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# Energy Efficiency and GHG Emissions: Prospective Scenarios for the Aluminium Industry

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**Abstract**

This study examines the possibilities for energy efficiency and GHG emission improvements in the European aluminium industry. The first part of the study presents the status quo of the industry in the EU28 and Iceland by compiling a database of existing plants with their production characteristics and the best available and innovative technologies (BATs/ITs). A model of the EU industry is then developed to simulate the trend in each plant towards 2050. The use of the model in different scenarios allows the analysis of the cost-effectiveness of investments in BATs/ITs. The results show that in absolute terms, for the whole industry the energy consumption and direct GHG emissions can decrease from 2010 to 2050 by 21 % and 66 % respectively. And, in almost all scenarios, for primary aluminium production there is a convergence in the reduction of specific energy consumption and direct GHG emissions of 23 % and 72 % respectively. Since most of the savings come from technologies that are in early stages of research, there is a clear need of a decided push and of creating the right conditions to make these potential savings happen.

# Table of Contents

<b>Preamble .....</b>	<b>1</b>
<b>1 Introduction.....</b>	<b>2</b>
1.1 <i>Scope of the study</i> .....	2
1.2 <i>European Aluminium industry</i> .....	4
<b>2 Energy analysis of the European Aluminium industry .....</b>	<b>5</b>
2.1 <i>Production of primary aluminium</i> .....	6
2.2 <i>Production of secondary aluminium</i> .....	9
2.3 <i>GHG emissions benchmark curves of the EU aluminium industry</i> .....	10
2.4 <i>Potential GHG emission reduction through implementation of all BATs in 2010</i> .....	12
<b>3 Database of individual plants .....</b>	<b>13</b>
3.1 <i>Description of database</i> .....	13
3.2 <i>Discussion of quality of data</i> .....	13
3.3 <i>Approach regarding secondary melters</i> .....	17
<b>4 Analysis of the availability and remaining potential of scrap and bauxite .....</b>	<b>19</b>
4.1 <i>Current and future recycling rates of scrap</i> .....	19
4.2 <i>Current availability of bauxite and projected reserves</i> .....	20
<b>5 Best available technologies (BATs) .....</b>	<b>21</b>
5.1 <i>Overview of BATs</i> .....	21
5.2 <i>Bayer process</i> .....	22
5.3 <i>Hall-Hérout process</i> .....	24
5.4 <i>Anode baking</i> .....	29
5.5 <i>On-site Power Production</i> .....	29
5.6 <i>Secondary melters</i> .....	30
5.7 <i>Combined, Bayer &amp; Hall-Hérout</i> .....	30
<b>6 Estimation of the degree of implementation of the BATs .....</b>	<b>31</b>
6.1 <i>Methodology for estimating implementation of BAT based on ‘distance-to-target’ SEC</i> .....	31
6.2 <i>Assessing distance-to-target</i> .....	32
6.3 <i>Optimisation of the electrolysis process and estimating implementation of BAT</i> .....	34
<b>7 Innovative technologies (ITs) .....</b>	<b>36</b>
7.1 <i>Overview of ITs</i> .....	36
7.2 <i>Bayer process</i> .....	36

7.3	<i>Hall-Héroult process</i> .....	37
7.4	<i>On-site power production</i> .....	40
<b>8</b>	<b>Model of the European aluminium sector</b> .....	<b>41</b>
8.1	<i>Model core structure</i> .....	41
8.2	<i>Plant performance</i> .....	43
8.3	<i>Installation of new BATs/ITs</i> .....	44
8.4	<i>Input data</i> .....	44
8.5	<i>Limitations and possible improvements</i> .....	45
<b>9</b>	<b>Initial values and input scenarios</b> .....	<b>47</b>
9.1	<i>Qualitative description of global aluminium sector trends</i> .....	47
9.2	<i>Baseline scenario and alternative scenarios</i> .....	49
9.3	<i>Variables common to all scenarios</i> .....	52
<b>10</b>	<b>Simulation Results</b> .....	<b>55</b>
10.1	<i>Baseline scenario</i> .....	55
10.2	<i>Rest of scenarios</i> .....	64
<b>11</b>	<b>Conclusions</b> .....	<b>66</b>
<b>12</b>	<b>Bibliography</b> .....	<b>68</b>

## TABLES

Table 2-1 Energy consumption per tonne of sawn aluminium ingot production (EAA, 2013) .....	9
Table 3-1 Assessment of the plant characteristics database .....	15
Table 3-2 Production share and emissions remelting and refining .....	18
Table 5-1 Best Available Technologies (BATs) considered .....	21
Table 5-2 Specific PFC emissions of each primary aluminium smelter technology.....	25
Table 5-3 Indication of investment costs for a 250 000 tonne cast house.....	26
Table 5-4 Operational costs for a 250 000 tonne cast house. ....	26
Table 5-5 Increase in number and diameter of the rods holding the anode .....	28
Table 5-6 Making slots in the anode to allow the flue gas to escape.....	28
Table 5-7 Anode baking BATs.....	29
Table 5-8 CAPEX and OPEX on-site renewables.....	30
Table 6-1 AP30 technology results in potlines worldwide (1988-2012) .....	32
Table 6-2 Maximum attainable efficiencies and distance-to-target (energy efficiency) per plant .....	33
Table 6-3 Cost distribution 'optimisation of the electrolysis process' .....	34
Table 6-4 Estimated implementation level BAT 'optimisation of the electrolysis process' per smelter .....	35
Table 7-1 Innovative Technologies.....	36
Table 7-2 Costs and availability of CCS techniques for a 260 000 t primary aluminium smelter (Lassagne, 2013a) .....	40
Table 9-1 Initial and final values that define the different scenarios.....	50
Table 9-2. Values in 2050 of the parameters common to all scenarios.....	53
Table 9-3 US import bauxite prices, (USGS, 2014). ....	54
Table 10-1 Model settings.....	55
Table 10-2 Number of plants that have specific BAT and IT measures installed in the aluminium industry in Europe, per plant type for selected years (excluding secondary smelters).....	63

## FIGURES

Figure 2-1 Simplified life cycle material flow chart of an aluminium product (Source: EAA, 2013) .....	6
Figure 2-2: Benchmarking curve for pre-baked anode production .....	11
Figure 2-3: Benchmarking curve for unwrought non-alloy liquid aluminium production from electrolysis	11
Figure 2-4 GHG emissions reduction potential through the full implementation of all BATs in 2010.....	12
Figure 3-1 Cost breakdown of Western refiners.....	14
Figure 4-1 Aluminium material flows in Europe in 2013, source: (IAI, 2015) .....	20
Figure 8-1 Core structure of the aluminium-plants model.....	42
Figure 9-1 Carbon price projection (EC, 2013, IHS CERA, 2012).....	50
Figure 10-1 Total energy consumption in the manufacturing of the total cast aluminium produced in the EU and Iceland, considering or not the retrofits in the model.....	57
Figure 10-2 GHG emissions (both direct and indirect on the left-hand figure, and only direct on the right-hand figure) of total cast aluminium produced in the EU and Iceland, considering or not the retrofits in the model. ....	57
Figure 10-3 Total energy consumption per tonne cast aluminium produced in the baseline scenario (including primary and secondary Aluminium production). ....	59
Figure 10-4 Total GHG emissions — direct and indirect (from the electricity consumed in aluminium manufacturing) emissions per tonne of cast aluminium in the baseline scenario (including primary and secondary aluminium production). ....	59
Figure 10-5 Energy consumption per tonne of cast primary aluminium production in the baseline scenario (arranged by process) .....	61
Figure 10-6 Energy consumption per tonne of cast primary aluminium production in the baseline scenario (arranged by kind of fuel) .....	61
Figure 10-7 Direct GHG emissions per tonne of cast primary aluminium production in the baseline scenario (arranged by process) .....	62
Figure 10-8. Direct GHG emissions per tonne of cast primary aluminium production in the baseline scenario (arranged by kind of fuel) .....	62
Figure 10-9. Energy consumption per tonne of cast primary aluminium production in all scenarios.....	65
Figure 10-10. Direct GHG emissions per tonne of cast primary aluminium production in all scenarios .....	65

## Preamble

In relation to climate action, there is an overall goal at global level to keep the average temperature increase caused by human activities below two degrees Celsius compared to pre-industrial levels. To achieve this goal, EU action alone is not enough, since the EU is responsible for only 11 % of global emissions (PBL, 2014). European emissions are expected to decrease by 24 % by 2020, as a result of current policies (EC, 2014b). Yet there is a need for further progress in all areas if the EU is to achieve the 2050 goal (EC, 2011a) of reducing gas emissions to 80-95 % below 1990 levels. This document shows what potential contribution the European Aluminium industry could make to achieving this goal.

At the core of the model developed in this document to analyse the trend in energy consumption and GHG emissions up to 2050 is a cost-effectiveness analysis of the potential implementation of best available and innovative technologies. Making these innovations happen can be the way to develop an ambitious industrial policy that in the short-term aims for industrial production accounting for 20 % of the EU GDP by 2020, as compared to around 15 % today (EC, 2014a)

One of the findings of this report is in line with the need of additional research priorities identified in the Energy Union Package (EC, 2015a) such as carbon capture and storage (CCS) and inert anode technology to reach the 2050 climate objectives in a cost-effective way.

Since the biggest part of the savings uncovered in this study comes from technologies that are in early stages of research, before being effectively implemented in the industry, these technologies will need a demonstration stage, and to go through the rest of the usual processes for the diffusion of technological innovation. This study reveals the need for an effective push and the need to create the right conditions for these potential savings to happen.

This document relies on the deliverables of a project carried out by Triple E and TNO, under contract to the European commission, JRC-IET Petten (contract no. 111203).

# 1 Introduction

## 1.1 *Scope of the study*

In recent years, the European aluminium industry has made substantial efforts to improve its performance in terms of energy efficiency and greenhouse gas emissions. However, to achieve the ambitious EU greenhouse gas and energy efficiency targets, still further improvements are required. These have to be obtained within a context in which the overall economic situation of the European aluminium industry is difficult. Several aluminium smelters were closed over the past few years, and the economic perspectives of many other smelters seem not to be positive either. This study analyses the possibilities for energy efficiency and greenhouse gas emission improvements up to 2050 in the EU and Iceland, taking into account the current economic situation of the industry. Processes (and facilities that only operate those processes) where the cumulative effect on GHG emissions and energy consumption does not surpass 5 % of total GHG emissions or energy consumption of the aluminium production chain are excluded from the scope of this study. This means that hot rolling, cold rolling, shape casting and extrusion plants are excluded from the study. Also, secondary production is represented by four hypothetical average plants.

The detailed database compiled and used by the model contains information at facility level, such as material input and output, energy consumption of the processes, GHG emissions, production costs and technologies installed. However, this database lacks detailed information about the technical and economic specifications for each plant. To overcome the fact that part of the information needed is not publicly available, we have had to resort to some estimates. Also, completion of the gaps in the information has required a certain degree of reverse engineering. The main gaps were in the investment, operation and maintenance (O&M) costs of some BATs and ITs, in the detailed technical configuration of the facilities, and the implementation level of certain BATs.

