00/00/95/9565/ed_deDE/Internetversion.pdf**



In the main fire zone the burner ramps are placed above the top openings in the flue walls, parallel to the head walls. In this way, the gas firing takes place inside the flue walls, creating flows of hot air heating the flue wall surfaces, equally (see Figure 16).

**Figure 16 Construction of anode baking pits. Adapted from *Riedhammer* website, by Riedhammer, 2010, retrieved from http://www.riedhammer.de/System/00/00/95/9565/ed_deDE/Internetversion.pdf**



From the flue walls the heat is gradually transferred to the batch of green anodes. The remaining heat in the gas flows is passed on to the next section, where it can used to preheat the next section of anodes. By using flue walls as heat medium, the whole section/chamber can be baked gradually at once. However, in practice a significant part of the input heat remains stored in the walls itself, accounting for a loss of around 30% (Lin et al., 2012). In addition, the fumes leaving the section contain another 30% of the input heat. Finally, part of the input heat escapes from the top the furnace, or is consumed during the heating of the packing coke.

## 2.2.4 Gas emissions

### *$CO_2$ emissions*

By using a net caloric value of 31.65 MJ / $Nm^3$ and an emission factor of 56.1 kg / GJ, approximately 40% to 45% of the $CO_2$ emissions can be allocated to firing natural gas (Aluchemie, 2012; Century, 2018d; NEa, 2014, p. 98). The remaining emissions are mainly a result of the combustion of VOCs and packing coke (U.S. Environmental Protection Agency, 2018).

### *F emissions (inorganic, non GHG)*

During the baking process also an amount of inorganic F-gases is emitted, originating from fluoride impurities enclosed in anode residues. To reduce these F emissions, both companies make use of a Fume Treatment System (FTS), treating the flue gases of the baking furnaces. In the case of Century, the FTS has a maximum total air volume of 110,000 $Nm^3$ / h (average of 87,000 $Nm^3$ / h) and consists of three pre-filter units, three regenerative thermal oxidizers, and a wet scrubber using sodium hydroxide (NaOH) (Hagen et al., 2015). By including a wet scrubber, air emissions of HF and $SO_2$ are significantly reduced. At Aluchemie the FTS consists of pre-filters, three regenerative thermal oxidizers and dry scrubbers (Aluchemie, 2011; DCMR, 2018).

***$SO_2$ emissions***

During the last 7 years Aluchemie faced difficulties in meeting the permitted $SO_2$ level. This resulted in a new permit application procedure since then, which permit has been granted in 2015 and renewed according to the new activity degree in 2018 by the regional environmental protection agency (DCMR). Aluchemie is currently allowed to emit 1,100 tons of $SO_2$ per year (2.93 kg per tonne anode), on the condition that Aluchemie has to carry out investigations on $SO_2$ reduction options, including a new cost-effectiveness study on implementing a desulfurization plant (i.e. wet scrubber) (DCMR, 2018). According to a former study, investments costs for building such a plant approximate EUR 20 million per stack.

## 2.3 Casting of liquid primary aluminium into billets and slabs

After primary aluminium is extracted from alumina (see Section 2.1), it is casted into semi-finished products by a technique called “direct chill (DC) casting”. Essentially three types of semi-finished aluminium products can be distinguished: ingots, extrusion billets, and rolling slabs. In case of the Netherlands liquid primary aluminium is directly casted into billets and slabs on site (Aldel, 2007, p.11). Table 5 and Figure 17 show the input materials and energy consumed during the casting of one tonne of aluminium. Currently, Aldel recycles around 33% of secondary flows, which is more than the EU average of 9%.

### 2.3.1 General process

Looking at Figure 17, the following four main steps in the casting process of aluminium can be made: remelting and mixing, degassing, casting, and heat treatment.

**Table 5 Average characteristics of the casting of liquid primary aluminium into billets and slabs at Aldel, compared to the European average (EAA, 2018) and the ranges given in the BREF (Cusano et al., 2017)**

| Type | Value per tonne of casted aluminium | Source |
|---|---|---|
| **Raw materials** | | |
| Liquid primary aluminium | Aldel: 667 kg (67%)<br>EAA: 912 kg (91%) | (Aldel, 2007, pp. 22–23)<br>(EAA, 2018, p. 34) |
| Clean industrial aluminium scrap | Aldel: 127 kg (12%)<br>EAA: 23 kg (1%) | (Aldel, 2007, p. 23)<br>(EAA, 2018, p. 34) |
| Clean (pre-alloyed) aluminium | Aldel: 202 kg (19%)<br>EAA: 69 kg (1%) | (Aldel, 2007, p. 23)<br>(EAA, 2018, p. 34) |
| Alloys | Aldel: 20 kg (2%[23])<br>EAA: 23 kg (1%) | (EAA, 2018, p. 34) |
| Losses due to dross formation (net) | Aldel: 20 kg (2%)<br>EAA: 26 kg (3%)<br>BREF: 10–15 kg | (Overduin and Ozinga, 2010)<br>(EAA, 2018, p. 34)<br>(Cusano et al., 2017, p. 398) |

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[23] Assumption based on average share of alloys in the production of secondary aluminium billets and slabs.

| Type | Value per tonne of casted aluminium | Source |
|---|---|---|
| **Energy inputs** | | |
| Electricity consumption | Aldel: 67 kWh (0.24 GJ)<br>EAA: 95 kWh (0.34 GJ) | (Aldel, 2007, p. *V*.2)<br>(EAA, 2018, p. 34) |
| Thermal energy consumption | Aldel: 83 $Nm^3$ natural gas (2.63 GJ) incl. homogenisation<br>EAA: 1.6 GJ (excl. homogenisation)<br>BREF: 0.3–2.5 GJ (excl. homogenisation and remelt) | (Aldel, 2007, p. *V*.2)<br>(EAA, 2018, p. 34)<br>(Cusano et al., 2017, p. 398) |
| **Gas emissions** | | |
| Carbon dioxide ($CO_2$) (direct) | Aldel: 147.5 kg<br>EAA: 103.6 kg[24] (fuel-based) | (Aldel, 2007, p. *V*.2) |

### *Remelting and mixing*

To achieve the desired chemical composition of the input aluminium mix, primary smelters make use of remelting, mixing, and casting furnaces. According to its environmental application (2007, p. 23), Aldel operates:

- a gas-fired smelting furnace, used for remelting solid aluminium scrap and ingots;
- five gas-fired mixing furnaces, used to mix liquid aluminium with alloys, and with molten/solid aluminium scrap and ingots;
- three gas-fired casting furnaces, used for casting aluminium;
- three electrical casting furnaces, used for casting aluminium;
- two gas-fired mixing / casting furnaces, used as mixing or casting furnace.

As illustrated in Figure 17 various casting routes are possible. The characteristics of the incoming scrap/ingots, and the customer requirements, determine which types of furnaces are used.

### *Filtering and degassing*

Once the composition of the aluminium mix matches with the desired chemical properties, the aluminium leaving gas-fired casting furnaces is guided through a foam filter and degasser. By making use of a purge gas consisting of argon and chlorine (2%–10%), the degasser separates sodium and hydrogen gas impurities (Aldel, 2007, p. 23). Due to the reactive character of chlorine, resulting in unwanted chlorinated hydrocarbons, the use of argon is preferred (Goovaerts, Veys, Meulepas, Vercaemst and Dijkmans, 2001). In 2016, Aldel (Klesch) halved its chlorine consumption, indicating that the degassing process is currently mainly done by argon (Klesch, 2016).

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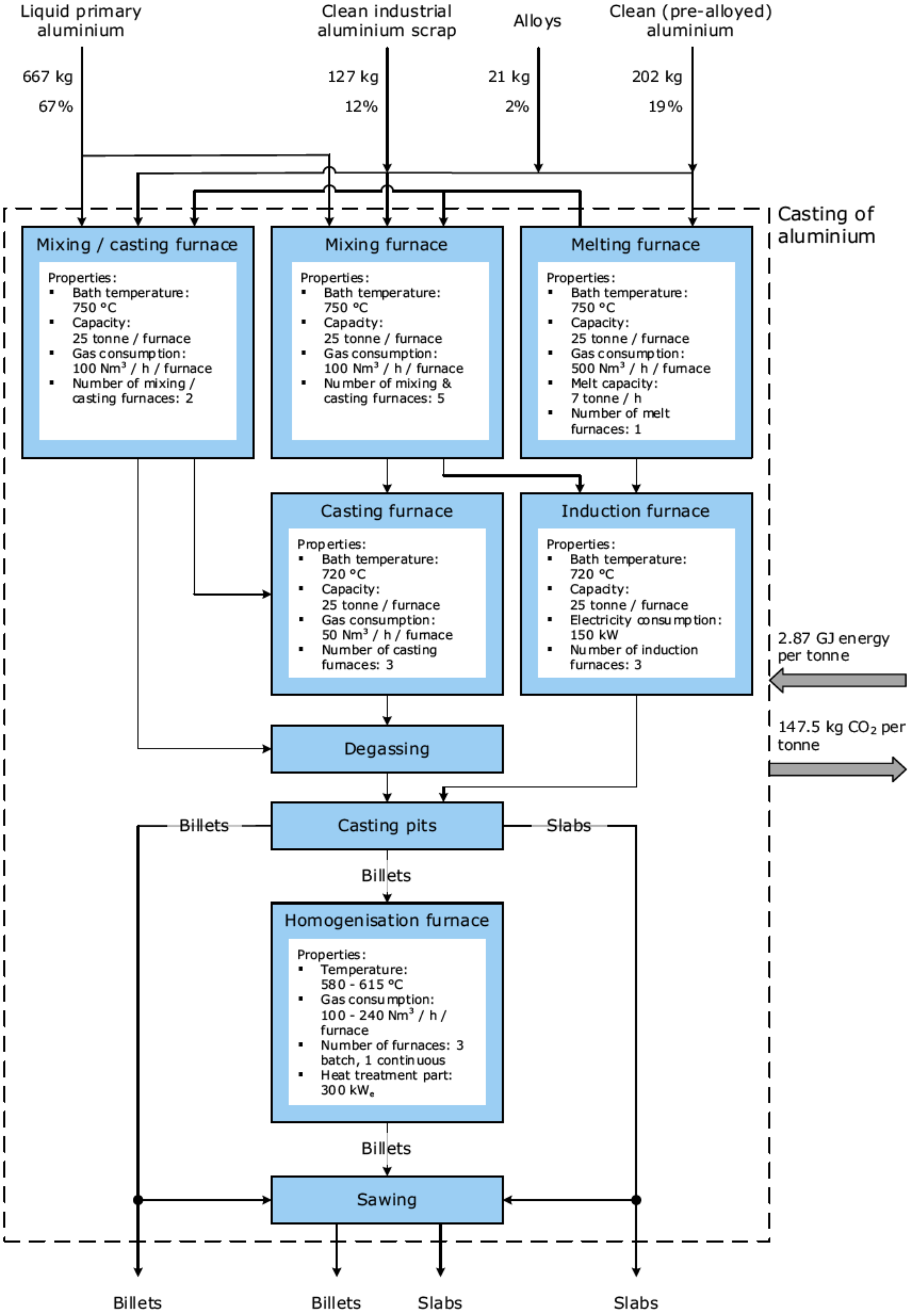
[24] Calculated based on the energy input mix and $CO_2$ conversion factors given by the EAA (2018, p. 15).

**Figure 17. Simplified overview of the casting of primary aluminium into billets and slabs at Aldel, numbers are per average tonne of billet/slab (Aldel, 2007; Aldel, 2019).**



### *Casting*

After having being degassed for an hour, the molten aluminium is passed from the degasser to the vertical casting pits. Here the aluminium is casted into billets or rolling slabs of 4 to 8 metres long. The casting machine exists of a hollow ring of which the bottom is closed by a cast dummy. Subsequently liquid aluminium is added at the top of the ring, while at the same time the ring is cooled with water. As a result the aluminium starts to solidify at the bottom of the ring. By lowering the cast dummy (together with the solidified aluminium), new liquid aluminium can be added at the top of the ring, growing an aluminium billet or slab.

### *Heat treatment*

Depending on the type of alloy and desired physical properties, the produced aluminium billets  will be mostly treated in homogenisation furnaces. Typically, the temperature in a homogenisation furnace of 580–615 °C is lower than the melting point of aluminium (660.3 °C), but is high enough to reduce the physical tension, increase the malleability, and improve the structure of the end products. A distinction can be made between batch homogenisation furnaces in which batches of billets and slabs are homogenised, and continuous homogenisation furnaces in which a continuous flow of products is treated.

After the heat treatment, the billets are cooled with air or water, depending on the treatment. Subsequently they are sawn at the required length; saw residues are collected and reused internally.