The model is built up based on qualitative data, estimating the trend in energy consumption and GHG emissions of the industry depending only on a cost-effectiveness analysis of potential improvements. Other factors, such as potential policy development (at both national and European level) are incorporated into the analysis only to the extent at which they are already incorporated into the parameters of the reference scenario of the 2013 update of the energy and GHG trends up to 2050 (EC, 2013). In any case, developments in the world market for aluminium may influence European demand for alumina and aluminium. In the model, production of both alumina and liquid aluminium is distributed over the available production facilities in order of production cost, i.e. the production of the cheapest facility is allocated first and then the rest of the capacity is added in ascending order of production costs. For this purpose, energy and electricity costs are used as a proxy for the production costs.

The chapters of this document cover two main tasks:

**Task 1. Status of the industry.** Aims to analyse the current technology status and technology prospects of the European aluminium industry and assess the resulting margin of improvement for energy efficiency gains and GHG emissions reduction for the sector and its impact on cost-competitiveness.

**Chapter 2** discusses the energy flow-sheet of the EU and Icelandic aluminium industry

**Chapter 3** describes the database on aluminium plant characteristics developed for this project

**Chapter 4** analyses the availability of scrap and bauxite in the EU.

**Chapter 5** describes a list of the Best Available Technologies (BATs) considered in this document.

**Chapter 6** discusses the approach to investigate implementation of BATs.

**Chapter 7** describes a list of the innovative technologies (ITs) considered in this document.

**Chapter 8** describes the aluminium sector model built for this study;

**Task 2. Prospective scenarios.** Describes the scenarios developed to determine the deployment of low carbon and efficient energy technologies up to 2050 in the sector and quantify the impact on energy efficiency, reduction of GHG emissions and the cost-competitiveness of the sector up to 2050.

**Chapter 9** discusses the input variables and values used for the scenarios developed;

**Chapter 10** in conclusion, describes and analyses the outputs for the different scenarios

## **1.2 European Aluminium industry**

The total indigenous production of European <sup>(1)</sup> aluminium industry was about 8.9 Mt in 2013 (IAI, 2015), this amount neither includes the ingots imported (3.3 Mt) nor the remelted aluminium (6.1 Mt). The primary aluminium contributes to the aluminium output with about 4.2 Mt and the recycling route with 4.7 Mt.

The four main steps of the primary aluminium production process are the mining of bauxite, the subsequent extraction of the alumina (aluminium oxide) using the Bayer process, the production of primary aluminium through the Hall-Héroult electrolytic process and the casting of the liquid aluminium. All these steps require approximately 37 GJ of thermal energy and 58 GJ of electricity per tonne of sawn aluminium ingot produced (EAA, 2013). The highest demand for energy is in the electrolysis process, in the form of electricity consumption.

On the other hand, the production of secondary aluminium from scrap is less energy intensive. Secondary aluminium can be produced from new scrap (arising during the fabrication of aluminium products up to the point where they are sold to the final consumer) in remelters, and from old scrap (material recovered after product use) in refiners. The production of one tonne of ingot from clean process scrap in a remelter requires about 3.8 GJ/t of thermal energy and 0.45 GJ/t of electricity (EAA, 2013). This is only a fraction of the energy consumption per tonne of primary aluminium production. Recycling of old scrap uses somewhat more energy because of the required scrap preparation step.

Increased competition over raw materials and high energy costs are driving use of secondary materials in the aluminium sector in Europe. Recycling plays an important role in the EU, with more than 270 recycling plants and levels of recycling of over 70 % in transport, building and beverage cans (CEPS, 2013, EAA, 2013). However, not all scrap is recycled in the EU with part of it being exported, primarily to Asia. Even though scrap is important, it is not available in sufficiently high quantities, or of such a high quality as to fully substitute primary aluminium, so primary materials are likely to remain a key source for production of aluminium.

EU extraction of bauxite (aluminium ore) is very limited, approximately 1.5 % of the global total, and the EU is dependent on imports of bauxite. Nevertheless, bauxite availability is not expected to become a bottleneck in aluminium production as this is one of the most common elements in the Earth's crust.

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<sup>(1)</sup> In (IAI, 2015) the values corresponding to Europe encompasses the EU, Albania, Belarus, Bosnia-Herzegovina, Iceland, Macedonia, Moldova, Norway, Serbia-Montenegro, Turkey and Ukraine.

## 2 Energy analysis of the European Aluminium industry

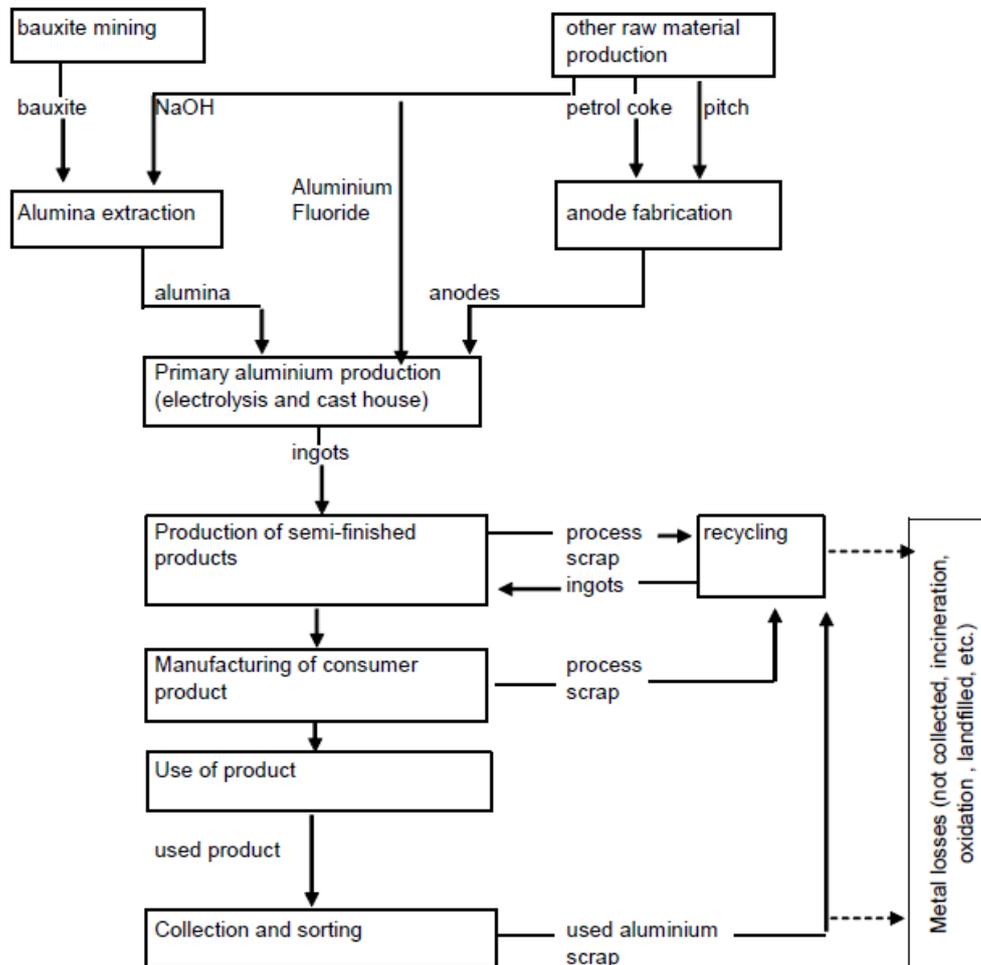
This chapter provides an energy and raw material analysis of both primary and secondary production. As already shown in the previous chapter, the production of primary aluminium is much more energy intensive than that of secondary production. The main focus of this analysis is therefore primary production, later addressing the question as to what extent secondary production can replace primary production.

Although the model and scenarios analysed are based on detailed plant-specific data, this introduction to the main energy flows of the overall EU aluminium industry only provides aggregated data.

Besides the indigenous production of aluminium already mentioned in the first chapter, there is also significant import of aluminium ingots from outside the EU-28 and Iceland, for remelting. These ingots are mixed with the production of primary and secondary aluminium, increasing the apparent output of aluminium by approximately 10 % (EAA, 2013).

Figure 2-1 shows the typical life cycle of an aluminium product system, broken down into the various different process steps (from EAA, 2013). This is worked out in more detail in sections 2.1 and 2.2, in which the production of primary and secondary aluminium is discussed. Section 2.2 contains general information on energy efficiency and greenhouse gas emissions of the industry, which is later expanded in the detailed calculations carried out in this study.

Figure 2-1 Simplified life cycle material flow chart of an aluminium product (Source: EAA, 2013)



## 2.1 Production of primary aluminium

Primary aluminium production starts with the mining of **bauxite** (a mixture of aluminium hydroxides, oxyhydroxides and other impurities) and the subsequent extraction of the alumina (aluminium oxide). In the Bayer process, bauxite is washed with a hot solution of sodium hydroxide at 250 °C, dissolving aluminium hydroxide. The other components of bauxite do not dissolve and can be filtered out as solid impurities (red mud). Afterwards, the hydroxide solution is cooled and the aluminium hydroxide precipitates out. When heated to 1050°C, the aluminium hydroxide decomposes to **alumina**, giving off water vapour in the process. A more detailed description of the processes can be found in Chapter 3 of the EAA Environmental profile report as well as several other documents (e.g. BREF, 2014; Lumley, 2011; NTNU, 2004).

As input and output data for the production of bauxite and refining of alumina, this study uses the values reported in tables 3-2 and 3-3 of the Environmental profile report (EAA, 2013). These tables distinguish main raw materials and other materials consumed, energy use (fuel, steam and electricity), air and water emissions (including direct GHG emissions), by-products and solid wastes, all per tonne of product (bauxite and alumina respectively).

From (EAA, 2013), the production of one tonne of bauxite requires about 0.02 GJ of thermal energy and 0.003 GJ of electricity. And, there is a consumption of 2.3 tonnes of bauxite per tonne of alumina manufactured. Moreover, the specific energy consumed in the alumina manufacturing processes is about 10 GJ of thermal energy and 0.65 GJ of electricity.

Despite the strong trend since 2005 to substitute heavy oil by natural gas, European alumina production still mainly uses heavy oil as a source of thermal energy (about 55 % in 2010). Nevertheless, that substitution depends on the local availability and supply of natural gas.

Besides alumina, **carbon anodes** are the second main raw material needed to produce primary aluminium. Even though there are still two Söderberg aluminium smelters in Spain, the pre-baked carbon anode is the predominant technology in the EU-28 plus Iceland. The main technologies used in the smelters (the Hall-Héroult process) differ in how the anode is produced. In the Söderberg technologies it is fabricated in situ by adding pitch to the top of the anode. In pre-bake technologies, the anodes are baked in gas-fired ovens and later transferred to the cell. Anodes are produced by baking a mixture of hard calcined petroleum coke, recycled anode butts, and coal tar pitch at 1150°C, most often in an on-site anode plant, but some smelters procure carbon anodes externally. The fraction of the carbon input consisting of recycled butts has been increasing during the last decade, while overall fuel and electricity consumption has been decreasing. Detailed information on the anode fabrication process can be obtained from, among others, (EAA, 2013; BREF, 2014; Lumley, 2011; NTNU, 2004).

The direct input and output data for the anode production process, see Table 3-4 of the Environmental profile report (EAA, 2013), can be summarised as a specific thermal and electricity energy consumption of about 2.8 GJ/t anode (mostly natural gas) and 0.4 GJ/t anode, respectively.

The Hall-Héroult process for smelting aluminium involves dissolving the alumina ( $\text{Al}_2\text{O}_3$ ) in molten cryolite ( $\text{Na}_3\text{AlF}_6$ ), and electrolysing the molten salt. The presence of cryolite reduces the melting point of the alumina, facilitating electrolysis. In the operation of the cell, aluminium is deposited on the cathode, while the oxygen from the alumina is combined with the carbon from the anode to produce  $\text{CO}_2$ .

As direct input and output data related to the production of liquid aluminium at the electrolysis step we use the information from Table 3-5 (EAA, 2013). This reference also contains the raw material inputs (including anodes and alumina), electricity consumption, air and water emissions (including direct GHG emissions) and solid

wastes (mainly consisting of spent pot lining). The electrolysis step does not require additional thermal energy input to that provided by the Joule effect.

On average, the specific consumption of electrical energy is approximately 55 GJ per metric tonne of aluminium, which makes electrolysis the most energy-intensive step of the whole aluminium cycle. About half of this energy is converted to heat in the process. Electricity is either produced on site or is procured on the market. Input of carbon anodes is about 550 kg per tonne of Al of which about 80 % is consumed and 20 % is recycled to bake new anodes. If we assume that the amount consumed is fully converted to carbon dioxide, this represents a further energy input of 14 GJ/t Al. Alumina consumption is on average 1920 kg/t Al.

Liquid aluminium, from the electrolysis process, is transferred to the cast house, which is usually an integrated part of the smelter. Besides the liquid aluminium, the input of the cast house consists of cold solid metals like alloying elements, ingots for remelting and new scrap. This serves to prepare the appropriate alloy composition and recover some of the energy from the hot liquid aluminium stream. In 2010, the average input of liquid metal from electrolysis to the cast house was about 750 kg per tonne of sawn ingot.

The information for the input/output data for the cast house in Table 3-6 of the 2013 EAA Environmental profile report (EAA, 2013) includes hot and cold metal input, input of raw materials, thermal energy by fuel type, and electricity. Total thermal energy input is about 1.6 GJ per tonne of sawn ingot (mostly natural gas). The electricity consumption is about 0.4 GJ per tonne of sawn ingot. Outputs are air and water emissions (including GHG), by-products for external recycling and solid waste streams.

- **Total energy requirement to produce a tonne of sawn primary aluminium ingot**

In the 2013 EAA Environmental profile report (EAA, 2013) all data refers to the EU-27 plus Iceland and Norway as a whole. Since this study excludes Norway, the weighted average 2010 input/output data for electrolysis are not entirely representative, as one Norwegian plant has a different smelter technology (Söderberg instead of pre-bake).

As far as possible, the calculation in the model developed in this study uses plant-specific input/output data. Data not available by plant are estimated based on plant-specific circumstances, or otherwise derived from the aggregated EAA data if they show little inter-plant variation.

By combining the guide numbers given in the previous section, the total amount of energy required to produce one tonne of sawn primary aluminium ingot can be estimated. The table below shows the results. Considering anode carbon as a fuel, **approximately 37 GJ of thermal energy and 58 GJ of electricity would be needed per tonne of sawn aluminium ingot.**

Table 2-1 Energy consumption per tonne of sawn aluminium ingot production (EAA, 2013)

Process	Relative amount of product used	Specific energy requirement (GJ/t product)		Total energy requirement (GJ)		
		Thermal Energy	Electricity	Thermal Energy	Electricity	Total
Bauxite mining	4.5	0.02	0.003	0.089	0.013	0.10
Alumina refining	1.9	10	0.65	19	1.3	21
Anode production	0.56	2.8	0.4	1.6	0.22	1.8
Electrolysis	1.0	14(*)	55	14(*)	56	70
Ingot casting	1.0	1.6	0.4	1.6	0.40	2.0
<b>Total</b>	-	-	-	<b>37</b>	<b>58</b>	<b>95</b>

(\*) When anode carbon is regarded as a fuel

The input/output tables of the EAA (2013 Environmental Profile report) provide emission factors for direct CO<sub>2</sub> emissions by process. In a similar way to Table 2-1, the overall direct CO<sub>2</sub> emission can be calculated, which results in **around 3.5 tCO<sub>2</sub> per tonne of sawn aluminium ingot**. The total electricity energy consumed is approximately 16 000 kWh/t Al, of which electrolysis consumes more than 95 %. If we assume an average CO<sub>2</sub> emission factor of 0.465 kg CO<sub>2</sub>/kWh –as in the carbon leakage assessments performed by DG Climate Action(EC, 2009) – this would equal an **additional 7.4 tCO<sub>2</sub>/t Al**. Needless to say, the CO<sub>2</sub> emission factor varies greatly among Member States.

## 2.2 Production of secondary aluminium

Secondary aluminium production requires as little as 5 % of the energy needed for primary aluminium production (BREF, 2014). The production route is also much more diverse and fragmented compared to primary aluminium production.

The aluminium recycling industry includes remelters and recyclers. The difference between them depends on the type of scrap that is processed (EAA, 2013), either new or old scrap. New scrap is surplus material that arises during the production and fabrication of aluminium products up to the point where they are sold to the final consumer. It consists of almost pure aluminium. Remelters process new scrap to produce aluminium (alloy) ingots. This also takes place at cast houses of primary aluminium smelters to a certain extent. Old scrap is the aluminium material that is recovered after an aluminium product or component has been produced, used and finally collected for recycling. Recyclers process old scrap to produce aluminium (alloy) ingots. The aluminium content of old scrap has been often lower than that of new scrap and requires additional effort to remove impurities.

**Remelters** use mainly reverberatory furnaces while recyclers/refiners mostly use a combination of rotary and reverberatory furnaces (EAA, 2013). In this report the direct inputs and outputs per tonne of ingot production from clean process scrap in a reverberatory furnace used are those from Table 7-2 of the 2013 EAA Environmental profile report. In short, the specific **thermal and electricity input is about 3.8 GJ/t and 0.45 GJ/t, respectively**. This is only a small fraction of the consumption of 37 GJ of thermal energy and 58 GJ of electricity per tonne of primary aluminium. However, this is only for secondary aluminium production from new scrap. Recycling old scrap will use somewhat more energy because of the required additional scrap preparation step.

The average specific CO<sub>2</sub> emission from the specific fuel consumption is around **0.265 tCO<sub>2</sub>/t Al**.

### **2.3 GHG emissions benchmark curves of the EU aluminium industry**

Figures 2-2 and 2-3 are based on the benchmarking curves used in the Commission's decision (EU, 2011) that establishes the free allowances allocated to the industry to prevent carbon leakage. The benchmark values in the decision are 0.324 t CO<sub>2</sub>/t and 1.514 t CO<sub>2</sub>/t for pre-bake and aluminium manufacturing respectively.

Each series of values in figures 2-2 and 2-3 are sorted by increasing specific emissions and, aside from the benchmark curve, we include the specific CO<sub>2</sub> emissions estimated from bibliography, and the initial calibration of the emissions from the facilities used in this analysis. With this exercise we can ensure that the values used in this document resemble the values on which the Commission's decision is based (EU, 2011).

Figure 2-2: Benchmarking curve for pre-baked anode production

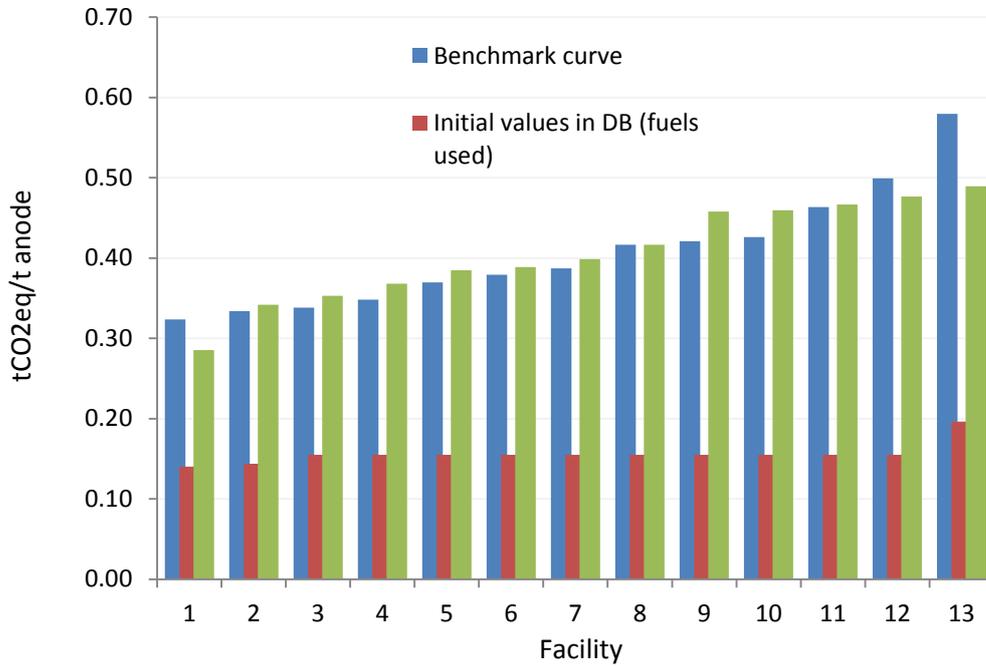
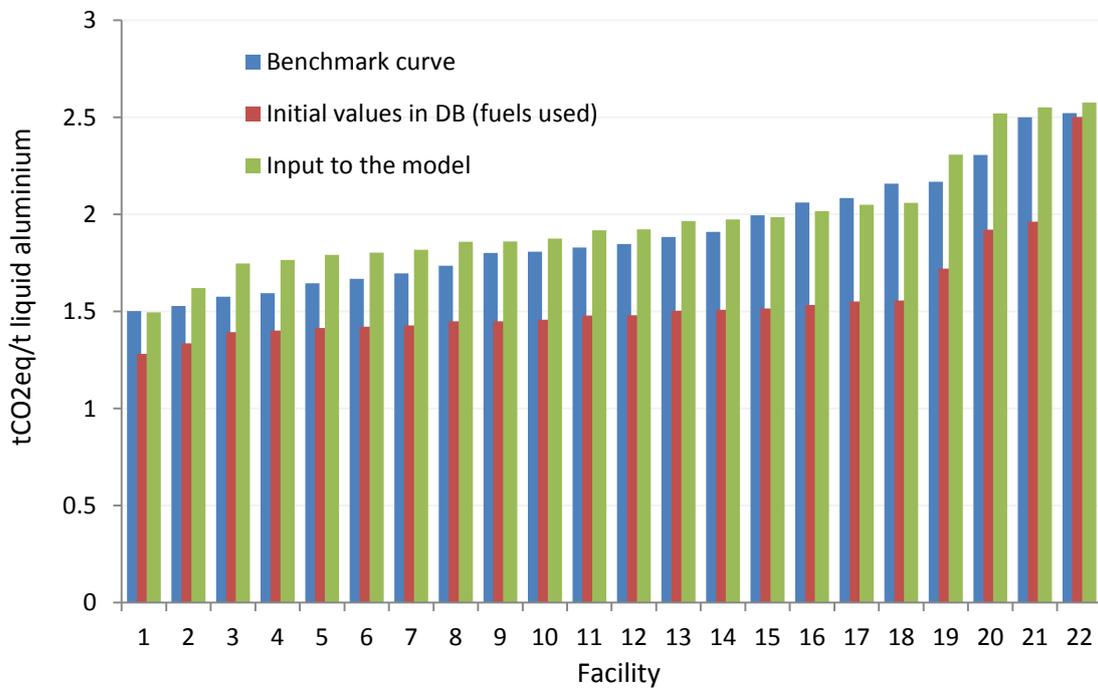