## 2.3.2 Raw materials

### *Liquid primary aluminium*

The majority, 667 kg[25], of input aluminium consists of liquid aluminium coming from the electrolysis department. This is lower than the European average of 912 kg liquid aluminium per tonne of aluminium (EAA, 2018, p. 34). When leaving the pots, the liquid aluminium has a temperature of ≈ 960 °C, almost 300 °C higher than its melting point. As shown in Figure 17 the temperature of the mixing furnaces is 750 °C.

### *Solid clean aluminium and alloys*

To reduce on electricity costs, liquid primary aluminium is mixed with solid clean aluminium before it is casted. After all, remelting and casting one tonne of clean aluminium scrap/ingots requires only 5% of the final energy needed to produce one tonne of primary aluminium (Lumley, 2011, p. 70). In the Netherlands, on average almost a third of the input material consists of industrial aluminium scrap (12%) and purchased aluminium ingots (19%) (see Table 2). In addition, it is assumed that 2% of alloys are added to give the billets and slabs the desired chemical and physical properties. This value is common for the type of alloys (wrought alloys) Aldel produces. Typical alloy additives are iron, silicon, magnesium and manganese (Aldel, 2007, p. 23).

A part of the scrap is coming from Aldel's own sawing department, while another part is purchased from customers (Aldel, 2008, p. 16). Clean (pre-alloyed) aluminium ingots are purchased from the neighbouring company Roba Metals Delfzijl, which is among others a recycler/remelter of (contaminated) aluminium scrap (VNMI and AVNeG, 2011, p. 33). The input shares for aluminium scrap and ingots are based on ranges given by Aldel (2007, p.23): 10%–16.7% for scrap and 16.7%–23.3% for ingots. At a maximum 33% of the total input, values of 13% and 20% are assumed. Considering that 2% of solid aluminium will be replaced by alloy additives, the corrected input values become: 13% - 1% = 12%, and 20%

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[25] Assuming an annual primary aluminium capacity of 120,000 tonne, and an annual casting capacity of 180,000 tonne.

- 1% = 19%. The absolute input values for aluminium scrap (127 kg) and ingots (202 kg), however, are slightly higher than the relative values would suggest, since they take into account aluminium losses due to dross formation. When smelting aluminium, the top surface will start to react with its environment, forming a sort of foam layer of impurities called dross. In the Netherlands, approximately net 2% (20kg) of the aluminium will be lost as dross (Overduin and Ozinga, 2010, p.6). Dross losses are assumed to be compensated by adding extra solid aluminium scrap, ingots and alloy metals, considering the maximum annually permitted liquid aluminium production level of 120,000 tonnes.

The percentages above reflect the situation at full scale. In the recent transition period from 2015 to 2017, the part of solid aluminium (scrap, ingots and alloy) at Aldel varied between 29% and 46%.

### 2.3.3 Energy input

At full capacity (180,000 tonnes) Aldel’s cast house consumes 14,950,000 Nm$^3$ of natural gas and 12 GWh of electricity annually, mostly needed for (Aldel, 2007, p. 23, *V*.2):

- a gas-fired smelting furnace with regenerative burners (T = 750 °C), with an average gas consumption of 500 m$^3$ per hour, that can be filled up to 25 tonnes, smelting 7 tonnes per hour;
- seven gas-fired mixing/holding furnaces (T = 750 °C), with an average gas consumption of 100 m$^3$ per hour per furnace, and a capacity of 25 tonnes per furnace;
- three gas-fired casting furnaces (T = 720 °C), with an average gas consumption of 50 m$^3$ per hour per furnace, and a capacity of 25 tonnes per furnace;
- three induction casting furnaces, operating on 150 kW, and a capacity of 25 tonnes per furnace. Also used for smelting cast iron on the anode site.
- three gas-fired batch homogenizing furnaces (T = 580–615 °C), with a gas consumption varying between 100 and 240 m$^3$ per hour per furnace;
- a gas-fired continuous homogenizing furnace (T = 580–615 °C), with a gas consumption varying between 100 and 220 m$^3$ per hour;
- electric heat treatment equipment, operating on 300 kW.

Assuming a net caloric value for natural gas of 31.65 MJ / Nm$^3$ gives an average specific final energy consumption of: (473.2 TJ$_{GAS}$[26] + 43.2 TJ$_{ELECTRICITY}$[27] ) / 180,000 tonnes = 2.87 GJ / tonne. On first sight Aldel performs less than the European average of 1.94 GJ / tonne, however, the European average is based on a higher share (91%) of liquid aluminium (T ≈ 960 °C) (EAA, 2018, p. 34). In addition, the European value does not include the energy consumed during the homogenisation phase. According to the BREF, homogenising the billets and slabs takes 0.5 to 1.2 GJ of thermal energy per tonne (Cusano et al., 2017, p. 398).

By having a specific thermal energy consumption of 2.87 GJ / tonne, Aldel has improved significantly compared to its consumption in 2002: 3.47 GJ / tonne (Aldel, 2007, p. *V*.2). Nevertheless, there may be still room for further improvement since the theoretical energy requirement to heat pure aluminium from 25 °C to 960 °C amounts to 1.2 GJ per tonne (U.S. Department of Energy's Office of EREE, 2007, p. 129).

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[26] 473.2 TJ = 14,950,000 Nm$^3$ · 31.65 MJ / Nm$^3$.

[27] 43.2 TJ = 3.6 · 12 GWh.

### 2.3.4 Gas emissions

***$CO_2$ emissions***

Assuming an average annual gas consumption of 473.2 TJ and a $CO_2$ emission factor of 56.1 tonnes $CO_2$ per TJ of gas, results in a total annual cast house emission of ≈26.5 kt of $CO_2$ (147.5 kg per tonne of aluminium) (NEa, 2014, p. 98).

## 2.4 Recycling and casting of aluminium from scrap into billets and slabs

An alternative, energy-saving way for producing aluminium billets and rolling slabs out of liquid primary aluminium, is that of recycling aluminium scrap. Here, a distinction can be made between industrial scrap and end-of-life scrap. In the Netherlands, there are two EU ETS companies that produce secondary aluminium out of aluminium scrap: E-MAX and Zalco. Aluminium scrap is also collected and recycled by Roba Metals Delfzijl; however, this company is not registered under the EU ETS and not included in this report (RMD, 2013).

As the name suggests, industrial scrap originates from the aluminium processing industry, and consists of circulation scrap, such as saw residues and internally rejected products for instance. The industrial aluminium scrap used can be divided into clean scrap and lightly contaminated scrap. This contamination consists mostly of plastic profile material from window frames and lacquer, including both pre- and post-consumer scrap. E-MAX recycles both contaminated and clean scrap to produce extrusion billets, while Zalco uses only clean scrap to produce extrusion billets and rolling slabs. To see the similarities and differences between the production processes, the main process characteristics (see Table 6 and Table 7) are described below.

### 2.4.1 General process

The flow diagram for recycling aluminium scrap, Figure 18 (page 39), can be roughly divided into the same four mains steps as for casting primary aluminium: remelting and mixing, filtering and degassing, casting, and heat treatment. Regarding the last three steps, no major differences between the companies/processes can be identified. Both companies make use of a foam filter and argon degasser to purify the molten aluminium before it enters the vertical casting pits. In addition, both companies apply the DC-casting technique (see Section 2.3.1), and also the homogenisation treatments are essentially similar (E-MAX, 2018b; Zalco, 2018c). But when looking at the first stage of the production process, remelting and mixing, some significant differences can be noticed between the two sites.

***Recycling of clean industrial aluminium scrap***

As shown in Figure 18, E-MAX uses a tiltable reverberatory furnace (equipped with recuperative burners) that can serve as smelting furnace or as casting furnace (not simultaneously), while Zalco makes use of stand-alone reverberatory smelting (2; equipped with regenerative burners) and casting (6) furnaces. At E-MAX the smelting / casting furnace is responsible for a production of approximately 10,000 tonnes of aluminium billets per year, which is significantly lower than Zalco’s annual production of aluminium billets/slabs. On the other hand, the recycling percentage of E-MAX’s clean scrap production line is significantly higher (average 80%), compared to the estimated range of Zalco (65%–70%) (E-MAX, 2018b).

### *Recycling of contaminated industrial aluminium scrap*

For recycling lightly contaminated aluminium scrap, E-MAX has another production line consisting of two multi-chamber furnaces and one casting furnace, all reverberatory furnaces (E-MAX, 2018b). Each multi-chamber furnace has two chambers, chamber 1 for smelting solid primary aluminium (i.e. ingots, T-bars), and chamber 2 for smelting contaminated scrap. The chambers are separated by a wall hanging in an aluminium bath, in this way the two chambers are only connected by the bath. In chamber

**Table 6 Average characteristics of the recycling clean industrial aluminium scrap into billets and slabs at E-MAX and Zalco, compared to the European average (EAA, 2018) and the ranges given in the BREF (Cusano et al., 2017)**

| Type | Value per tonne of casted aluminium | Source |
|---|---|---|
| **Raw materials** | | |
| Clean industrial aluminium scrap | E-MAX: 750–850 kg (75%–85%)<br>Zalco: 650–700 kg (65%–70%)<br>EAA: 65%–75% | (E-MAX, 2018b)<br>(Zalco, 2018c)<br>(EAA, 2018, p. 74) |
| Primary (pre-alloyed) aluminium | E-MAX: 150–250 kg (15%–25%)<br>Zalco: 300–350 kg (30%–35%)<br>EAA: 20%–25% | (E-MAX, 2018b)<br>(Zalco, 2018c)<br>(EAA, 2018, p. 74) |
| Alloys | E-MAX, Zalco: 20 kg (2%)<br>EAA: 1% | (E-MAX, 2018b)<br>(Zalco, 2018c)<br>(EAA, 2018, p. 74) |
| Liquid aluminium | E-MAX, Zalco: 0 kg<br>EAA: 5%–10% | (E-MAX, 2018b; Zalco, 2018c)<br>(EAA, 2018, p. 74) |
| Losses due to dross formation (net) | E-MAX, Zalco: 20 kg (2%)<br>EAA: 2%<br>BREF: 15–30 kg | (E-MAX, 2018b; Zalco, 2018c)<br>(EAA, 2018, p. 74)<br>(Cusano et al., 2017, p. 415) |
| **Energy inputs** | | |
| Electricity consumption | E-MAX, Zalco: 120–200 kWh (0.4–0.7 GJ)<br>EAA: 150 kWh (0.54 GJ) | (E-MAX, 2018b; Zalco, 2018c)<br>(EAA, 2018, p. 74) |
| Thermal energy consumption | E-MAX, Zalco: 150–250 $Nm^3$ natural gas (5–8 GJ)<br>EAA: 3.2 GJ<br>BREF: 2–9 GJ | (E-MAX, 2018b; Zalco, 2018c)<br>(EAA, 2018, p. 74)<br>(Cusano et al., 2017, p. 417) |
| **Gas emissions** | | |
| Carbon dioxide ($CO_2$) (direct) | E-MAX, Zalco: 280–450 kg<br>EAA: 205 kg (fuel-based)[28] | (E-MAX, 2018b; Zalco, 2018c) |

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[28] Calculated based on the energy input mix and $CO_2$ conversion factors given by the EAA (2018, p. 15).

**Table 7 Average characteristics of the recycling contaminated aluminium scrap into billets at E-MAX, compared to the North American average (AA, 2013) and the ranges given in the BREF (Cusano et al., 2017)**

| Type | Value per tonne of casted aluminium | Source |
|---|---|---|
| **Raw materials** | | |
| Aluminium scrap | E-MAX: 750–850 kg (75%–85%) of which 200–400 kg is contaminated<br>AA: 968 kg | (E-MAX, 2018b)<br>(AA, 2013, p. 66) |
| Primary (pre-alloyed) aluminium | E-MAX: 150–250 kg (15%–25%)<br>AA: 65 kg | (E-MAX, 2018b)<br>(AA, 2013, p. 66) |
| Alloys | E-MAX: 5–10 kg (0.5%–1%)<br>AA: 15 kg | (E-MAX, 2018b)<br>(AA, 2013, p. 66) |
| Losses due to dross formation (net) | E-MAX: 20 kg (2%)<br>AA: 67 kg | (E-MAX, 2018b)<br>(AA, 2013, p. 66) |
| **Energy input** | | |
| Electricity consumption | E-MAX: 120–200 kWh (0.4–0.7 GJ)<br>AA: 110 kWh (0.40 GJ) | (E-MAX, 2018b)<br>(AA, 2013, p. 66) |
| Thermal energy consumption (*non-electrical*) | E-MAX: 150–250 $Nm^3$ (5–8 GJ)<br>AA: 4.8 GJ[29] (natural gas)<br>BREF: 2–9 GJ | (E-MAX, 2018b)<br>(AA, 2013, p. 66)<br>(Cusano et al., 2017, p. 417) |
| **Gas emission** | | |
| Carbon dioxide ($CO_2$) (direct) | E-MAX: 280–450 kg<br>AA: 303 kg[30] (fuel-based) | (E-MAX, 2018b)<br>(AA, 2013, p. 66) |

1, three gas-fired regenerative burners are used to smelt clean aluminium, resulting in an aluminium bath of 700–720 °C. Subsequently, ventilators are used to preheat chamber 2 with hot air (800–900 °C) coming from chamber 1. Next, contaminated scrap is loaded on the bridge of chamber 2, and smelted using hot air and bath radiation. During the process, the oxygen level in chamber 2 is kept low on 1.5%–2%, resulting in pyrolysis of the contaminated scrap. The molten aluminium flows from the bridge into the bath, and the released organic gases are captured and mixed with oxygen, to serve as fuel for the regenerative burners in chamber 1. The overall recycling percentage of the production line varies between 75% and 85%[31], depending on the quality of the scrap and the type of alloy required by the customer (E-MAX, 2018b).