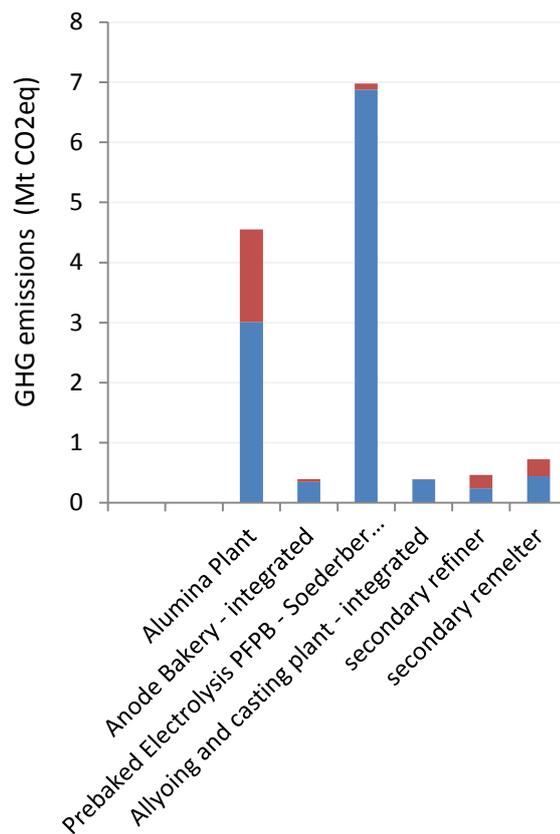
Figure 2-3: Benchmarking curve for unwrought non-alloy liquid aluminium production from electrolysis



## 2.4 Potential GHG emission reduction through implementation of all BATs in 2010

In theory, all existing BATs could have been fully implemented already in 2010. This could lead to a reduction of around 10 % of GHG emission in the studied area. Figure 2-4 shows the potential GHG emissions savings (in red) and the remaining emissions (in blue) after the installation of all BATs. Although there are some GHG emission reductions in the electrolysis process and the secondary aluminium production route, the highest reduction potential lies in alumina production. Figure 2-4 also includes the indirect GHG emissions produced during the generation of the electricity consumed by the aluminium industry. Although those emissions are released in the power sector, we provide them in order to give an idea of the amounts involved. The savings in indirect GHG emissions are due to the accumulated decrease in electricity consumption when all pending BATs are incorporated in the aluminium industry.

Figure 2-4 GHG emissions reduction potential through the full implementation of all BATs in 2010



The analysis of when these BATs and innovative technologies (yet to come) will be incorporated over time is left until chapter 10, according to the cost-effective analysis carried out using the model described in chapters 8 and 9.

## **3 Database of individual plants**

All information necessary to develop a bottom-up model to estimate the energy consumption and GHG emission trends up to 2050 is incorporated into a database of existing facilities. This chapter describes the characteristics collected, providing an overall description of the database in section 3.1. Section 3.2 discusses the quality of the data, providing in table 3.1 all the sources of information used. Finally, section 3.3 focuses on the approach followed for secondary melters, for which, due to lack of data, some estimates have been made.

### **3.1 Description of database**

The plant characteristics database covers various variables such as capacity, production, energy consumption and GHG emissions. The database covers 35 plants, 9 of which are alumina refineries, being the rest smelters. There are 4 aggregated plants to represent the secondary aluminium industry (more details in section 3.2). The database also identifies the primary smelters with an integrated anode bakery. Most of the primary smelters have on-site anode bakeries. A further distinction is made in the cases of on-site power plants. Two of the alumina refineries and two of the primary smelters in the database have on-site power generation. The power plants of the two alumina refineries are CHP plants based on natural gas. Only one of the two smelters with power plants is still operational (it has a hydro power plant). Although the other smelter was mothballed in 2012, its on-site coal-fired power plant is still operational.

A relevant parameter in the database is the status of the plant. While most plants are operational, some are mothballed or closed. For instance, there is a closed Romanian alumina plant and an Italian one mothballed. Furthermore, six of the smelters in the database are mothballed and three are closed. The mothballed and closed smelters are in Germany, Italy, the Netherlands, Spain and the UK. The plant characteristics database also provides information on the latest year of modernisation, which could be used to define the maximum number of simultaneous retrofits allowed annually in the European industry. Furthermore, key information such as annual production is also used for the scenarios database and extrapolations.

### **3.2 Discussion of quality of data**

Table 3.1 summarises the source of the information used in the database. Most of the data derives from the literature and is plant specific. In case of data gaps, we use average industry values and our own estimates. Table 3.1 also contains details about how the estimations have been done. The assumptions regarding costs are provided below, while the approach for BATs implementation is described in detail in chapters 5 and 6. The specific approach regarding secondary melters is explained in section 3.3.

### Assumptions regarding costs

There is no data available for production costs at each plant. Therefore, for the capital and O&M we use average costs for the industry, as described below. In any case, the largest share of the costs is due to raw materials and energy. Prices for these variables are discussed in detail in chapter 9.

### Alumina refineries

We assume an average production cost for alumina refineries in Europe of EUR 190 /t. More than half of these costs are bauxite and energy costs (JRC, 2007; CEPS, 2013). Therefore, using the most recent figures, for all plants in the database 22 % of production costs are for non-electrical energy, 3 % is for electricity and 34 % for bauxite. The remaining costs are the average capital and O&M costs.

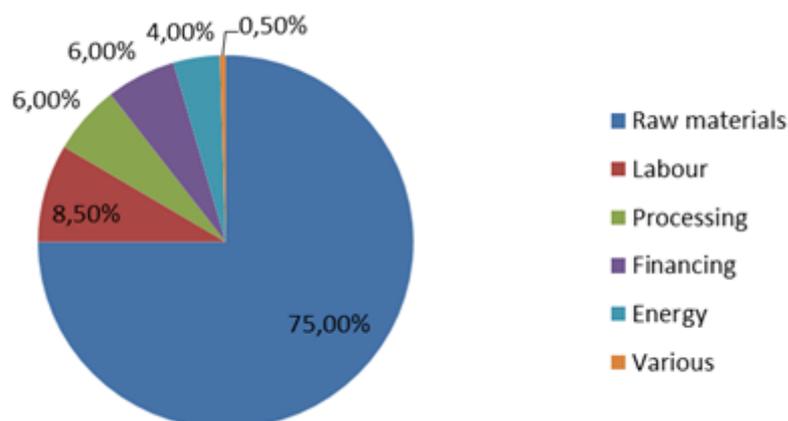
### Primary smelters

The average production cost for primary smelters in Europe is around EUR 2088 /t (CEPS, 2013). As for the alumina refineries the majority (more than 60 %) of this cost corresponds to the main raw material (alumina) and electricity (Djukanovic, 2012; CEPS, 2013). Using more recent figures, the electricity cost accounts for 32.5 % and the alumina for 34.8 % of the total production cost. The remaining components of the cost are the average capital and O&M cost.

### Secondary smelters

The production cost of secondary aluminium varies strongly with the quality of the scrap and aluminium produced. The range of scrap prices varies from EUR 344 /t to EUR 982 /t. Using an average value of EUR 700 /t, and the fact that scrap price makes up around 75 % of the secondary aluminium production costs (figure 3-1), we can conclude that the remaining non-energy costs (mainly capital, labour and processing) are around EUR 186 /t.

Figure 3-1 Cost breakdown of Western refiners



Source: Metal Bulletin's 13th International Recycled Aluminium Conference, 2005

Table 3-1 Assessment of the plant characteristics database

Variable	Plant-specific data	Data source(s) used	Remarks
Plant name & long name	Yes	(Pawlek, 2014a; Pawlek, 2014b)	
Plant type	Yes	(Pawlek, 2014a; Pawlek, 2014b)	
City	Yes	(Pawlek, 2014a; Pawlek, 2014b)	
Country (ISO3code)	Yes	(Pawlek, 2014a; Pawlek, 2014b)	
Nominal production capacity	Yes (except for secondary aluminium plants)	(Pawlek, 2014a; Pawlek, 2014b; CEPS, 2013) own estimations	For aggregated secondary aluminium plants this is estimated using the annual production of the sector (assuming 61 % share for the secondary aluminium sector after CEPS). For more details on the general approach for secondary aluminium producers refer to sub-section 3.2.
Anode baking capacity	Yes	(Pawlek, 2014a; Pawlek, 2014b); own estimations	Estimates are based on the average ratio between anode plant capacity and smelting capacity (0.55) derived from the actual values for the remaining smelters.
Potline technology	Yes	(Pawlek, 2014a; Pawlek, 2014b)	
Cast house capacity	Yes	(Pawlek, 2014a; Pawlek, 2014b); own estimations	Estimates are based on the average ratio between casthouse capacity and smelting capacity (1.36) derived from the actual values for the remaining smelters.
Start-up year	Yes	(Pawlek, 2014a; Pawlek, 2014b)	
Year (of inventory)	Yes	All listed sources	The year of inventory differs for some variables and sources.
Last modernisation year	Yes	(Pawlek, 2014a; Pawlek, 2014b)	
Plant status	Yes	(Pawlek, 2014a; Pawlek, 2014b); company reports; news	
Annual production	Yes	(Pawlek, 2014a; Pawlek, 2014b); company reports; USGS; own estimations	The last available yearly production is listed. Estimates made using nominal production capacity and assuming 80 % capacity factor.
Capacity factor	Mostly* — yes	Own estimations	All values are own estimations derived as annual production/ prod. Capacity; assuming average 80 % when annual production was not available.
Input coal	Mostly — no	(Pawlek, 2014a; Pawlek, 2014b; EAA, 2008; EAA, 2013); own estimations	These variables refer to the alumina plants; primary smelters — casthouses and anode plants; and secondary aluminium plants. Average industry values for the anode plants, primary smelter casthouses and secondary aluminium producers are based on EAA. Own estimations are made using E-PRTR emission data, annual production and fuel conversion factors based on IPCC.
Input heavy oil			
Input diesel oil			
Input natural gas			