## 2.4.2 Raw materials

### *Recycling of clean industrial aluminium scrap*

Both E-MAX and Zalco retrieve a part of the required industrial aluminium scrap from their billets/slabs customers (aluminium processing companies). Another part is coming from internal processes, such as saw residues. But most of the input is bought on the international scrap market. The input percentages given in Figure 18 are indicative.

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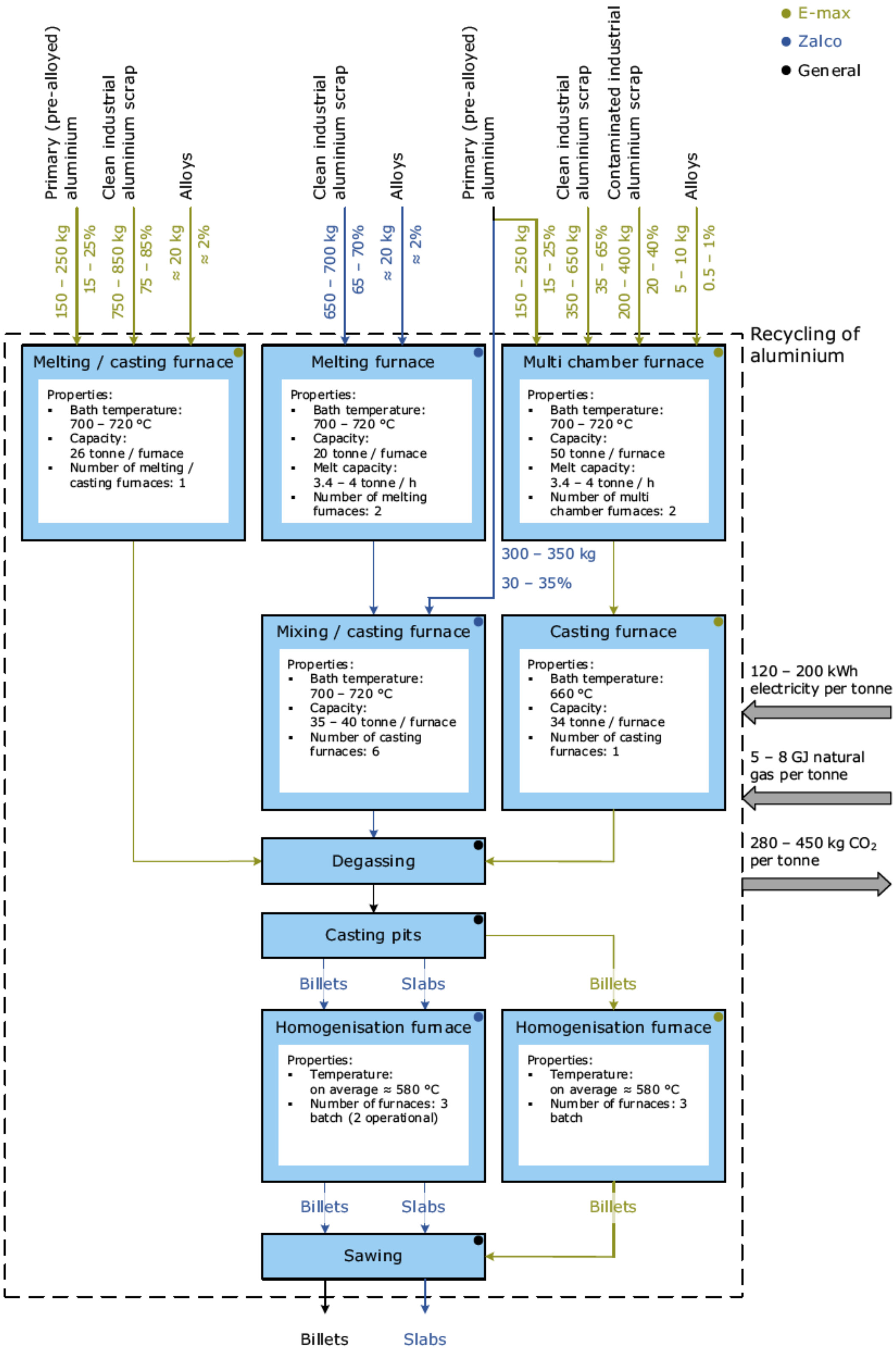
[29] Based on an average input mix of: 92% scrap, 6% primary ingot, and 2% alloys (AA, 2013, p. 66).

[30] Calculated based on a $CO_2$ conversion factor of 63.2 kg $CO_2$ per GJ of natural gas given by the EAA (2018, p. 15). $CO_2$ emissions from organic materials are not included.

[31] Concerns an average range. Outliners can occur.

**Figure 18. Simplified overview of the recycling of clean and contaminated aluminium scrap into billets and slabs at E-MAX and Zalco, numbers are per average tonne of billet/slab (E-MAX, 2018b; Zalco, 2018c). Before the scrap is loaded into a furnace, first it is sorted by using the principles of optical emission spectroscopy (E-MAX, 2018b; Zalco, 2018c).**



To compensate for aluminium losses due to dross formation, the absolute input values per tonne of casted aluminium are slightly higher than the relative input values would suggest. Approximately, net 2% (20kg) of the aluminium will be lost as dross (Overduin and Ozinga, 2010, p.6). In this report it is assumed that the dross losses are compensated equally over all input flows. To recover aluminium out of dross Zalco operates an onsite dross press, while E-MAX makes use of the dross recovery services of a third party.

#### ***Recycling of contaminated aluminium scrap***

On average, the recycling of scrap requires additional primary aluminium, clean industrial aluminium scrap, and some alloy metals. By adding primary aluminium and clean scrap, the quality of the end product can be increased to match with that of pure primary aluminium. The input shares shown in Figure 18 are adjusted to the chemical and physical properties of the incoming scrap and the required quality of the end product; the share of primary aluminium, for example, ranges between 15% and 25% (E-MAX, 2018b). As done for the other processes, the absolute input values are corrected for dross formation.

At E-MAX the average share of contaminated scrap depends on the contamination grade of the scrap. The majority of the contaminated scrap consists of aluminium window frame profiles. These contain plastic isolation material and coating. To prevent that the total contamination grade of the incoming aluminium exceeds the furnace limitations, additional visual selection takes place.

### 2.4.3 Energy input

Based on E-MAX’s and Zalco’s annual consumption of gas and electricity, and annual production of billets/slabs, it requires 5–8 GJ of natural gas, and 120–200 kWh of electricity, to produce one tonne of aluminium out of aluminium scrap. In this process, natural gas is mainly used for remelting, casting, and homogenizing aluminium, while electricity is used by auxiliary equipment, such as electric motors. Remelting contaminated scrap should theoretically require more energy compared to remelting clean scrap, due to the plastics incorporated in the scrap. However, during the pyrolysis of contaminated scrap, organic gases are released that are used as additional fuel for E-MAX’s multi-chamber furnaces. As a result, in practice the organic gases can supply up to 20% of the required thermal energy input, compensating a significant part of the otherwise extra needed energy (Huurdeman, 2017, p.33).

To put the energy consumption of E-MAX and Zalco in perspective, Table 6 and Table 7 include the average energy consumed by European and North American secondary aluminium producers. The Dutch industry scores lower in terms of gas consumption, however, the European average relates to an input of liquid aluminium of 5% to 10%, meaning that already less energy is needed to smelt the remaining aluminium input (EAA, 2018, p. 74). The North American average serves as a better reference, since no liquid input aluminium is involved.

### 2.4.4 Gas emissions

#### ***$CO_2$ emissions***

Assuming that all direct $CO_2$ emissions result from firing natural gas, recycling one tonne of clean industrial aluminium scrap results in 280–450 kg[32] of $CO_2$. Concerning the refining of contaminated scrap, approximately 10% to 20% of the direct $CO_2$ emissions is coming from organic contamination, the remaining part is coming from firing natural gas (E-MAX, 2018b).

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[32] Based on a specific natural gas consumption of 5 – 8 GJ (see Table 7), a net caloric value of 31.65 MJ / $Nm^3$ and an emission factor of 56.1 kg / GJ (NEa, 2014, p. 98).

# 3 Aluminium products and application

In general, the Dutch aluminium industry focuses mainly on the production of aluminium profiles and castings. To understand the market positions of Aldel, Aluchemie, Century, E-MAX and Zalco, this chapter starts with giving an overview of the main players in the Dutch aluminium production chain (Section 3.1). Subsequently, the properties of the products produced by EU ETS registered companies are addressed (Section3.2), followed by the characteristics of the materials required to manufacture these products (Section 3.3).

## 3.1 Aluminium production chain

To get an idea of the steps needed to produce aluminium products such as aluminium foil, aluminium window profiles, or aluminium engine blocks, Figure 19 gives an overview of the main manufacturing companies in the Netherlands, with the aluminium companies registered under the EU ETS in blue[33]. In the schematic, each block represents a production step, a company, or a set of companies. The blocks include an indication of the required material and (final) energy inputs, and the amount of $CO_2$ that is emitted during the process. Subsequently, estimated figures about annual (expected future) production capacities, and workforces are given. In cases where information on the current production capacity is lacking, it is assumed that the annual capacity equals the capacity permitted by the local authorities. Based on public available data on production/consumption rates, indications of annual material flows are presented in red.

Starting at the top of the scheme it can be seen that producing 120 kt of liquid aluminium requires ≈232 kt of alumina (≈540 kt of bauxite[34]), ≈66 kt of prebaked anodes (gross), and ≈1.8–2.2 kt of aluminium fluoride. As mentioned in Section 1.1.1 (page 9), it is likely to assume that the alumina and bauxite originate from, for instance, the United States and Jamaica, respectively. Since no bauxite mining or alumina refining takes place in the Netherlands, life cycle data from the Aluminium Association (AA, 2013) and the EAA (2018) on average final energy use and emission factors is used, to give an indication/idea of the final energy use and direct $CO_2$ emissions involved. Concerning the supply of anodes and aluminium fluoride, specific supplier data for Aldel is missing. Aluchemie is able to produce anodes for different electrolysis cell configurations, while Century only produces for its Icelandic aluminium smelters. To determine the total annual Dutch production capacity of carbon anodes, figures of Aluchemie’s permitted capacity (375 kt), and Century’s intended future capacity (165 kt) are used.

After the electrolysis stage, the liquid aluminium at Aldel is mixed with 60 kt of clean aluminium, clean industrial scrap, and alloy metals, and casted into billets and slabs. According to the roadmap towards 2030 of the branch organizations VMNI and AVNeG (2011, p.33), the clean aluminium ingots are coming from the neighbouring scrap refining company

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[33] The blocks coloured in grey were not part of this MIDDEN study, but are only included in Figure 19 to give a general indication of which positions Aldel, Aluchemie, Century, E-MAX and Zalco have in the Dutch aluminium industry. Therefore, the grey blocks only contain limited and/or general average data/information.

[34] Assuming that refining 1 tonne of alumina requires 2.333 tonne of bauxite (Sustainable Business Magazine, 2017, p. 18).

Roba Metals Delfzijl (RMD). RMD recycles aluminium scrap, up to a contamination level of 20% (Overduin, and Ozinga, 2010; RMD, 2013). The company is not participating in the EU ETS, although its capacity is comparable to E-MAX and Zalco. However, due to its role in the Dutch aluminium cycle, it is included in the diagram as secondary aluminium smelter. For the same reason, the (master) alloys supplier KBM Master Alloys (KBM) is also added to the scheme. KBM is not registered under the EU ETS, but the company is located next to Aldel and RMD, and supplies also to E-MAX. Permits of KBM (2006) and RMD (2013) are used to make an estimation of their annual production capacity and final energy consumption[35].