Variable	Plant-specific data	Data source(s) used	Remarks
Input electricity	No	(EAA, 2008; EAA, 2013)	This variable refers to the consumption of electricity for the non-electrolysis processes in the primary smelters (anode baking and casting) and the rest of the plants. Average industry values are based on EAA.
Input electricity (electrolysis)	Yes	(Pawlek, 2014a; Pawlek, 2014b); company information	This variable applies only to the electrolysis process in the primary smelters. The value for the Alcoa Fjardaal smelter is based on the average consumption reported by the company for all its smelters in Europe.
Current efficiency	Yes	(Pawlek, 2014a, Pawlek, 2014b); own estimations	The value for the Alcoa Fjardaal smelter is derived from the actual values for the remaining smelters.
Gross & Net anode consumption	Mostly — yes	(Pawlek, 2014a; Pawlek, 2014b, EAA, 2013)	Gaps are filled with average industry values from EAA.
Output CO <sub>2</sub> emissions per tonne produced	Yes (except for secondary aluminium plants)	Own estimations; (EAA, 2008; EAA, 2013)	There are separate estimates for the CO <sub>2</sub> emissions from thermal energy and electricity consumption. Estimates for the alumina refineries are made using the specific energy consumption and IPCC fuel conversion factors. For the primary smelters, CO <sub>2</sub> emissions from the different processes (electrolysis, anode production, and casting) are estimated and added. For the secondary aluminium plants, average total output values from EAA are taken.
Output PFC emissions per tonne produced	Mostly — yes	Own estimations; (EAA, 2013)	Estimates for the primary smelters are made using E-PRTR total emissions and annual production. Where actual emissions were missing, average values from EAA are used.
Total CO <sub>2</sub> emissions	Yes	(EEA, 2014); own estimations; (IPCC, 2006)	This variable is used for comparison with the estimated emissions per tonne produced. Data gaps for the alumina plants are filled using the specific energy consumption, IPCC fuel conversion factors and annual production. For the primary smelters data gaps are filled based on own estimates of emissions per tonne and total production.
Total PFC emissions	Yes	(EEA, 2014); own estimations; (EAA, 2013)	This variable is used for comparison with the estimated emissions per tonne produced. Data gaps are filled using average emissions per tonne based on EAA and annual production.
Capital and O&M costs EUR/t	No	Own estimations based on (JRC, 2007; CEPS, 2013)	Average industry values derived from the literature. For a detailed description of the assumptions refer to sub-section 3.3 above.
BATs installed	Yes (except for secondary aluminium plants)	Own estimations	For a detailed description of the approach refer to chapter 6.

\*) Mostly — applies for more than 50 % of the entries

### 3.3 Approach regarding secondary melters

In the secondary aluminium industry we can distinguish new scrap, which consists of almost pure aluminium arising during the production and fabrication of aluminium products and old scrap; the latter is recovered after an aluminium product or component has been discarded. New and old scrap is remelted and casted into semi-finished casting products. The old scrap needs a preparation step (for instance to remove coatings like paint) before it can be remelted. Furthermore, the molten aluminium might also need refinement and the addition of alloying elements. All these steps (scrap preparation, melting, refining, alloying and casting) consume energy, mostly in the form of heat generated in a furnace. However, the whole process of remelting the aluminium metal into a new ingot only requires a fraction of the energy needed for the primary aluminium production from its ore.

There are hundreds of aluminium remelting/recycling facilities in Europe and the industry is highly fragmented and complex. Therefore, instead of collecting data on specific energy use for each of these facilities, we have opted to use average data for the whole sector to calculate GHG emissions and assess their potential energy savings.

The thermal energy needed to melt the scrap for large smelters, and then refine, alloy and cast, is 4.3 GJ/t Al (EAA, 2013). The theoretical amount of energy needed to heat up and melt pure aluminium from 20°C up to 720°C is 1.14 GJ/t. Scrap preparation requires approximately 1.4 GJ/t, mostly to burn off organic coatings. More than 86 % of the fuel used is natural gas, while use of heating oils is 3.3 %. The remaining part (10 %) is electrically heated. To summarise, the energy requirements per tonne of secondary aluminium production are:

Scrap preparation	1.4 GJ/t (only for old scrap)
Heating and melting	2.8 GJ/t (40 % efficiency assumed)
Refining, alloying, casting	1.2 GJ/t

There are three technologies that can be considered BAT for the secondary aluminium industry. These BATs can bring about certain increases in energy efficiencies (and GHGs emission reduction). However, based on the total energy requirements outlined before, we do not expect that the implementation of any of these BATs will bring a GHG emission reduction comparable to what can be achieved in the primary aluminium industry, including alumina production. Moreover, the recognition that the differences in energy efficiencies of remelting/recycling plants can be considered small leads us to model the secondary aluminium industry by defining hypothetical, 'average', plants.

#### *Hypothetical average plants*

The hypothetical plants are defined so as to cover the diversity of two of the most relevant parameters regarding energy consumption; that is, the plant size and the type of plant (remelter/refiner).

We therefore define four plants:

- A large (>75 000 t) remelter (new scrap);
- A small (<75 000 t) remelter;
- A large refiner (>75 000 t) recycling old scrap;
- A small refiner(<75 000 t).

The table below shows the share of remelting and refining in total secondary production and the CO<sub>2</sub> emissions associated with these activities.

Table 3-2 Production share and emissions remelting and refining

Activity	Production share EU-27	Direct emissions (kg CO <sub>2</sub> /t)
Secondary remelting	62 %	150-350
Secondary refining	38 %	250-390

Source: (Ecofys, 2009).

The information in this table is provided for EU-27. Based on the small secondary aluminium sector in Croatia and Iceland, we assume that the effect of these two countries on the above figures is negligible.

The difference in energy terms between remelting and refining is less important than the difference in GHG emissions due to the additional energy (around 15 %) provided by contaminants, mainly plastics, which contribute to the CO<sub>2</sub> emissions (Ecofys, 2009).

Secondary aluminium melters typically use gas-fired furnaces, and range in capacity from a couple of thousand tonnes up to 400 000 tonnes for the largest facilities. The furnaces have thermal efficiencies ranging from approximately 20 to 45 %, using between 0.87 and 1.96 kWh/kg of aluminium (Green, 2007). Implementation of BAT measures can reduce fuel usage to less than 0.57 kWh/kg (Green, 2007). Some large commercial gas-fired furnaces report efficiencies as high as 56 %, or 0.30 kWh/kg (Green, 2007). Based on this data, we assume that the larger facilities (>75 000 t) are 30 % more efficient than the smaller facilities (<75 000 t).

#### **Implementation of BAT**

Based on an initial feedback from EAA, we assume that only a small percentage of the secondary aluminium plants have the BATs installed (5 %).

## 4 Analysis of the availability and remaining potential of scrap and bauxite

This chapter discusses recycling rates of scrap (section 4.1) and the availability of bauxite (section 4.2).

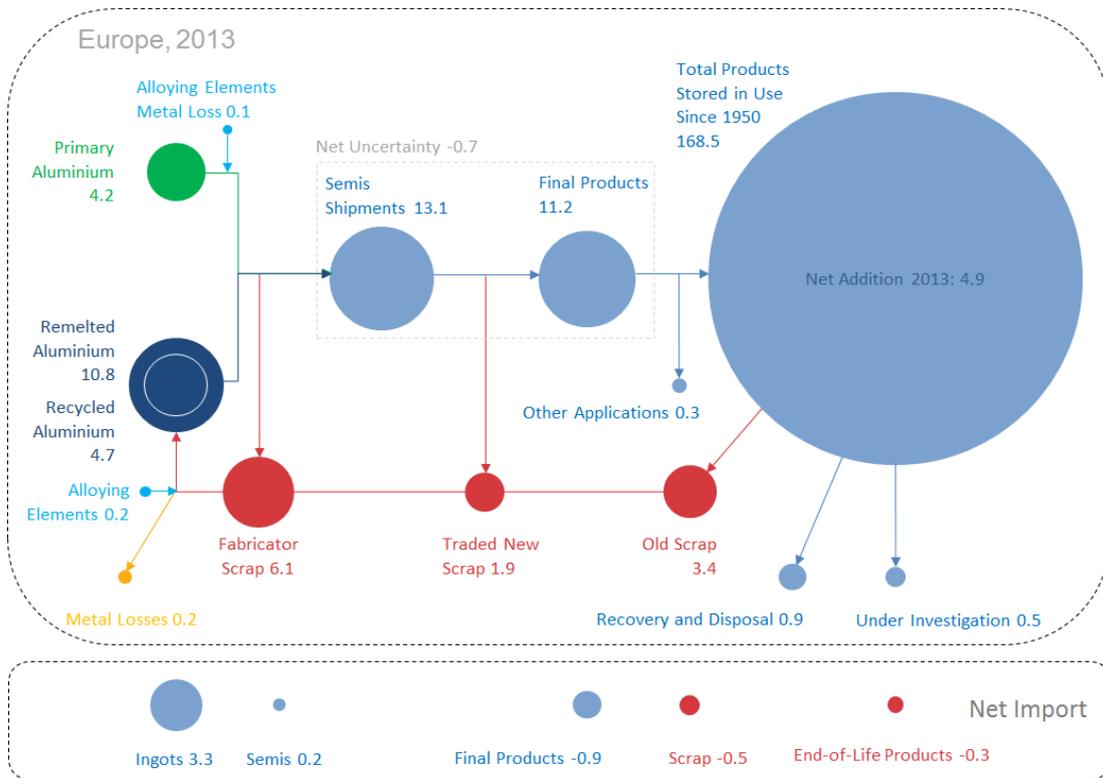
### 4.1 *Current and future recycling rates of scrap*

In recent years, the mounting competition over raw materials and high energy costs have been driving increased use of secondary materials (scrap) in the European aluminium sector. However, secondary materials are not available in sufficiently high quantities or are not of sufficient quality. Therefore, primary materials are likely to remain a key source for the use of aluminium.

Worldwide, recycled aluminium in 2013 is estimated to account for around one third of all aluminium production, while in Europe, recycled aluminium represented more than half of all aluminium production, indicating that recycling is proportionally a little more important source of aluminium in Europe than globally. Figure 4-1 represents the flow of primary and recycled aluminium in Europe in 2013 (In this figure, Europe encompasses the EU, Albania, Belarus, Bosnia-Herzegovina, Iceland, Macedonia, Moldavia, Norway, Serbia-Montenegro, Turkey and Ukraine); it shows domestic production and net imports. Both domestically produced and imported ingots serve as input for fabricated and finished products, while a small part of the finished product is later exported. The majority of finished aluminium products enter the use cycle and add to total products; around 75 % of the aluminium ever produced is still in use (Hydro, 2012), and a small part of total finished products becomes scrap. In 2013, the net addition to all aluminium products stored since 1950 was 4.9 million tonnes.

Recycling plays an important role in the EU, with over 270 recycling plants and sufficient technology and sources of scrap to be economically competitive. Levels of recycling of over 70 % are found for aluminium in transport, building and drinks cans. It should be noted that metal scrap does not necessarily have to be recycled in the EU, indeed it was estimated that in 2006 over 350 000 tonnes were exported to China and India for recycling. This is one of the biggest problems the EU aluminium sector is facing (EC, 2011b), since recycling of scrap is crucial to maintain the competitiveness of the EU non-ferrous metals industry. In 2000, the EU was a small net importer, while in 2013 the net balance was around 610 000 tonnes of aluminium scrap import (JRC, 2014).

Figure 4-1 Aluminium material flows in Europe in 2013, source: (IAI, 2015)



Aluminium recycling rates are good in many parts of Europe — although there is still both scope and a pressing need to improve that rate because of increasing demand (Foeurope, 2014). An analysis by the industry forecasts that aluminium recycling will continue to increase in the EU (ECORYS, 2012), about 1 % per year, up to 2050 (Fraunhofer ISI, 2009). Existing potential is mainly in eastern and southern Europe, where recycling rates are still lower than in western Europe. Yet, although recycling rates are expected to increase, this does not automatically mean that secondary aluminium production will increase to the same extent. Aluminium scrap is a valuable resource, and competition for this material is increasing, pushing up secondary material prices. China is an important and growing net importer of scrap, taking considerable amounts out of the US and European scrap markets (NTNU, 2004). Low Chinese labour costs make scrap separation more economic. The increased competition is leading to a restructuring of the recycling industry, from small facilities to fewer and larger units, thereby increasing energy efficiency.

#### 4.2 Current availability of bauxite and projected reserves

EU bauxite production (aluminium ore) is very limited, around 1.5 % of the global total (BGS, 2011), of which 60 % is produced by Greece (ECORYS, 2012). These production levels are much lower than the EU consumption and illustrate that the EU is greatly dependent on imports of bauxite. Aluminium, however, is the 3rd most common element in the Earth’s crust and the most common metal. The primary mining areas for aluminium

ore (bauxite) are Australia, Brazil, China, India, Guinea, Indonesia, Jamaica, Russia and Surinam. Deposits are also found in Greece and Turkey. Therefore, bauxite availability is not expected to become a bottleneck in aluminium production.

## 5 Best available technologies (BATs)

Best Available Technologies (BATs) are different technologies that can be applied in different manufacturing processes to improve the performance of the industry. In many cases, the application and specific savings and costs will depend not only on the technical lay-out of the facility but also, on geographical factors (e.g. access to a natural gas network).

### 5.1 Overview of BATs

Table 5-1 contains a brief summary of the most relevant BATs in primary aluminium production, including the Bayer and Hall-Héroult processes, anode baking and on-site power production.

Table 5-1 Best Available Technologies (BATs) considered

Process	Best Available Technology (BAT)
Bayer	Natural gas used as fuel Calcination with fluidised bed kilns Co-generation
Hall-Héroult	Use of pre-baked anodes Direct casting with aluminium transferred hot to the alloying furnace Optimisation of the electrolysis process <ul style="list-style-type: none"> <li>• Point feeding system with computer control</li> <li>• Magnetic compensation</li> <li>• Carbon anode design</li> <li>• Improvement of hooding and ventilation</li> </ul>
Anode Baking	Natural gas use as fuel Recuperative or regenerative burners
On-site Power Production	On-site renewables — Hydropower, geothermal and biomass
Secondary Smelting	New de-coating equipment Recuperative or regenerative burners

These BATs are selected based on an extensive literature research. One of the main references used for this study is the JRC BREF document for Non-Ferrous Metal Industries (Draft 3, February 2013). The information in the BREF has been complemented with a wide range of sources from academics, consultants and the industry.

## **5.2 Bayer process**

Alumina production through the Bayer process requires energy mainly for digestion and calcination. The energy consumption depends on the type of fuel, the origin and chemical composition of the bauxite, the type of digesters and the type of calciners.

### **Natural gas use as a fuel**

Natural gas as a fuel has the lowest specific emissions of all types of fossil fuels used in alumina refineries. The change from oil-fired boilers to gas-powered steam generators can reduce carbon emissions by 5 %. The investment cost needed to implement this fuel switch in the Rusal Aughinish alumina refinery amounted to around EUR 15 million (Rusal, 2014), or EUR 7.5 /t.

### **Fluidised bed calcination**

Circulating fluid bed (CFB) calciners have much higher energy efficiency than rotary kilns, since the heat recovery from the alumina and the flue-gas is greater. In the Bayer process, the calcination of gibbsite or hydrate to alumina is one of the most energy-consuming steps. Approximately 30 % of the thermal energy input is used for the calcination process (Klett, 2011). CFB technology was introduced in 1961 as an alternative to rotary kilns. Since then, CFB calciners have been constantly improved and improvements have reduced consumption even further. Improving alumina refining by replacing rotary kilns with fluid bed kilns would cut energy demand at this stage by 60 % (Gale, 2001, HWWI, 2005), corresponding to 15 % savings in the total Bayer process (Paspaliaris, 2000).

Circulating fluid bed calciners are applicable only to smelter grade alumina. They are not applicable to speciality/nonsmelter grade alumina, as these require a higher level of calcination that can only be achieved with a rotary kiln (BREF, 2014). Investment costs for fluidised bed kilns are around EUR 20 /t Al (Dijkmans, 2012).

### **Tube digesters**

A significant reduction of energy demand can be achieved by using tube digesters, which are able to operate at higher temperatures using a molten salt heat transfer medium. The tube digesters enable plants to operate with an energy consumption of less than 10 GJ per tonne (BREF, 2014).

However, tube digesters may not be compatible with the layout of most existing plants. A tube digester is an example of a single stream digestion design. Plants with a double-stream digestion design using steam injection cannot be converted to single stream digestion design without a total redesign and rebuilding of the plant; in many cases the main constraint is the land available. Tube digestion is therefore virtually impossible to consider for existing plants for both cost and space reasons. Moreover, the installation of tube digesters in some plants has caused a scale problem, and consumption takes up a

large proportion of the savings. Only one plant in the EU (Germany) has tube digesters installed (Pawlek, 2014b). In fact, the German plant is one out of two plants worldwide that use this technique (BREF, 2014).

The specific energy consumption can be reduced to below 7.0 GJ/t when using tube digesters. For other plants with traditional digestion, technology-specific energy consumption can be reduced to below 10 GJ/t (BREF, 2014).

Since this technology is unfeasible for other existing plants, it is included in the model only to account for the low energy consumption of the German alumina refinery, without allowing its use to retrofit any other facility.

### Optimisation of the refining process

The refining process can be further optimised in terms of energy consumption by implementing plant-specific measures. There are many factors, such as the technical configuration of the plant or the quality of alumina they produce, that limit the applicability measures such as:

- Plate heat exchangers
- Selection of bauxite

#### Plate heat exchangers

Plate heat exchangers recover heat from the liquor flowing to precipitation. The potential heat recovery is higher than other techniques such as flash cooling plants. However, this technology is only appropriate for cases where the energy from the cooling fluid can be reused in the process, that is, when the condensate balance and the liquor conditions allow it (BREF, 2014).

The costs and applicability of these measures are dependent on the configuration of each plant. The lack of common technical and economic values for these measures leads us to exclude them from the model.

#### Selection of the bauxite

The quality of the bauxite ore has an influence on the energy consumption. Bauxite with higher moisture content carries more water into the process, which then needs to be evaporated. In addition, bauxites with high mono-hydrate content (boehmite and/or diaspore) require higher pressure and temperature in the digestion process, leading to higher energy consumption. However, since some plants are specifically designed for a certain quality of bauxite, and we cannot assess the costs to adapt each particular refinery configuration to treat different bauxite ores, we exclude this measure from the model.

## Cogeneration

Cogeneration or combined heat and power (CHP) could save 15 % of the primary fuel consumption of the plant (JRC, 2007), and can in fact be considered as a must-have in order to compete in the world alumina market (JRC, 2007).

Cogeneration, where fuel is combusted to generate both electricity and useful heat simultaneously, is increasingly being employed in refineries. While a significant capital investment is required to build a CHP plant, there can be significant benefits, both in terms of energy efficiency and as a valuable resource for local communities. In an alumina refinery, cogeneration uses waste heat to produce steam for the refining process; at the same time, power production provides all the electricity needed for the refining process and supporting systems (such as lighting, offices etc.). The CHP plant is sometimes designed to produce surplus electricity for export to local communities, a local customer or to the grid. In some cases, excess or lower quality steam can also be exported.

In a combined site with both an alumina and aluminium plant, the heat produced can be used in the Bayer process and the electricity for the electrolysis process.

The investment costs for a CHP plant are calculated to be around EUR 242 /t Al (own estimations using IEA ETSAP, 2010; Pawlek, 2014b).

### 5.3 *Hall-Héroult process*

#### Use of pre-baked anodes

According to (Berkeley Lab, 2008), the best practice is to use pre-baked carbon anodes. There is a trend to move from Söderberg technologies (Vertical Stud Söderberg (VSS), Horizontal Stud Söderberg (HSS)) to pre-baked anodes (Point Feeder Pre-Bake (PFPB), Centre Worked Pre-Bake (CWPB), Side Worked Pre-Bake (SWPB)) (Ecofys, 2009b). In fact, the use of pre-bake technology has increased from about 63 % in 1990 to about 90 % in 2010 (IEA ETSAP, 2012).

The use of Point Feeder Pre-Bake (PFPB) cells with automatic multiple feeding points is considered to be BAT for primary aluminium production (Finlay, 2004; Berkeley Lab, 2008; BREF, 2014; HWWI, 2005.)

Conversion to the state-of-the-art PFPB technology is the most accepted route for increasing operational and environmental efficiency for both CWPB and SWPB. Even for Söderberg cells, this conversion is one of the most feasible retrofitting options, although with a relatively high cost. The reduction in electricity consumption can reach from 10 to 30 %, depending on the starting technology and cell design. Modern PFPB smelters (in greenfield or optimised brownfield scenario<sup>(2)</sup>) can operate at 12.8 — 13.0 kWh/kg (Dijkmans, 2014)).

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<sup>(2)</sup> In many disciplines a greenfield is a project that lacks any constraints imposed by prior work. The analogy is to that of construction on greenfield land where there is no need to work within the constraints of existing buildings or infrastructure.

Besides the high potential of electricity saving, the electrolysis process has a great potential to reduce the emission of perfluorocarbons (PFCs). Two PFCs, (CF<sub>4</sub> and C<sub>2</sub>F<sub>6</sub>) contribute about 20 % of primary aluminium CO<sub>2eq</sub> emissions (Dijkmans, 2014). Emissions of PFCs are strictly the result of electrolytic reduction. They are formed only during the so-called anode effect, when the electrolyte becomes depleted in alumina (Harhish, 1998). As this ‘anode effect’ reduces productivity, manufacturers have been trying to reduce it. Table 5-2 shows specific PFC (CF<sub>4</sub> and C<sub>2</sub>F<sub>6</sub>) emissions of each primary aluminium smelter technology. A shift from old smelter technologies to new ones improves energy efficiency while reducing PFC emissions.

Table 5-2 Specific PFC emissions of each primary aluminium smelter technology

Technology	PFC intensity (t CO <sub>2eq</sub> /t Al)
CWPB	0.20
PFPB	0.27
SWPB	3.65
VSS	1.22
HSS	2.46
ALL	0.55

Source: (IAI, 2014)

PFPB allow better control of the process and is the most commonly used technology. Indeed, there are no more CWPB or SWPB plants in operation in Europe now. The PFPB system is the most efficient in terms of energy consumption and low in PFC emissions (CSE India, 2014). The current best-practice designs use 90-360 kA currents (current densities of 0.8-0.85 A/cm<sup>2</sup>), and consume 410-450 kg anode/t aluminium (BREF, 2014).