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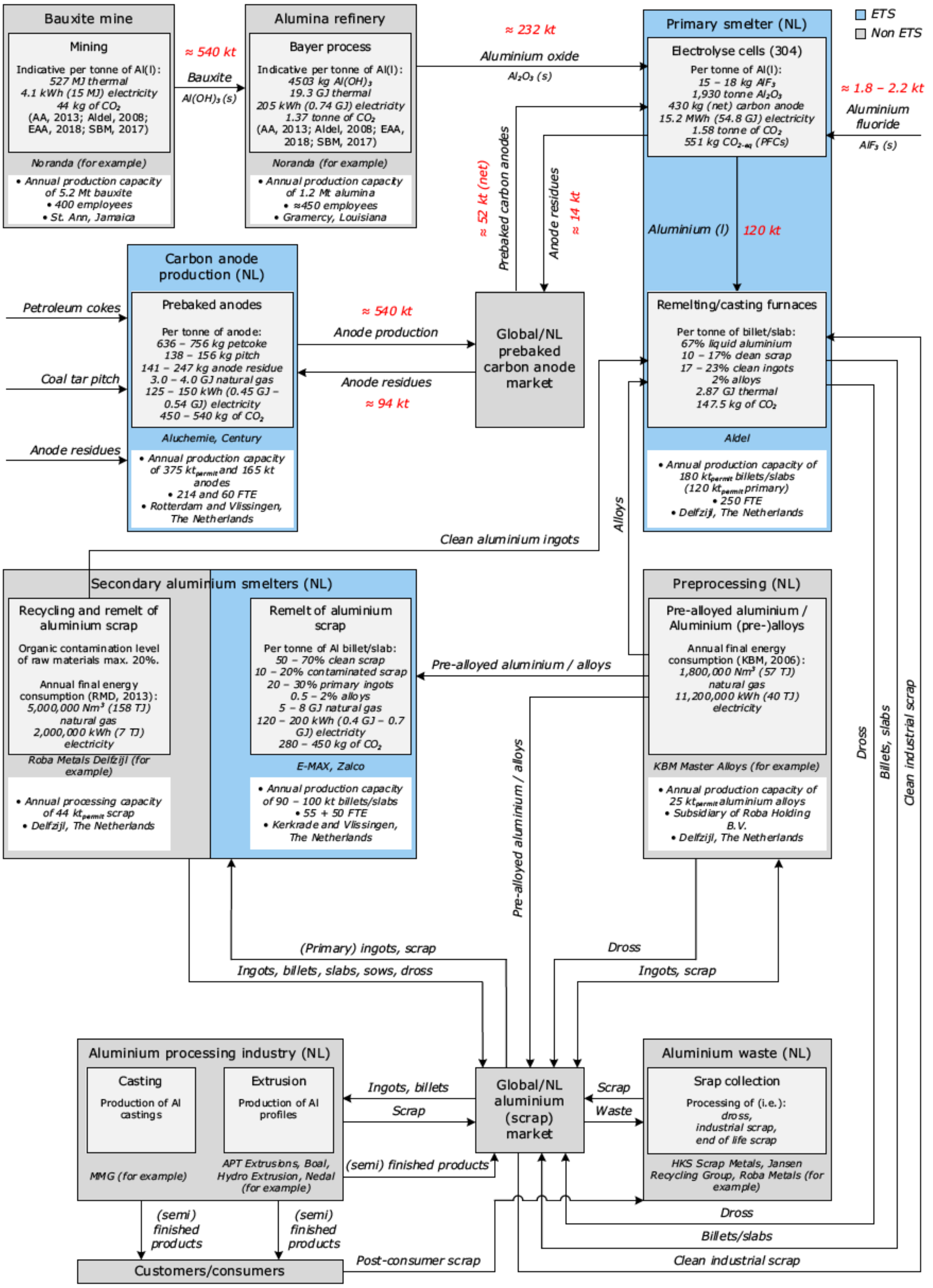
[35] Assuming a net caloric value of 31.65 MJ / Nm$^3$ for natural gas (NEa, 2014, p. 98).

**Figure 19. Indication of material, final energy, and $CO_2$ flows in the Dutch aluminium production chain (AA, 2013; Aldel, 2007; Aldel, 2008; Aluchemie, 2018e; Century, 2018d; EAA, 2018; E-MAX, 2018b; KBM, 2006; Noranda, 2016; Overduin and Ozinga, 2010; RMD, 2013; Sustainable Business Magazine (SBM), 2017, p. 18; VNMI and AVNeG, 2011; Zalco, 2018c).**



Together with the two other Dutch secondary smelters, E-MAX and Zalco, Aldel and RMD produce billets, slabs and ingots for the aluminium processing industry. Since RMD is the only producer of ingots in the Netherlands, the Dutch production of ingots is limited, and additional import of ingots is required to meet the demand for primary aluminium ingots (see Figure 16) (Overduin, and Ozinga, 2010, p. 9). In contrast, the Dutch production capacity of billets and slabs is significantly higher. With companies such as APT Extrusions, Boal, Hydro Extrusions and Nedal, the billet extrusion industry is represented well in the Netherlands, while the processing of slabs only takes place abroad. Aluminium extrusion products are applied in all kinds of building components and other metal products, equipment and vehicles.

## 3.2 Characteristics of main products

When looking at the main product outputs of the EU ETS companies in more detail, the following three product categories can be distinguished: aluminium billets, aluminium slabs, and prebaked carbon anodes. An overview of production volumes, production applications and trading prices is given in Table 8, after which each product is individually addressed.

The production of billets and slabs at Aldel under full capacity varied in the past between 42% and 38% in billets and from 58% to 62% in slabs, the cast house production in 2017 did not reach the top of 180,000 tonnes, by far. Table 8 gives an estimate of future market characteristics under full output for Aldel. Aldel is working on more flexibility at the casting pit to allow for switching to either product group to optimise output. The amount of scrap input depends largely on availability, market price and tends to be higher with billet production because customers deliver their extruder scrap to be reprocessed.

**Table 8 General market characteristics of aluminium billets, aluminium slabs, and prebaked carbon anodes (Aldel, 2007; Aluchemie, 2018b; Century, 2017a; E-MAX, 2018b; Zalco, 2018c)**

| Product | Production volume in 2017 | Examples of product applications | Product price |
|---|---|---|---|
| **Aluminium billets** | Aldel: 90 kt[36]<br>E-MAX: 55–60 kt<br>Zalco: 28–32 kt[37] | Housing for pumps, street lighting, window frames | For roughly 80% based on the LME price for primary aluminium (Zalco, 2015) |
| **Aluminium slabs** | Aldel: 90 kt<br>Zalco: 7–8 kt | Packing materials, street lighting, body parts for airplanes and cars | For roughly 80% based on the LME price for primary aluminium (Zalco, 2015) |
| **Prebaked carbon anodes** | Aluchemie: 334 kt<br>Century: 145 kt | Aluminium electrolysis | In the range of EUR 500–600 per tonne of anode[38] |

### *Aluminium billets*

In the Netherlands aluminium billets are produced by Aldel, E-MAX and Zalco. The length and diameter of the billets vary typically between 3–8 m and 140–420 mm respectively (Aldel, 2007; E-MAX, 2018f; Zalco, 2018d). Assuming that Aldel will be operating at full capacity by mid 2019, and that half of the production capacity will be used for producing billets, 50% of the total Dutch billet production comes from Aldel (see Table 8). A part of Aldel's output is

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[36] Assuming that in future 50% of Aldel's aluminium production consists of billets, and 50% of slabs.
[37] Approximately 80% of Zalco production consists of billets.
[38] Based on Century's annual reports of 2014, 2015, 2016 and 2017. The USDs are converted to EURs by using annual average exchange rates retrieved from the European Central Bank (2018).

purchased by its alumina supplier, Concord Resources Limited (see Section 1.1.1, page 9) (Aldel, 2017).

By means of extrusion presses, the billets are converted into aluminium profiles, which are used by, for example, manufacturers of aluminium window frames. E-MAX sells the majority of billets to its sister extrusion companies in Belgium. In 2010, the E-MAX concern has developed its X-ECO profiles, that are fully made of recycled aluminium while having the same properties as primary aluminium (E-MAX, 2018e). It is expected that production of these profiles will start by 2020, making E-MAX a front runner in the field of low-carbon products. Zalco's products,  based on various consumer specifications, find their way largely to applications in the European automotive and aircraft industry.

Trading prices of aluminium billets are mainly based on the London Metal Exchange (LME) for primary aluminium. Internationally, the LME price serves as a reference price, and determines generally roughly 80% the market price for aluminium products (Zalco, 2015). The remaining part of the market price is affected by regional premiums (availability/price of raw materials) and commodity mark ups, which relate to the desired type of alloy, and physical and chemical properties of the product.

On the LME various types of contracts are offered for buying or selling LME futures, providing the option to hedge prices for up to 123 months (LME, 2018a). In this, LME contracts for three-month delivery are typically the most actively traded (LME, 2018a). Therefore, the price of three-month seller contracts is commonly used as a reference price for aluminium products. Figure 20 presents the trends in the price of three-months seller contracts for primary aluminium over the period 2007–2018. As shown, in 2009 the aluminium prices dropped significantly, which can be related to the financial crisis started in 2008. Currently, LME prices fluctuate around USD 2,000 per tonne of primary aluminium.

**Figure 20 Trends in the price of LME three-month seller contracts for primary aluminium over the period 2007–2018 (LME, 2018b)**

### *Aluminium slabs*

Besides billets, Aldel and Zalco also produces slabs for the aluminium plate, sheet and foil industry. By means of a rolling mill the thickness of the slabs can be reduced to a few micrometres, depending on the product application. Aldel produces slabs with a length of 4 to 8 m, while Zalco offers a range from 0.5 to 8 m. The thickness and width of the slabs vary roughly between 1,000–2,000 mm and 400–600 mm (Zalco, 2018d). Customers of Aldel and

Zalco are mainly located in Western Europe. Trading prices of aluminium slabs are determined in the same way as with aluminium billets.

### ***Prebaked carbon anodes***

Together Aluchemie and Century are responsible for a total Dutch prebaked carbon anode production of 334 kt + 145 kt = 479 kt of anodes (Aluchemie, 2018b; Century, 2017a). Century is planning to renew one of its baking furnaces, expanding the company's annual production capacity from 150 kt to 165 kt of anodes (Century, 2018d). By permit Aluchemie and Century are allowed to produce 375 kt and 180 kt of anodes respectively, so both companies have some margin to expand their production in the short term.

Aluchemie delivers customer-specific anodes to primary aluminium smelters located in Canada, Norway, Iceland and Scotland, whereas Century produces only anodes for its mother company in Iceland (Aluchemie, 2013). The length and weight of Aluchemie's anodes varying between 1,300–1,500 mm and 750–1,500 kg, while Century manufactures anodes of 1.7 m x 0.7 m x 0.7 m, weighting 1,200 kg each (Aluchemie, 2018f; Century, 2018d). To reduce energy losses of gases accumulating under the anodes, both Aluchemie and Century cut slots in the bottom surfaces of their anodes, providing the gasses a way to escape. Moreover, to reduce material consumption, the top anode surface edges are chamfered.

Based on Century's social and statutory reports of 2014, 2015, 2016 and 2017, it is found that trading prices of prebaked carbon anodes vary roughly between USD 550 and 730 per tonne of anode. Converting these prices to EURs by using annual average exchange rates retrieved from the European Central Bank (2018), anodes are sold at EUR 490–630. Although recent public data on Aluchemie's anode prices is lacking, analysing data from 2010 to 2014 makes it likely to assume that Century's anode prices are representative for the Dutch anode market as a whole.

## 3.3 Aluminium economics

This section gives an indication of the cost structure (Section 3.3.1), and capital for machines and installations (Section 3.3.2).

### 3.3.1 Cost structure

In terms of money, for producing primary aluminium or recycling aluminium cost structures differ (Zalco, 2015). Production costs for manufacturing liquid aluminium are made up of costs for electricity (32.5%), alumina (34.8%), carbon anodes (13%), labour (6.8%), and average capital and O&M[39] (Moya et al., 2015, p. 14; Pelkmans et al., 2013, p. 94). In principal, fluctuations in raw materials prices are included in the LME price for primary aluminium. However, currently (summer 2018) alumina prices, for example, almost doubled as a result of US sanctions against UC Rusal, a large producer of alumina and aluminium, while LME prices remained on the same level (Djukanovic, 2018). Although Aldel has made long-term agreements about fixed alumina and electricity prices, sudden price developments could result in unwanted indirect effects for the whole market.

Price variations in the LME price also affect the trading prices of aluminium scrap. These prices correspond with 75% of the total production costs of producing secondary aluminium, the remaining 25% with labour (6%), processing (6%), financing (6%) and energy (4%) (Moya et al., 2015, p. 14). Depending on the quality and the type of alloy, prices for scrap can be higher or lower that the LME price for primary aluminium. Lightly contaminated scrap,

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[39] Depreciation costs excluded.

for instance, is often sold at 80% of the LME price, while prices for high quality industrial scrap typically have a USD 100 surcharge (Huurdeman, 2017, p. 38).

### 3.3.2 Machines and installations

Considering the processes described in Chapter 2, an overview of the characteristics of the machines and installations required for the production and casting of primary aluminium, the recycling casting of secondary aluminium, and the manufacturing of prebaked carbon anodes, are given in Table 9, Table 10, and Table 11. It need to be noted that the numbers serve as an indication and could vary in practice.

**Table 9 Indication of the characteristics of the typical machines and installations required for the production and casting of primary aluminium (Aldel, 2007; Aldel, 2008; Basemet, 2010; IEA ETSAP, 2012; Inland Revenue, 2018; Moya et al., 2015)**

| Item | Indicative investment costs | Indicative lifetime |
|---|---|---|
| **New casting furnace** | EUR 10–15 million | Economic: 10 years<br>Technical: 20 years |
| **Renew carbon lining electrolysis cell** | EUR 330 per tonne[A] | Economic: 4 years<br>Technical: 6 years |
| **Homogenisation furnace** | … | Economic: …<br>Technical: 15–20 years |
| **Mixing furnace** | EUR 10–15 million | Economic: 10 years<br>Technical: 20 years |
| **Melting furnace** | EUR 10–15 million | Economic: 10 years<br>Technical: 20 years |
| **New electrolytic department** | EUR 4,000–5,000 per tonne | Economic: …<br>Technical: … |
| **New cast house** | EUR 720 per tonne | Economic: …<br>Technical: … |

[A] Based on information from Eemsbode (2018), assuming an annual capacity of 120,000 t / 304 = 395 t per cell.

**Table 10 Indication of the characteristics of the typical machines and installations required for the production and casting of secondary aluminium (E-MAX, 2018b; Moya et al., 2015; Zalco, 2018c)**

| Item | Indicative investment costs | Indicative lifetime |
|---|---|---|
| **New casting furnace (capacity: 35 t / casting)** | EUR 10–15 million | Economic: 10 years<br>Technical: 20 years |
| **New homogenisation furnace** | … | Economic: …<br>Technical: 15–20 years |
| **New smelting furnace** | EUR 10–15 million | Economic: 10 years<br>Technical: 20 years |
| **New multi-chamber furnace (capacity: 160 t / day)** | EUR 8–10 million | Economic: 8–12 years<br>Technical: 30 years |

**Table 11 Indication of the characteristics of the typical machines and installations required for the manufacturing of prebaked carbon anodes (Business Wire, 2007; Century, 2014; Century, 2015b; Century, 2018d; DCMR, 2018; Glader, 2004; Port of Rotterdam, 2016)**

| Item | Indicative investment costs | Indicative lifetime |
|---|---|---|
| **Renew baking furnace (capacity: 75 kt / year)** | EUR 30–35 million | Economic:…<br>Technical:<br>18–20 years (headwalls)<br>6–7 years (flue walls) |
| **New fume treatment system (100,000 Nm$^3$ / hour)** | EUR 28–30 million | Economic:<br>…<br>Technical:<br>… |
| **New desulfurization plant (275,000 Nm$^3$ / hour)** | EUR 20 million per stack | Economic: …<br>Technical: … |
| **New anode plant** | USD 1,000–1,500 per tonne | Economic: …<br>Technical: … |

# 4 Options for decarbonisation

To achieve deep carbonisation of the Dutch aluminium industry by 2050, a combination of decarbonisation options will be needed. Table 12, Table 14, and Table 15 (pages 50, 58 and 61 respectively) present a selection of options that have the potential to reduce the energy and $CO_2$ intensity of the processes described in Chapter 2 significantly. As shown in the tables, decarbonisation can be achieved from multiple perspectives, ranging from options focused on improving the energy efficiency (EE) of current technologies, to options that introduce new innovative concepts of which the development is ongoing. The list of options is not exhaustive, but includes the options/technologies that are expected to be relevant and applicable to the Dutch aluminium industry. A short description of each option is given in the sections below.

## 4.1 Hall – Héroult process

Starting with the most energy-intensive process—the electrolysis of alumina—the following decarbonisation opportunities can be distinguished.

### 4.1.1 Energy-efficiency improvements

***Implementing BATs***

Based on literature the following most relevant BATs for the Hall – Héroult process have been found (Moya et al., 2015, p. 21):

- Use of prebaked carbon anodes;
- Liquid aluminium transported directly to casting furnace;
- Optimisation of the electrolysis process:
    - Implementation of a central point feeder (see Section 2.1.4, page 23);
    - Magnetic compensation. The high currents required for the reduction in alumina generate Lorentz and Laplace forces in the cell, affecting the efficiency of the Hall – Héroult process. By improved busbar design the magnetic losses can be reduced;
    - Slotted carbon anodes (see Section 3.2);
    - Improvement of hooding and ventilation.

When implementing the above technologies, in best practice the electricity consumption amounts to 13.6 MWh[40] per tonne of liquid aluminium, including an additional consumption of 0.7–1.0 MWh for rectifier losses, pollution control, and auxiliaries (Worrell, Price, Neelis, Galitsky and Nan, 2008, p. 20). In this a “side to side” electrolysis cell configuration is applied. At Aldel BATs are implemented, however, the electrolysis cells are placed “end to end”, creating a limit on the effectiveness of the BATs (especially for magnetic compensation). Considering Aldel’s technology class (end to end), best practice smelters

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[40] Several indications of electrolysis cells with a lower electricity consumption can be found on the Internet. In 2018, for instance, Hydro has opened a pilot plant at Karmøy, having 48 cells consuming 12.3 MWh per tonne liquid aluminium, and 12 cells with an energy consumption of 11.5 – 11.8 MWh (Hydro, 2016). It is, however, unclear if this includes for example rectifier losses. Therefore, a best practice of 13.6 MWh per tonne of liquid aluminium is used in this study (including losses).

consume 15.1 MWh per tonne of liquid aluminium, which is in the order of Aldel's electricity consumption of 15.21 MWh per tonne when operating at full capacity (120 kt). According to Aldel (2007, p. *IX*.3) changing

**Table 12 Overview of decarbonisation options for the current Hall – Héroult process in the Netherlands. Unit: <value> per tonne of liquid aluminium**

| Decarbonisation option | Category | Indicative energy or $CO_2$ savings | Indicative investment costs |
|---|---|---|---|
| **Implementing BATs (availability: now)** | Energy efficiency | 5.8 GJ of electricity (Worrell et al., 2008) | EUR 4,000–5,000 (Aldel, 2007) |
| **Incremental EE improvements (available: now)** | Energy efficiency | 1%–2% of electricity (Kermeli, ter Weer, Crijns-Graus, Worrell, 2015) | EUR 100–150 (Kermeli et al., 2015) (Schwartz, 2008) |
| **Dynamic AC magnetic field (availability: 2020–2030)** | Energy efficiency | 5%–20% of electricity (Carbon Trust, 2014) | EUR 80 (Moya et al., 2015) |
| **Wetted cathodes (availability: 2020–2025)** | Energy efficiency | 15%–23% of electricity (Moya et al., 2015) (Obaidat et al., 2018) | EUR 524 (Moya et al., 2015) |
| **Inert anodes (availability: 2024–2030)** | Feedstock substitution | 100% of direct $CO_2$ (Moya et al., 2015) | EUR 86 (Moya et al., 2015) |
| **Kaolinite reduction (availability: 2035–2045)** | Feedstock substitution | See page 53. | 4,000–5,000 EUR |
| **Carbothermic reduction in alumina (availability: 2050)** | Process substitution | 30%–35% of electricity -15% of direct $CO_2$ (Obaidat et al., 2018) | EUR 3,000 (Moya et al., 2015) |
| **Carbon capture and storage (availability: 2020–2030)** | Carbon capture and storage | 85%–90% of direct $CO_2$; excl. extra energy required (Lassagne, et al. 2013; Jilvero et al. 2014) | EUR 200–400 excl. retrofit costs based on (Lassagne et al. 2013; Jilvero et al. 2014) |
| **Recycling of aluminium (availability: now)** | Volume reduction | See 4.1.5 | See 4.1.5 |

the setup up to "side by side" is only possible when constructing new electrolysis halls, requiring an investment of EUR 500 million. Furthermore, Aldel states that their anode size is too small to allow for a slotted design (Aldel, 2019).

### *Incremental energy-efficiency improvements*

Incremental improvements in cell control lead to more operational bath conditions and reduces the number of anode effects (Kermeli, ter Weer, Crijns-Graus, Worrell, 2015, p. 644). It is expected that by investing EUR 100–150 per tonne of liquid aluminium capacity, the specific electricity consumption of the Hall – Héroult process will decrease by 0.2 MWh (Kermeli et al., 2015, p. 644; Schwarz, 2008).

### *Dynamic AC magnetic field*

As mentioned in Section 2.1.1 (page 21), in practise the anode to cathode distance (ACD) varies between 4 to 5 cm. To reduce cell losses, it favours to have an ACD as small as possible without shortcutting the cell. Currently the ACD is kept relatively large because of ripples in the liquid aluminium at the bottom of the cell (Moya et al., 2015, p. 39). These ripples are caused by so-called magneto hydrodynamic (MHD) forces, which are enforced when bringing the anode and cathode closer to each other. By applying a dynamic alternative current (AC) magnetic field these ripples can be reduced, allowing a smaller ACD, leading to estimated energy savings in the range of 5% to 20% (Carbon Trust, 2014). Currently, researchers of the Coventry University, for example, have performed successful experiments with this technology, and are planning to design, build and commission a commercial scale model cell (Carbon Trust, 2014).

Based on Moya et al. (2015) it is expected that the technology of dynamic AC magnetic fields in general will be available in the next decade, at estimated investment costs of EUR 80 per tonne of liquid aluminium capacity (Moya et al., 2015). However, Aldel states that the ACD zone cannot be too small because the $CO_2$ zone will be too close to the metal which then in return eases the backreaction of $CO_2$ with the metal to form CO, resulting in yield loss (current efficiency loss) (Aldel, 2019).

### *Wetted cathodes*

Another way to reduce the ACD, is to use wettable cathodes. Here the term wettable refers to the electrical contact between the liquid aluminium and the cell cathode (= carbon lining). This electrical contact determines to what extent the liquid aluminium reacts to the aforementioned MHD forces. In a traditional electrolysis cell the electrical contact is relatively low since the liquid aluminium is resting on a thin layer of bath material, leading to an intensification of the ripples when reducing the ACD (U.S. Department of Energy's Office of EREE, 2007, p. 43). By increasing the wettability of the cathode surface, the electrical contact between the liquid aluminium and the carbon cathode improves, and the ACD can be reduced without leading to high MHD instability (Springer and Hasanbeigi, 2016, p. 13).

A promising wettable material that can withstand the thermal ($T \approx 960$ °C) and chemical (corrosive) properties of the cell bath is titanium diboride ($TiB_2$). It has a high electrical conductivity and low solubility in aluminium (Haslund, 2017). From an economic perspective, however, in its pure form, the material is less favourable. as it has relatively high production and maintenance costs (Pawlek, 2010). Pure $TiB_2$ industrial cathodes degrade rapidly due to penetration of aluminium along grain boundaries (Haslund, 2017). Nevertheless, $TiB_2$ still has the potential to be useful in carbon composites. Once a suitable mix has been found between the wettability and the particle size of $TiB_2$ in the composites, it is expected that the ACD can be reduced to 2 cm. In this, the fully drained sloped cathode design (see Figures 19 and 20) offers the greatest energy saving potential. The voltage drop through the electrolysis bath can be decreased by 1 V, corresponding with estimated saving in electricity in the range of 15% to 23% at an investment of EUR 524 per tonne liquid Al (Moya et al., 2015, p. 37; Obaidat et al., 2018, p. 9). In this, no extra operation costs are assumed.