The current best practice of Hall–Héroult electrolysis cells (using currents of 300-400 kA) consumes about 12.9-13 MWh/t aluminium (World Bank, 2014).

#### **Direct casting with aluminium transferred heat to the alloying furnace.**

Best-practice electricity use is estimated to be 0.35 GJ/t aluminium ingot (Berkeley Lab, 2008).

The investment costs for a 250 000 tonne cast house are around EUR 180 million, O&M costs for the same plant are around EUR 17.4 million (Dijkmans, 2012).

Table 5-3 Indication of investment costs for a 250 000 tonne cast house

<b>Installation</b>	<b>Investment costs (million EUR)</b>
2 ovens with feeding lanes and saws	50
4 integrated holding/preparation/casting ovens + gullies	60
4 metal cleaning installations and auxiliary	16
4 casting pits	30
Casting material to allow for simultaneous operations of 4 pits	24
Total	180
<b>Total (EUR/t)</b>	<b>720</b>

Table 5-4 Operational costs for a 250 000 tonne cast house.

<b>Operation</b>	<b>Annual costs (million EUR)</b>
20 extra operators and staff	1.2
Resources: alloys and cleaning salt	8
Energy use	3
Water use	1
Analysis costs incl. computer support staff	1
Maintenance costs	3
Total	17.2
<b>Total (EUR/t)</b>	<b>68.8</b>

This equals EUR 720 /t Al and EUR 68.8 /t Al respectively.

It is assumed that this BAT is already implemented in all cast houses in the EU (Dijkmans, 2014).

### Optimisation of the electrolysis process

Optimisation of the electrolysis process includes a range of hardware and software upgrades that can be installed on a smelter. The most notable upgrades include:

- Design upgrades to the smelter, e.g.:
  - Point feeding system with computer control
  - Magnetic compensation
  - Carbon anode design
  - Improvement of hooding and ventilation

The exact nature of the upgrades differs by potline. Design of anodes and busbars for magnetic compensation, for example, has to be tailored to the potline technology. These upgrades are typically implemented to some extent, and they are almost always possible. The implications of this for modelling this BAT are discussed in chapter 6.

The total costs of optimisation can increase to around EUR 650 /t capacity, with modest operational costs of around EUR 1.8 /t capacity (Alsema, 2000, JRC, 2007, Dijkmans, 2012, Norsk Hydro, 2006).

The main design upgrades that can be installed on a smelter are discussed below, with associated costs and energy savings.

- Point-feeding system with computer control (JRC, 2007)

Aluminium smelters use continuous point-feeding and sophisticated control systems of the electrolysis process to limit anode effects. The control system aims to keep voltage in the pot under the best conditions. Aluminium smelting energy efficiency depends on the quality of control of the cells, and on the decisions made by their human operators. The major advantage of continuous computer-controlled point-feeding is that it reduces the occurrence of the anode effect and thereby the emission of perfluorocarbons (PFCs) from the pots. A secondary effect is the reduction of electricity consumption by 0.2-0.4 kWh/kg.

The projected cost is EUR 200 per tonne of production capacity (Alsema, 2000).

Apparently, all smelters in the EU-28+ have computer-controlled point feeding installed to some extent (Pawlek, 2014a), though not always corresponding to the latest technology. Therefore, we assume that the personnel is already in place and no additional operational costs are associated with this BAT.

- Magnetic compensation

An improved busbar design can compensate for magnetic fields that destabilise the alumina reduction process and increase electricity consumption. The electric current traversing the various conducting elements – anode, electrolyte, liquid metal, cathode and connecting conductors – creates large magnetic fields. These fields, together with the electrical current in the liquid electrolyte and metal, form the basis for the Magneto Hydro Dynamic (MHD) behaviour in the electrolyte and in the liquid metal contained in the crucible. The so-called Laplace forces, created by the electric current and the magnetic field, are responsible for the motion of the electrolyte and the liquid metal. For the efficiency of the process, it is essential that the flow created is stationary (Norsk Hydro, 2006).

The design of the selection of busbar lengths and cross-sectional areas will balance the magnetic fields, thereby allowing the optimising of the cell performance and the electricity consumption.

The investment costs are around EUR 200 /t Al (Dijkmans, 2012). No additional operational costs are expected.

- Carbon anode design

Improved carbon anode design allows the potline to operate at higher amperages (current strengths). This improves smelter capacity and usually also energy efficiency. The main measures are fixing larger anodes on the rods with a canal between the blocks and saw cuts in the blocks to allow the flue gases to escape, thereby lowering electrical resistance. Tables 5-5 and 5.6 summarise the costs associated with these options. The first option does not have any extra operational cost, and both of them together would mean a Capex of EUR 96/t and an Opex of EUR 1.8/t

Table 5-5 Increase in number and diameter of the rods holding the anode

Installation	Investment costs (million EUR)
New rods	12.25
New molds for the anodes	0.25
Upgrading rodding shop	7.5
Total	20
<b>Total (EUR/t Al)</b>	<b>80 EUR/t</b>

Table 5-6 Making slots in the anode to allow the flue gas to escape

Installation/operation	Costs
Automatic sawing machine	Investment EUR 4 million, <b>16 EUR/t</b>
annual operational cost	Personnel EUR 0.6 /t saw blades EUR 0.2 /t maintenance EUR 1 /t
<b>Total operational cost (EUR/t Al)</b>	<b>EUR 1.8 /t</b>

- Improved hooding ventilation and suction

Improved hooding, ventilation and suction installations are beneficial for heat balance and energy use. Investment costs would amount to approximately EUR 120 /t Al (Dijkmans, 2012), without additional operational costs.

### Reducing productivity

In plants where this is implemented, the energy consumption is reduced by about 0.3 MWh/t (Alsema, 2000). Productivity loss is estimated as some 10 % (Dijkmans, 2012). If we assume an aluminium price of EUR 1500 /t, the financial losses would be around EUR 150 /t (Dijkmans, 2012).

## 5.4 Anode baking

### Natural gas use as fuel

When natural gas is used as fuel replacing fuel oil, there is a decrease of CO<sub>2</sub> and SO<sub>2</sub> emissions. However, the application of this Best Available Technology relies on the availability of natural gas at each site.

The estimated investment costs are about EUR 13 million for a 250 000 tonne smelter, (Dijkmans, 2012). This equals EUR 52 /t Al.

Table 5-7 Anode baking BATs

Installation	Investment costs (million EUR)
New gas combustion system for 2 ovens, incl. regulation and computer systems	5
Gas transport and distribution infrastructure for 2 ovens (200 m pipeline internal, 1000 m external)	8
Total	13
<b>Total (EUR /t Al)</b>	<b>52</b>

### Recuperative or regenerative burners <sup>(3)</sup>

In anode production, the application of enhanced furnace designs, with recuperative or regenerative burners, may produce fuel savings of 30-50 % with an investment cost of EUR 4-10 /GJ and an operation and maintenance costs of EUR 0.2 /GJ (Worrell, 1997; Alsema, 2000).

## 5.5 On-site Power Production

The two existing on-site conventional power plants are both state-of-the-art CHP plants, constructed in 2006 and 2008 respectively. In this study we rule out analysis of the potential savings that new on-site power production could offer.

### On-site renewables — Hydropower, geothermal and biomass

Constructing on-site renewable energy capacity for power supply can be considered as a BAT from a GHG emission perspective. Hydropower, geothermal and biomass are considered in this study. Hydropower and geothermal are preferred from a cost perspective. However, these resources are not available everywhere. Biomass is the only alternative that can theoretically provide a stable supply of renewable energy everywhere.

<sup>(3)</sup> Some experts contest the applicability of these techniques in this process

Table 5-8 CAPEX and OPEX on-site renewables

	Capital costs EUR /t	Fixed O&M EUR /t	Variable O&M (incl. fuel) EUR /t	Total O&M
Hydropower	727.5	41.4	64.7	106.1
Biomass	478.9	146.5	399.1	545.6
Geothermal	345.6	123.3	0.0	123.3

Source: Own estimations based on (US EIA, 2013)

## 5.6 Secondary melters

### New de-coating equipment

In secondary aluminium production, new de-coating equipment has been demonstrated. This new equipment employs an indirectly fired kiln and uses the heating energy of released volatile organic compounds to pre-heat the scrap to 480°C before it goes into the melting furnace (Insertec, 2014; Alsema, 2000). This technology is applicable to the secondary aluminium industry that processes both scrap from the manufacturing process and used aluminium (US DOE, 1999). This kind of technology can save 50 % on fuel costs for scrap pre-treatment (=0.5\*725 MJ/t, EAA, 2008). The investment cost is estimated at EUR 40 per tonne of aluminium and the extra revenues from increased productivity are also about EUR 40 /t (Alsema, 2000).

### Recuperative or regenerative burners <sup>(4)</sup>

In the same way as in anode baking, in secondary smelters, the application of enhanced furnace designs, with recuperative or regenerative burners, can save up to 30-50 % of energy use at investment costs of EUR 4-10 /GJ and O&M costs of EUR 0.2 /GJ (Worrell, 1997, Alsema, 2000).

## 5.7 Combined, Bayer & Hall-Hérout

### Heat recovery

Approximately 22 GJ/t Al can be saved when retrieving the heat content of the off-gases (assuming 75 % efficiency in the heat exchanger) of the Hall-Hérout process, and then using it in the Bayer process to substitute fossil fuel consumption (Balomenos, 2009). This would also mitigate CO<sub>2</sub> emissions by 1.5 kg CO<sub>2</sub>/kg Al (Balomenos, 2009). However, the estimated savings potential can be considered very optimistic in practical terms. The EAA's evaluation of the accessible heat is closer to 3-5 GJ/t, maybe even 8 GJ/t in the long term, considering that the heat generated on the top part of the pot is partly lost to ambient and that issues with the dew point of the acid prevent cooling the gases at a too low temperature.

This BAT is only applicable when the smelter and refinery are both located on the same site. A more widely applicable use of waste heat would be to use it in the local

<sup>(4)</sup> Some experts challenge the applicability of these techniques in this process

environment (e.g. district heating, desalination). There is no major technological or scientific hurdle to recovering heat and valorising it. However, there can be some other practical barriers affecting the cost-effectiveness of the measure. All in all, the analysis of the cost-effectiveness of a wider application of waste heat is excluded from the model.

## **6 Estimation of the degree of implementation of the BATs**

The question about whether some BATs are present in some aluminium plants requires a more elaborate response than a simple and straightforward ‘yes’ or ‘no’. Several BATs, like computer-controlled point feeding, can be installed partially, or their operation can depend on the degree of optimisation of the computer control. Such detailed data are not available at a plant level. Therefore, in this section we describe the methodology devised to estimate the degree of implementation of individual BATs by way of what we will call the ‘distance-to-target’ approach.