**Figure 21. Reduction in the anode to cathode distance by implementing wetted sloped cathodes (b) compared to the traditional Hall – Héroult process (a).**

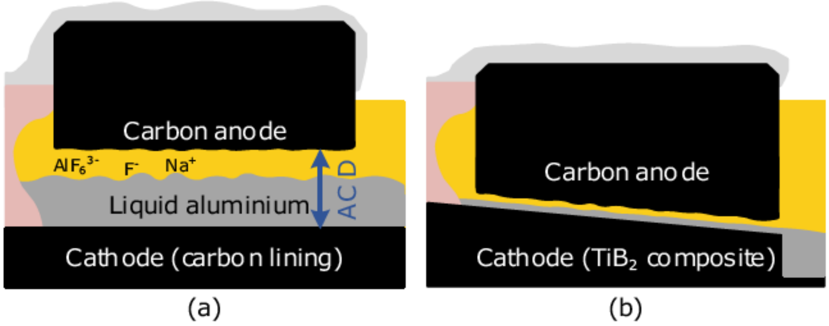
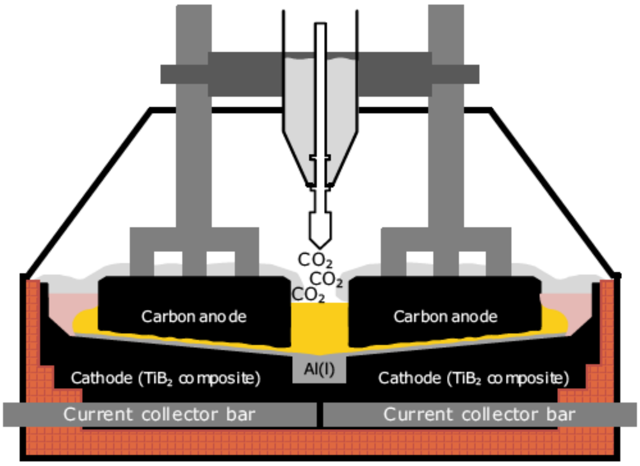


**Figure 22. Concept design for implementation of wetted cathodes in a traditional electrolysis cell (see Figure 9 for the original cell design).**



Moreover, PFC emissions are expected to decrease by 75% $CO_2$ eq since the sloped surfaces prevent bath gases to accumulate under the anode (U.S. Department of Energy's Office of EREE, 2007, p. 110). Considering the economic viability of wetted sloped cathodes, commercialisation is expected to be taken place in the next five years (Moya et al., 2015).

## 4.1.2 Feedstock substitution

### *Inert anodes*

Currently, the use of carbon anodes has two major drawbacks: 1) the anodes have to be replaced every four weeks, 2) the oxidation of carbon leads to significant direct $CO_2$ emissions (see Section 2.1, page 20). For this reason companies started looking for inert anodes to replace carbon anodes, aiming to change the alumina reduction reaction to:

$$2\ Al_2O_3\ (bath) \rightarrow 4\ Al\ (l) + 3\ O_2\ (g) \qquad \textbf{Eq 5}$$

By implementing inert anodes anode effects will no longer take place, avoiding PFC emissions. Moreover, inert anodes are expected to have a lifetime similar to that of electrolysis cells, meaning that the cell covers have to be opened less frequently, which improves the operating efficiencies of the cells (Springer and Hasanbeigi, 2016, p.11).

The development of inert anodes, however, is inhibited by finding a material that is economically attractive, and at the same time, can withstand the corrosivity of the bath. Research into suitable materials is among others focussed on: ceramics, cermets (composites of ceramics and metals), and metals (U.S. Department of Energy's Office of EREE, 2007, p. 47). In this respect, especially $NiFe_2O_4$-based cermets and NiFe-based alloys[41] seem to be promising (Pawlek, 2014, p. 1312). But also anodes sheathed with zirconium oxide (zirconia) tubes, for instance, are investigated (Springer and Hasanbeigi, 2016, p.11). The company INFINIUM, for example, is investigating a cell technology using new anodes that have the potential to reduce $CO_2$ emissions by 50% to 90% (ARPA-E, 2013; Springer and Hasanbeigi, 2016, p.11).

More recently (spring 2018), the companies Alcoa and Rio Tinto announced to have found a way to produce aluminium while emitting zero direct GHGs (Alcoa, 2018a; Alcoa, 2018b; Rio Tinto, 2018b). The joint venture is called “Elysis”, which refers to the electrolysis of alumina. The project is a partnership between Alcoa, Apple, Rio Tinto, and the governments of Canada and Quebec, together investing 188 million CAD in total (Alcoa, 2018a). Although the press releases do not provide information on how the new cell technology works and which materials are used for instance, in this MIDDEN study it is assumed that it involves the development towards inert anodes, since according to the companies, the anodes will have a lifetime 30 times longer than the current carbon anodes (Alcoa, 2018b). In addition, by implementing the new inert anode smelting technology, production is expected to increase by 15%, while operating costs will decrease by 15% (Alcoa, 2018b). It is expected that the Elysis technology will be commercially available by 2024 (Rio Tinto, 2018b).

The above mentioned projects are just some examples of technologies that look promising for the development of inert anodes. The future will show which new cell technology will eventually be the most beneficial. Based on the information given in the press releases of Alcoa and Rio Tinto, and other information found in literature on the technological development of inert anodes in general, in Table 12 commercialisation of inert anodes is estimated around 2024–2030 (Alcoa, 2018a; Moya et al., 2015, p. 38). In addition, concerning average investment costs for inert anode technologies in general, according to Moya et al. (2015, p. 38) capital costs are estimated at around EUR 86 per tonne of liquid aluminium (including retrofit costs), and no extra operation costs are expected.

In literature, inert anodes are sometimes presented as a decarbonisation option in combination with wetted cathodes, since in theory, inert anodes on its own increase the electricity consumption of the traditional Hall – Héroult process by approximately 3 MWh[42] per tonne of liquid aluminium (representing an increase of ≈20%). By combining the two options, it is estimated that approximately 8% to 9% of electricity can be saved, while reducing the emission of direct $CO_2$ and PFCs by 100% (U.S. Department of Energy's Office of EREE, 2007, p. 132). In general, expected total investment costs will be in the order of EUR 610 per tonne of liquid aluminium capacity (Moya et al., 2015, p. 37; Worrell et al., 2004).

### *Kaolinite reduction*

Traditionally aluminium is produced by reducing alumina that is refined from bauxite ores consisting of gibbsite “$Al(OH)_3$”. An alternative to this process is the production of liquid aluminium by reduction in aluminium chloride processed from kaolin clay, made up of kaolinite ($Al_2{\cdot}O_3{\cdot}2SiO_2{\cdot}2H_2O$). The idea of making aluminium out of aluminium chloride was initially initially conceived in 1825, but the technology was never commercialised because of

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[41] According to Pawlek (2014, p. 1312) UC Rusal, for example, is working on inert anodes based on Ni-Fe alloys.

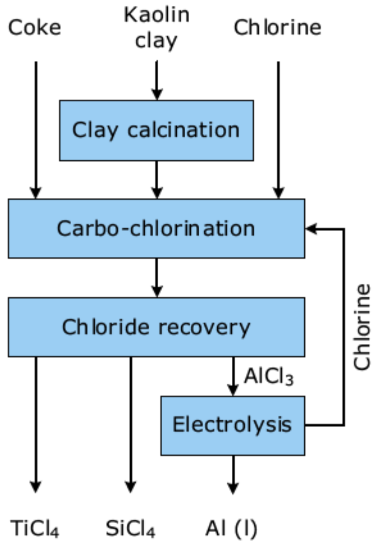
[42] In the traditional Hall – Héroult process the oxidation of carbon is an exothermal process, producing heat (≈3 MWh per tonne of liquid aluminium) that serves as input for the electrolysis (U.S. Department of Energy's Office of EREE, 2007, p. 49).

purity issues and high capital and operating costs (Springer and Hasanbeigi, 2016, p.19). Nevertheless, insights into new construction materials and economically attractive clays have again raised the interest in this reduction technology (U.S. Department of Energy's Office of EREE, 2007, p. 59).

Kaolinite reduction can be seen as an alternative for both the Bayer process (refining of alumina from bauxite) and the traditional Hall – Héroult process. A simplified schematic representation of the technology is given in Figure 21. As shown in the diagram, kaolin clay, chlorine and coke form the inputs for the carbochlorination in which the kaolin clay is converted into aluminium chloride ($AlCl_3$), silica chloride ($SiCl_4$), and titanium chloride ($TiCl_4$), producing direct $CO_2$ emissions. Subsequently, the aluminium chloride is supplied to so-called multi-polar cells in which electrolysis takes place and liquid aluminium is produced. From these cells chloride is fed back to the carbochlorination step. The cells consist of bipolar graphite electrodes[43] placed horizontally on top of each other, immersed in a bath of chloride. The electrodes are electrically isolated by inert spacers, having the anode and cathode placed at the top and the bottom of the cell respectively (U.S. Department of Energy's Office of EREE, 2007, p. 60). Since the cells operate on a lower bath temperature (≈ 700°C) and have a lower volume than traditional Hall – Héroult cells, the temperature in aluminium chloride reduction cells can be retained more efficiently (Springer and Hasanbeigi, 2016, p.18).

In 1976 Alcoa piloted an aluminium chloride electrolytic reduction facility achieving an electricity-efficiency improvement of 40% compared to a current Hall – Héroult cell (U.S. Department of Energy's Office of EREE, 2007, p. 52).

**Figure 23 Simplified process scheme of producing aluminium by kaolinite reduction. Adapted from *U.S. Energy Requirements for Aluminium Production – Historical Perspective, Theoretical Limits and Current Practices* (p. 59), by U.S. Department of Energy's Office of EREE, 2007, retrieved from https://www.energy.gov/sites/prod/files/2013/11/f4/al_theoretical.pdf**



Nevertheless, the pilot had to be stopped due to difficulties with: reaching full design capacity, removal of chlorine contaminants in the aluminium, high operation and maintenance costs (U.S. Department of Energy's Office of EREE, 2007, p. 53).

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[43] This means that one side of the electrode acts as an anode, while the opposite surface acts as a cathode. The electrodes are not consumed during the electrolysis.

Regarding final energy use, kaolinite reduction has the potential to reduce final energy consumption theoretically by ≈50%[44] when only taking into account the electricity needed for electrolysis. When including the energy needed to extract aluminium chloride from kaolin clay (≈29 GJ per tonne of liquid aluminium), in general approximately ≈23% of final energy can be saved compared to the current Bayer and Hall – Héroult processes, using the information given by Figure 19 and the U.S. Department of Energy's Office of EREE (2007, p. 62). However, nowadays alumina is refined abroad, only the Hall – Héroult process takes place in the Netherlands. So, while on a system level the final energy consumption can be reduced by ≈23%, it is estimated that when implementing the kaolinite reduction technology in the Netherlands it will increase Aldel's final energy consumption in the order of 10%. The same goes for direct $CO_2$ emissions; on a system level, direct $CO_2$ emissions are expected to decrease, while bringing the kaolinite reduction process to the Netherlands is estimated to lead to more than 35% higher direct $CO_2$ emissions (U.S. Department of Energy's Office of EREE, 2007, p. 110).

Since the technology differs fundamentally from the current electrolysis process, investment costs are estimated to be in the same order of placing a new electrolytic department (see Table 9). Deployment is estimated to take place between 2035 and 2045 (IEA, 2010, p. 197).

### 4.1.3 Process substitution

***Carbothermic reduction in alumina***

In contrast to earlier mentioned decarbonisation options, producing aluminium by carbothermic reduction is a non-electrochemical process. The idea of carbothermic reduction has been introduced 50 years ago, yet, in practice the technology has not been found economically viable due to its among others complex thermodynamics (U.S. Department of Energy's Office of EREE, 2007, p. 55). However, if successful, in theory electricity savings of 47%[45] could be achieved, which makes the technology interesting for aluminium companies to investigate (Obaidat et al., 2018, p. 9). In 2011, Alcoa, for example, established the Alcoa Norway Carbothermic group, piloting a reactor operating on an advanced reactor process (ARP) (Springer and Hasanbeigi, 2016, p.17). In addition, from 2010 to 2014, the European Commission co-financed the ENEXAL project, including experiments with carbothermic reduction under vacuum, and experiments to improve existing electric arc furnace technology (Balomenos, 2011; Labmet, 2014). Although these projects have resolved a set of technical problems, a successful implementation of the carbothermic reduction process has still to come due to the occurrence of side reactions, producing aluminium carbides (Balomenos, 2011).

While reducing alumina carbothermically has a major potential to reduce the final energy consumption, in terms of direct $CO_2$ emissions the technology is less beneficial since it requires the consumption of carbon (at T ≈2,000 °C) (Obaidat et al., 2018, p. 7):

$$Al_2O_3\,(s) \quad + \quad 3\,C\,(s) \quad -> \quad 2\,Al\,(l) \quad + \quad 3\,CO\,(g) \qquad \textbf{Eq. 5}$$

$$1.89\text{ kg} \quad + \quad 0.67\text{ kg} \quad -> \quad 1\text{ kg} \quad + \quad 1.56\text{ kg} \qquad \textbf{Eq. 7}$$

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[44] The minimum energy requirement for kaolinite reduction is estimated to be 7.57 MWh per tonne of liquid aluminium (T = 700 °C) (U.S. Department of Energy's Office of EREE, 2007, p. 61).

[45] Practical savings are expected to be in the order of 30 – 35%, assuming a reactor efficiency of 80% (Obaidat et al., 2018, p. 9).

As shown, producing 1 kg of liquid aluminium requires 1.89 kg of alumina and 0.67 kg of carbon. In addition, 1.56 kg of CO is emitted, which results eventually in 2.46 kg of $CO_2$[46]. For comparison (see Table 13), the present Hall – Héroult process consumes 1.93 kg of alumina and 0.43 kg of carbon, and emits: 1.58 kg of $CO_2$ (anode consumption) + 0.55 kg of $CO_2$ eq (PFCs) = 2.13 kg of $CO_2$ per kg of liquid aluminium. So in the end, when looking only at direct $CO_2$ that is emitted in the Netherlands, carbothermic reduction in alumina will increase the direct $CO_2$ footprint of Dutch primary aluminium with ≈2% (see Table 13).

When including the indirect $CO_2$ emissions related to the production of electricity needed for both technologies, however, carbothermic reduction has an advantage over the current Hall – Héroult process (U.S. Department of Energy's Office of EREE, 2007, p. 110). Yet, in general commercialisation of carbothermic reduction plants is not expected to take place before 2050 (Moya et al., 2015, p. 38). Once available, investment costs are estimated at EUR 3,000 per tonne of liquid aluminium capacity (Moya et al., 2015, p. 38). Finally, since no anodes have to be replaced every four weeks, operating costs will be significantly lower.

**Table 13 Present Hall – Héroult process compared to carbothermic reduction in terms of final energy use and direct $CO_2$ emissions per tonne of liquid aluminium, based on values given in Table 2, Figure 16 and (Obaidat et al., 2018). Values are indicative**

| Process | Hall – Héroult process (T ≈ 960 °C) | | Carbothermic reduction (T ≈ 2,000 °C) | |
|---|---|---|---|---|
| **Bauxite – Alumina** | 21 GJ | 1.4 t $CO_2$ | 21 GJ | 1.4 t $CO_2$ |
| **Anode production** | 2.2–2.4 GJ | 0.25–0.30 t $CO_2$ | - | - |
| **Electrolysis cell** | 55 GJ | 2.13 t $CO_2$ eq | | - |
| **Anode emissions** | - | 1.58 t $CO_2$ | - | - |
| **PFC emissions** | - | 0.55 t $CO_2$ eq | - | - |
| **Carbothermic reactor** | - | - | 37 GJ[A] | 2.46 t $CO_2$ |
| **Total** | ≈78 GJ | ≈3.8 t $CO_2$ eq | 58 GJ | ≈3.9 t $CO_2$ eq |

[A] Assuming a thermal efficiency of 80%, see Obaidat et al. (2018, p. 9).

### 4.1.4 Carbon capture and storage

In case the development of inert anodes will not be realised, alternatives need to be applied to reduce direct process $CO_2$ emissions. Post-combustion carbon capture and storage (CCS) can be one of those alternatives. At present only a limited amount of scientific research has been done into the application of CCS in the aluminium industry, yet, two general CCS technologies have been investigated. The first more general CCS technology uses monoethanolamine (MEA) to capture $CO_2$, while the relatively new second technology makes use of an ammonia-based adsorbent (Jilvero et al., 2014). Both technologies are not yet applied in the aluminium industry, but are estimated to be available for aluminium smelters in 2020 and 2030 respectively (Moya et al., 2015).

The concentration of $CO_2$ in the flue gases of the electrolysis cells determines which technology will be eventually preferred. For the MEA-based technology, $CO_2$ concentrations of 3% to 4% are techno-economic optimal, while the ammonia-based process is expected to be most cost-efficient at concentrations of 7% to 10% (Jilvero et al., 2014). Current cell concentrations of $CO_2$, however, are significant lower, making straightforward implementation of both CCS technologies in the aluminium industry economically unviable.

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[46] After two months the CO will be converted into $CO_2$ by reacting with other atmospheric compounds (ATSDR, 2012). So, assuming that all C molecules oxidize into $CO_2$ : 0.67 kg · (44/12) = 2.46 kg of $CO_2$ per kg of liquid aluminium.

At Aldel, the concentration of $CO_2$ in the outflow of its gas treatment centre amounts to 0.6% to 0.7%[47], which is similar to the concentration of 0.6% given in literature (Folkers et al., 2014; Jilvero et al., 2014).

To date, $CO_2$ concentrations of 4% or higher are never reached in the aluminium industry (Lassagne et al. 2013). Moreover, achieving $CO_2$ concentrations of 7% to 10% will require a completely new cell design, leading to high capital costs. $CO_2$ concentrations of 3% to 4% on the other hand, can be achieved with a retrofit of the current cell design, making the MEA process the preferred CCS technology for existing aluminium plants (Jilvero et al., 2014).

Lassagne et al. (2013) estimates that at a $CO_2$ concentration of 4%, up to 90%[48] of direct $CO_2$ emissions can be avoided at a cost of 70 $USD_{2012}$ per tonne $CO_2$ captured, corresponding with 100 $USD_{2012}$ per tonne of liquid aluminium. This excludes the costs of transporting $CO_2$ to a carbon network or storage facility. The costs for retrofitting the current cell design, to achieve higher $CO_2$ concentrations, are also not included. In case of Aldel these costs are expected to be significant, since literature assumes that higher $CO_2$ concentrations can be reached by lowering cell ventilation rates (Jilvero et al., 2014). However, Aldel’s gas treatment centre operates on high ventilation rates in order to maintain a sufficient fluoride capture efficiency (> 98%). So, further research will be needed to find a solution to increase the $CO_2$ concentration, without affecting the performance of the gas treatment centre. For now, it is estimated that capture investment costs will range between EUR 200 and 400 per tonne of liquid aluminium, excluding adjustments to the current flue gas system. Operating costs of the system will amount to EUR 26–50 per tonne of liquid aluminium excluding extra energy costs. Extra steam requirements amount to 6–10 GJ/tonne of liquid aluminium, extra electricity to 0.6–0.7 GJ per tonne of liquid aluminium.

### 4.1.5 Volume reduction

#### ***Recycling of aluminium***

At the moment 75% of all the aluminium ever produced is still in use, showing the high recyclability of the material (EAA, 2015). To achieve deep carbonisation in the total aluminium industry, recycling of aluminium scrap plays an important role since chain final energy consumption and direct $CO_2$ emissions can be reduced by an estimated 90% compared to current primary aluminium production.

This does not mean, however, that the production of primary aluminium will become unnecessary. The recycling of aluminium has some limits in terms of production quality and availability. To maintain a high quality of the end products for example, currently in most cases aluminium scrap is mixed with primary aluminium. Moreover, aluminium production is expected to continue growing, so over the long-term production of virgin material is expected to remain necessary (Kermeli et al., 2015).

At Aldel, approximately 33%[49] of the metal input mix consists of secondary aluminium or clean industrial scrap, which is significant compared to the average of 2% for European primary aluminium smelters (Aldel, 2007, p.23; EAA, 2018, p. 34). Therefore, in this study the potential to increase Aldel’s recycling rate is expected to be limited. Onsite research will be required to determine the techno-economic potential, since increasing the recycling rate implies lowering the productivity of the electrolysis department, or increasing the capacity of the casting house. Furthermore the availability of industrial scrap should be considered since

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[47] Based on a concentration of 12,000 – 14,000 mg $CO_2$ per $Nm^3$, or $CO_2$ rate of 60 – 70 kg $CO_2$ per hour (Folkers et al., 2014).

[48] Excluding the energy requirement of the CCS plant itself. The study further shows that part of the steam requirement can be met by using waste process heat.

[49] When operating at full capacity.

increasing the energy and material efficiency of the aluminium production chain as a whole, will result in less available industrial scrap.

## 4.2 Production of prebaked carbon anodes

Although the majority of direct $CO_2$ is emitted during the electrolysis of alumina, significant savings in $CO_2$ emissions can also be made in the anode manufacturing process. Table 14 shows a selection of options that are mentioned in literature.

**Table 14 Overview of decarbonisation options for the current production of prebaked carbon anodes in the Netherlands. Unit: <value> per tonne of anode**

| Decarbonisation option | Category | Indicative energy or $CO_2$ savings | Indicative investment costs |
|---|---|---|---|
| **Implementing BATs and incremental EE improvements (availability: now)** | Energy efficiency | 0.85–2.15 GJ of natural gas[A] (Akhtar et al., 2012) | See page 58. |
| **Bio-coke instead of petroleum coke (availability: unknown)** | Feedstock substitution | Up to 62%–72% of direct $CO_2$ emissions during the electrolysis of alumina | n/a |
| **Green gas or hydrogen fired baking furnaces (availability: unknown)** | Fuel substitution | n/a | n/a |
| **Carbon capture and storage (availability: 2020–2030)** | Carbon capture and storage | 85%–90% of direct $CO_2$ (Lassagne et al. 2013; Jilvero et al. 2014) | EUR 70–150, excl. retrofit costs based on (Lassagne et al. 2013; Jilvero et al. 2014) |
| **Inert anodes make carbon anodes redundant (availability: 2024–2030)** | Volume reduction | n/a | n/a |

[A] Energy savings that could be achieved compared to the EMAL greenfield project. This only includes energy savings that can be achieved in the anode baking process.

### 4.2.1 Energy-efficiency improvements

***Implementing BATs and incremental energy-efficiency improvements***

Considering the environmental permits granted to Aluchemie and Century, it can be concluded that both companies operate according to the BATs, as prescribed by the European Commission (2016). Still, in terms of energy efficiency, there is room for improvement. Looking at the most energy-intensive manufacturing process, the baking of carbon anodes, specific energy consumptions in the order of 2 GJ per tonne of anode are globally observed (Cusano et al., 2017, p. 393). Moreover, in 2010 Dubai Aluminium Company and Mubadala Development Company started a joint venture called EMAL, a greenfield project (Akhtar et al., 2012, 1175). Calculations on two open top baking furnaces, assuming optimal operation and BAT implementation, resulted in final energy consumptions of 1.69 GJ and 1.55 GJ per tonne of anode (Akhtar et al., 2012, p. 1178).

Without having detailed information on the heat balances of the baking furnaces installed at the Dutch anode manufacturers, it is difficult to determine which specific energy improvements can be made to perform on best practice. In general, however, it is estimated that final energy savings can be made by optimising the air to fuel ratio (saving of 5%–25%), by improving furnace pressure control (savings of 5%–10%), by optimising preheating of green anodes by using waste heat from flue gases (savings of 10%–30%), and by improved sensor and control systems (savings of 5%–10%) (Kermeli et al., 2015). It is unknown whether there is double counting in these potentials and to what extent these potentials are already implemented at Aluchemie and Century.

### 4.2.2 Feedstock substitution

#### ***Use of bio-coke instead of petroleum coke***

As mentioned in Section 2.2 (page 25), the material input mix for producing one tonne of anode consists of 62%–72% petroleum coke. Over the last decade, research has been done into the possibility to replace petroleum coke partially by bio-coke (i.e. charcoal), to reduce the environmental footprint of the aluminium production process (Monsen, Ratvik and Lossius, 2010). In case bio-coke can be successfully implemented in the anode manufacturing process, in potential direct $CO_2$ emissions from the electrolysis of alumina can be reduced up to a maximum of 62%–72%, considering the current share of petroleum coke in carbon anodes[50]. At the moment, successful experiments have been done with anodes of which 3% of petroleum coke is replaced by bio-coke (Huang, Kocaefe and Kocaefe, 2018). It is, however, unclear to which extent the share of bio-coke can be further increased. In this, the penetration of coal tar pitch into bio-coke is essential, since this determines the final anode quality (Huang, Kocaefe and Kocaefe, 2018). Further research will be needed to solve this issue, even to answer the question to what extent the use of bio-coke will have an influence on the future way of producing carbon anodes.

### 4.2.3 Fuel substitution

#### ***Green gas or hydrogen fired baking furnaces***

Approximately 40% to 45% (see Section 2.2.4, page 30) of direct $CO_2$ emissions from producing carbon anodes are related to firing natural gas[51]. So, switching from natural gas to a renewable energy source, such as green gas[52] or green hydrogen, means that 40% to 45% of direct $CO_2$ emissions can be avoided. Although the technologies are currently only tested on a small scale, yet, Gasunie (2018b) published an exploratory study towards a $CO_2$-neutral national energy supply by 2050, in which green gas and hydrogen play a promising role in the replacement of fossil natural gas.

Looking at the two technologies in more detail, green gas is in favour when considering the gas infrastructure needed, since it has the same characteristics as fossil natural gas, making it directly suitable to be transported with the current gas pipelines (Zwart et al., 2006). Moreover, current natural gas-fired installations do not have to be replaced. Substituting natural gas with hydrogen, on the other hand, requires adjustments[53] in the current gas infrastructure due to the lower gas density of hydrogen (Gasunie, 2018b, p. 27). Also, current gas-fired burners will need to be renewed. The advantage of hydrogen, however, is that it has a wide range of applications, which makes it an ideal energy carrier on a system

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[50] Excluding the content of petroleum coke in anode residues that serve as input for the production of new anodes.

[51] The remaining part can be mainly allocated to coal tar pitch combustion.

[52] Also known as bioSNG (substitute natural gas). Consist of bio-gas that is purified and upgraded in order to have the same properties as fossil natural gas (Zwart, Boerrigter, Deurwaarder, Van der Meijden, & Paasen, 2006).

[53] Concerns mainly investments in compressors.

level (IEA, 2018). Currently, several companies in the Dutch provinces of South Holland and Zeeland are interested in the construction of a green hydrogen network (Port of Rotterdam, 2018c; Smart Delta Resources, 2018).

Near future pilot projects in which regional companies and governments collaborate, will help to decide which fuel (green gas or hydrogen) will be the most optimal at regional level.

### 4.2.4 Carbon capture storage

Where the above decarbonisation options only focus on reducing direct $CO_2$ emissions from firing natural gas, post-combustion carbon capture storage technology can help to also mitigate the direct $CO_2$ emissions from pitch combustion. As explained in Section 4.1.4 (page 56), currently there are two technologies investigated on their applicability in the aluminium industry. The first technology uses monoethanolamine (MEA) to capture $CO_2$ and is optimal for $CO_2$ concentrations of 3% to 4%, while the second technology makes use of an ammonia-based adsorbent, optimized for $CO_2$ concentrations of 7% to 10% (Jilvero et al., 2014). Based on the capacity of Century's fume treatment system as given by Hagen et al. (2015), and the annual direct $CO_2$ emissions registered by the NEa (2018), it is estimated that the concentration of $CO_2$ in the flue gases ranges between 3.5% and 4.4%[54]. Since this range is similar to the range assumed for Aldel in Section 4.1.4, a similar CCS option can be defined for the Dutch anode manufacturing industry. After retrofitting the flue gas system, the MEA-based CCS technology can be seen as a suitable option to reduce direct $CO_2$ emissions from all carbon anode production plants. Lassagne et al. (2013) estimates that at a $CO_2$ concentration of 4%, up to 90%[55] of direct $CO_2$ emissions can be avoided at a cost of 70 $USD_{2012}$ per tonne $CO_2$ captured, which corresponds with around 30 $USD_{2012}$ per tonne of anode[56]. This excludes the costs of transporting $CO_2$ to a carbon network or storage facility. For now, it is estimated that capture investment costs will range between EUR 70 and 150 per tonne of anodes, excluding adjustments to the current flue gas systems. Operating costs of the capture system will amount to EUR 9–18 per tonne of anodes excluding extra energy costs. Extra steam requirements amount to 2.2–3.5 GJ/tonne of anodes, extra electricity to 0.2 GJ per tonne of anodes.

### 4.2.5 Volume reduction

***Development of inert anodes***

As discussed in 4.2.2 (page 59) direct $CO_2$ emissions from the electrolysis of alumina can be completely avoided by the development of inert anodes. Once inert anodes are commercialised, it is expected that the demand for carbon anodes will decrease significantly, reducing automatically the number of direct $CO_2$ emissions from the current carbon anode manufacturing. Further research will be needed to determine the final energy use and direct $CO_2$ emissions related to the production of inert anodes.

## 4.3 Melting and casting of primary and secondary aluminium

Considering the similarities of casting aluminium billets/slabs out of primary and secondary material (see Sections 2.3 and 2.4), Table 15 (page 61) gives a selection of decarbonisation options that are relevant for both practices. The following alternatives can be distinguished:

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[54] Direct $CO_2$ emissions in 2017: 65,102 tonne $CO_2$. Total volume flow of the fume treatment system varies between 87,000 and 110,000 $Nm^3$ per hour. Assuming that the system operates 8,760 hours per year gives that $CO_2$ concentrations vary between 3.5 and 4.4%.

[55] Excluding the energy requirement of the CCS plant itself

[56] Assuming that producing one tonne of anode results in 450 – 540 kg of $CO_2$ (see Table 3).

### 4.3.1 Energy-efficiency improvements

***Implementing BATs and incremental energy-efficiency improvements***
Currently Aldel, E-MAX and Zalco have each implemented the required BATs as stated in their environmental permits published by local authorities. However, comparing the current final energy consumptions of Aldel, E-MAX and Zalco with the theoretical amounts of energy needed, shows that the potential for energy-efficiency improvements is significant. The most energy-intensive process step—that of heating and melting aluminium—requires theoretically ≈1.1 GJ per tonne of aluminium (Worrell et al., 2008). By contrast, the final energy consumption of the smelting furnaces at E-MAX and Zalco ranges between 2 and 5 GJ per tonne of aluminium. Also at Aldel the final energy of its mixing furnaces, in which cold aluminium (33%) is heated up and mixed with liquid aluminium from the electrolysis cells (67%), is higher than the theoretical minimum: 1.6 GJ[57] compared to 0.4 GJ[58].

**Table 15 Overview of decarbonisation options for the melting and casting of primary and secondary aluminium in the Netherlands. Unit: <value> per tonne of casted aluminium**

| Decarbonisation option | Category | Indicative energy or $CO_2$ savings | Indicative investment costs |
|---|---|---|---|
| **Implementing BATs / incremental EE improvements (availability: now)** | Energy efficiency | See page 62. | See page 62. |
| **Green gas or hydrogen fired furnaces (availability: unknown)** | Fuel substitution | n/a | n/a |
| **Electrification of furnaces (availability: now)** | Fuel substitution | See page 62. | n/a |

So far is known, currently no company has come close to the theoretical minimum for melting and casting aluminium, however, there are some general options to reduce final energy consumption.

*Regenerative burners*
One way is by equipping furnaces with regenerative gas-fired burners[59] instead of using conventional cold-air gas-fired burners, saving up to 40% of natural gas usage at estimated investment costs of EUR 4–10 per GJ of natural gas fired per year (White, 2011; Worrell et al., 1997). At the moment Aldel, E-MAX and Zalco have already equipped their gas-fired melting and multi-chamber furnaces with regenerative burners (Aldel, 2007, p. 23; E-MAX, 2018b; Zalco, 2018c).

In addition, E-MAX operates a tiltable reverberatory furnace equipped with recuperative burners[60], that can serve as melting furnace or as casting furnace. Onsite research will be needed to determine of its beneficial to replace the recuperative burners by regenerative burners since Hassan and Al Kindi (2014) have shown that the feasibility of regenerative

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[57] Simplified calculation. At full capacity (180,000 tonne of casted aluminium) Aldel estimates an annual gas consumption of 285 TJ for its mixing furnaces (Aldel, 2007, p. *V.2*).
[58] Simplified calculation. 1.1 GJ per tonne · 33% = 0.4 GJ per tonne. In this the excess heat of the liquid aluminium from the electrolysis cells is not taken into account. Also the influence of alloy metals is excluded.
[59] Regenerative burners are able to recover 85% of the heat in exhaust gases by using a porous ceramic bed as heat storage. Subsequently, the stored heat is used to preheat inlet combustion air (Worrell, Bode, & de Beer, 1997).
[60] A type of heat exchanger, leading to natural gas savings up to 23% (White, 2011).

burners is significant lower for casting furnaces. This concerns the lower operating temperature of casting furnaces, compared to that of melting furnaces, which reduces the efficiency gain from heat recuperation. Moreover, regenerative burners are only considered to be profitable for furnaces used for melting aluminium, since in this way the excess heat from the regenerative burners can be absorbed properly by metal fusion (Hassan and Al Kindi, 2014).

The same goes for the gas-fired mixing furnaces used by Aldel to melt cold aluminium by mixing it with liquid aluminium coming from its electrolysis cells. Additional plant-specific research will be required to see if these mixing furnaces are suitable to equip with regenerative burners.

*Optimum combustion air flow*
In a reverberatory furnace, which is the common type of furnace operated by aluminium (re)melters, incomplete combustion of natural gas can lead to heat losses up to 25% (Birol, 2015a). By optimising the air to fuel ratio, however, these losses can be significantly avoided. Kermeli et al. (2015) estimates that 15% energy savings can be achieved at investment costs of USD 2.2–3.0 per tonne of casted aluminium.

*Optimising furnace insulation*
Another option is to make use of insulating materials to prevent heat to escape to the environment through convection and conduction (Kermeli et al., 2015, p. 645). It is estimated that, in this way, 2% to 5% of energy can be saved, at an investment cost of USD 0.4–0.6 per tonne of casted aluminium.

*Oxy-fuel burners*
An alternative to regenerative burners are burners using pure oxygen instead of conventional combustion air. It is estimated that oxy-fuel burners have the same fuel savings potential as regenerative burners (Schmitz, 2014). The economic profitability of these burners depends strongly on the ratio “natural gas price / oxygen price”. Currently Zalco is investigating the feasibility of equipping its mixing/casting furnaces with oxy-fuel burners (Zalco, 2018c).

### 4.3.2 Fuel substitution

#### ***Green gas or hydrogen fired furnaces***

As mentioned in Section 4.2.3 (page 59) green gas and hydrogen are seen as two promising renewable energy fuels for substituting natural gas completely by 2050. By replacing the fossil gas, both fuels have the potential to reduce direct $CO_2$ emissions from Aldel (cast house) and Zalco with 100% by 2050. Also for E-MAX the reduction potential is significant: 80%–90%[61].

By switching to green gas, the current transport infrastructure and gas-fired installations can continued to be used, while replacing natural gas by hydrogen will require adjustments in both gas infrastructure and gas-fired installations due to its lower gas density (Gasunie, 2018b, p. 27). On the other hand, hydrogen has a wide range of applications which makes it an ideal energy carrier on a system level (IEA, 2018). Future collaboration projects between regional companies and governments will help to decide whether green gas or hydrogen will be the most optimal fuel at regional level.

#### ***Electrification of furnaces***

At present Aldel, E-MAX and Zalco use mainly gas-fired furnaces for melting and casting aluminium into billets/slabs. By replacing these gas-fired furnaces with electric (induction)

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[61] 10 – 20% of E-MAX’s direct $CO_2$ emissions are coming from combusting plastics, see Section 2.4.4 (page 39).

furnaces, onsite combustion $CO_2$ emissions can be reduced to zero[62]. Moreover, electric furnaces have the advantages of a high melting efficiency, high quality melt, and low material loss (Eckenbach and Spitz, 2016). Not all electric furnaces, however, are suitable due to limited melt and hold capacities, and inflexibility regarding producing different types of alloys. Additional onsite research will be needed to determine which types of induction furnaces are the most profitable to integrate in the current casting processes. With this research, it can be also decided whether melting, casting or homogenisation furnaces are most likely to be replaced first.

In addition, for melting and casting aluminium electrically, connections to the national power grid should be prepared to supply more electricity[63]. In case all gas-fired furnaces are substituted by an electric equivalent with the same melting efficiency[64], the annual electricity consumption of Aldel, and E-MAX and Zalco would increase by a respective 0.7 MWh and 1.4–2.2 MWh per tonne aluminium. It is expected that Aldel's current connection to the 220 kV power grid, $3 \cdot 220/30$ kV transformers, is dimensioned to handle an additional power demand on top of the ≈200 MW needed for its electrolysis cells (Aldel, 2008). For E-MAX and Zalco, however, power grid connections will have to be significantly increased, since their electricity use increases with a factor 5 to 25. Considering the amount of power needed, and the outline of the Dutch power grid published by Tennet (2017), it is expected that both E-MAX and Zalco will require a connection to the national 150 kV power grid.

Plant-specific research will help to determine what the costs are of engineering and placing a new grid connection, and to which extent the existing onsite electricity infrastructure will have to be expanded.

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[62] By assuming that by 2050 the electricity of the national power grid will be only generated by renewable energy sources, related indirect $CO_2$ emissions are also avoided.

[63] Onsite generation of electricity from renewable energy sources is not studied.

[64] This is assumed to simplify the calculation. In general induction furnaces have a melting efficiency ranging between 59 – 76%, while the melting efficiency of, for instance, a gas-fired reverberatory melting furnace is on average 25% (Birol, 2015a, p. 123; Birol, 2015b, p. 53).

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