### **6.1 Methodology for estimating implementation of BAT based on ‘distance-to-target’ SEC**

As mentioned above, there are some BATs such as ‘Point feeding with computer control’ and ‘Optimisation of the electrolysis process’ that include several measures and technologies under one BAT. Therefore, a certain BAT may be only partially implemented at a certain plant (e.g. one or two out of a total of four sub-measures). Furthermore, some technologies, such as ‘Computer control of the electrolysis process’ are continuously improved and can come in multiple generations, with each subsequent generation performing slightly better than the previous one. The assessment of the exact degree of implementation for a certain plant requires very detailed knowledge of the exact technical status of the individual plants. In several cases this information is not directly available.

Almost all of these BATs have in common that they have a direct influence on energy efficiency. An indicator of energy efficiency for alumina plants is the total thermal energy consumed per unit of produced alumina. Whereas for electrolysis, the indicators can be the specific energy consumption (SEC, in kWh of electricity per tonne of aluminium) and the current efficiency (CE, in %), which is defined as the ratio between the actual and theoretical production given a certain electrolysis current.

For all plants in the database, we estimate the efficiency indicators, such as the SEC and CE, with a reasonable degree of accuracy. Knowing the particular technologies already in place, we can apply expert judgement to estimate the representative maximum achievable values for SEC. The difference between the actual and achievable SEC can be regarded as a measure of the potential for improvement. This ‘distance-to-target’ is subsequently linked to a certain degree of implementation of those BATs for which no

direct and complete information regarding the implementation degree is available. To do this, the range of the observed distances-to-target is divided into 4 distinct classes, whereas the BATs are divided into a similar number of classes representing a certain implementation stage. Each class or phase will effectively be treated as a different BAT measure in the model. Each implementation stage has different associated costs, which are presented in the BAT and IT chapter of this report.

## 6.2 Assessing distance-to-target

We define distance-to-target as the degree to which the smelter energy efficiency approaches the maximum achievable efficiency, given the limitations of their potline technology.

The first step in assessing distance-to-target of the smelters is to approach the maximum achievable efficiency for each smelter as accurately as possible. Where possible, this is done by using actual data. There is a limited number of companies that provide the basic technology for the potlines. We take advantage of the fact that many smelters around the world have similar technology installed. However, not all of them have been modernised. The most modern plant of each type worldwide is considered BAT, and their efficiency is then the target efficiency for the corresponding smelter types in the EU-28+. For the potline technologies where this data is not available, the maximum achievable efficiency is estimated based on knowledge of the technical configuration. Important indicators include the current strength (in kA) and current efficiency (<sup>5</sup>).

An example of actual data (worldwide) for AP30 technology is provided in the table below:

Table 6-1 AP30 technology results in potlines worldwide (1988-2012)

Periods	Mean Results		Most productive AP30		Most energy efficient AP30	
	2011	2012 11 months	2011	2012 11 months	2011	2012 11 months
<b>Number of potlines</b>	17	17	1	1	1	1
<b>Number of pots</b>	4 554	4 554	360	336	330	330
<b>Production (kt)</b>	4 453	3 737	373	315	308	285
<b>Current (kA)</b>	358	362	375	372	368	376
<b>CE (%)</b>	94.0	93.1	94.2	93.6	92.9	90.5
<b>kWh/t</b>	13 385	13 463	13 798	13 334	<b>12 683</b>	<b>12 839</b>
<b>AE per pot per day</b>	0.22	0.24	0.14	0.12	0.18	0.18

Source: AP Technology™ newsletter Issue 17, March 2013

Table 6-2 gives the maximum attainable efficiencies in the fourth column. These efficiencies are estimates, using the technical configuration of the potlines. The

<sup>5</sup>) Current efficiency is defined as the ratio between the actual production and the theoretical production given a certain electrolysis current

comparison of the maximum achievable and actual efficiencies from (Pawlek, 2014a) leads to the distances-to-target in the right-hand column of table 6-2.

Table 6-2 Maximum attainable efficiencies and distance-to-target (energy efficiency) per plant

Company	City	Technology	Max brownfield efficiency (MWh/t)	Distance-to-target (%)
Aluminium Dunkerque S.A.	Graveline-sur-Loon-Plage	AP30	12.8	95 %
Trimet Aluminium AG	St.-Jean-de-Maurienne	AP18 AP30	13.2	99 %
Hydro Aluminium Deutschland GmbH	Neuss	VAW CA-165	13.2	93 %
Trimet Aluminium AG	Essen	Alusuisse EPT-14	13.5	92 %
Trimet Aluminium AG	Hamburg	Reynolds P19	13.8	98 %
Voerdal GmbH	Voerde	Kaiser P69	13.6	91 %
Aluminium de Grece S.A. (ADG)	St. Nicolas (Distomon)	AP07 AP09	13.2	100 %
Atlantic Aluminium Co.	Keilisnes	-	13.2	100 %
Alcoa Fjarðaal	Reydarfjordur	AP30	12.8	97 %
Nordic Aluminium Company	Grundartangi	VAW CA-180	13.2	96 %
Nordural Helgúvik	Helgúvik	AP36	12.8	100 %
Rio Tinto Alcan Iceland Co. Ltd.	Straumsvík	Alusuisse EPT-10	13.2	88 %
Vimetco Arlo SA	Slatina	AP09	13.2	99 %
SLOVALCO	Ziar nad Hronom	Hydro HAL-230	13.2	98 %
Talum, d.d. Kidricevo	Kidricevo	AP18	13.2	94 %
Alcoa Inespal SA Aviles	Aviles	PF-VSS	13.8	98 %
Alcoa Inespal SA La Coruna	La Coruna	PF-VSS	13.8	91 %
Alcoa Inespal San Ciprian	San Ciprian	AP-14	13.2	95 %
Rusal Kubikenborg Aluminium AB	Sundsvall	Kaiser P86	13.5	100 %
Alcan Smelting & Power UK	Fort William	AP18	13.2	99 %

### **6.3 Optimisation of the electrolysis process and estimating implementation of BAT**

The optimisation of the electrolysis process includes a range of hardware and software upgrades that can be installed on a smelter. The most notable upgrades include:

- Computer control of the process
- Design upgrades to the smelter, e.g.:
  - o Magnetic compensation
  - o Anode design
  - o Improvement of hooding and ventilation

As mentioned before, these upgrades are already implemented to a certain extent. We split up the implementation of optimisation into 4 phases. The corresponding phase of each plant derives from the plant's distance-to-target, calculated in section 6-2.

The total cost of 'optimisation of the electrolysis process' is around EUR 750 /t (further explanation and references for this cost breakdown can be found in Chapter 5 on BATs and ITs). Since the marginal costs of subsequent energy efficiency gains tend to increase, the costs of each phase of implementation are distributed as follows:

Table 6-3 Cost distribution 'optimisation of the electrolysis process'

<b>Phase</b>	<b>Cost (EUR/t capacity)</b>
Phase 1	125
Phase 2	150
Phase 3	175
Phase 4	200
Total	650

Based on the smelter's distance-to-target (D2T) we derive the implementation level provided in Table 6-4:

Table 6-4 Estimated implementation level BAT 'optimisation of the electrolysis process' per smelter

Name	D2T (%)	Phases implemented (Y/N)			
		Phase 1	Phase 2	Phase 3	Phase 4
Rio Tinto Alcan Iceland Co. Ltd.- Alusuisse EPT-10	88.0	N	N	N	N
Alcoa Inespal SA-PF-VSS	91.4	Y	N	N	N
Trimet Aluminium AG-Alusuisse EPT-14	91.8	Y	N	N	N
Hydro Aluminium Deutschland GmbH- VAW CA-165	93.0	Y	N	N	N
Talum, d.d. Kidricevo-AP18	94.3	Y	N	N	N
Aluminium Dunkerque S.A.-AP30	94.8	Y	N	N	N
Alcoa Inespal -AP-14	95.0	Y	N	N	N
Nordic Aluminium Company-VAW CA- 180	96.4	Y	Y	N	N
Alcoa Fjardaal-AP30	97.0	Y	Y	N	N
SLOVALCO-Hydro HAL-230	97.8	Y	Y	Y	N
Alcoa Inespal SA-PF-VSS	97.8	Y	Y	Y	N
Trimet Aluminium AG-Reynolds P19	98.4	Y	Y	Y	N
Alcan Smelting & Power UK-AP18	98.5	Y	Y	Y	N
Rio Tinto Alcan-AP18 AP30	98.6	Y	Y	Y	N
Vimetco Arlo SA-AP09	98.8	Y	Y	Y	N
Aluminium de Grece S.A. (ADG)-AP07 AP09	100.0	Y	Y	Y	Y
Rusal Kubikenborg Aluminium AB-Kaiser P86	100.0	Y	Y	Y	Y
Nordural Helguvik-AP36	100.0	Y	Y	Y	Y

From the average potential for improvement per plant, and the implementation phase of the BATs associated with that potential, we derive that the energy efficiency gain per implementation phase is around 0.26 MWh/t Al.

## 7 Innovative technologies (ITs)

This section provides an overview of several prospective technologies (Innovative Technologies) that will become available in the years or decades to come. The characteristics of these ITs are always based on the smelter. In addition, specific savings and costs will depend not only on the technical layout of the facility, but also on geographical factors (e.g. access to a natural gas network).

### 7.1 Overview of ITs

Table 7-1 is a list of the most relevant Innovative Technologies (ITs) in primary aluminium production and their characteristics, including the Bayer and Hall-Héroult processes, anode baking and on-site power production. This list is mainly based on the latest available version of the (BREF, 2014), other sources (detailed in each section) and the expert judgement by (Dijkmans, 2014).

Table 7-1 Innovative Technologies

Process	Innovative Technology (IT)
Bayer	<ul style="list-style-type: none"> <li>• Red mud treatment</li> <li>• Boehmite instead of gibbsite precipitation</li> </ul>
Hall-Héroult	<ul style="list-style-type: none"> <li>• Wetted drained cathodes</li> <li>• Inert anode (PBANOD)</li> <li>• Lower the electrolysis temperature (PBRTE)</li> <li>• High temperature carbothermic reduction of alumina</li> <li>• Application of a dynamic AC magnetic field</li> <li>• Carbon capture and storage (CCS)</li> </ul>
Anode Baking	Inert anodes (PBANOD) could make this process unnecessary
Secondary melters	No alternate process known (UNEP/POPS, 2008)

### 7.2 Bayer process

#### Red mud treatment

Solid waste production with its costly disposal (red mud) could be replaced by more valuable by-products. A novel Electric Arc Furnace (EAF) technology, called Advanced Mineral Recovery Technology (AMRT), can be used in order to achieve the reductive smelting of red mud without any pre-treatment, producing pig iron and viscous slag suitable for industrial mineral wool production. In this technology, the solid charge is fed into the 'arc zones' of each electrode, where flash smelting takes place. Therefore, the reduction reactions occur in the melt (AMRT, 2014), and as a result, the solid waste of the Bayer Process (red mud), with chemical exergy of 0.49 GJ/t Al, is replaced by pig iron and

mineral wool products, with total chemical exergy 6.32 GJ/t Al (Balomenos, 2009). In total, the new proposed process for complete bauxite exploitation (for alumina, pig iron and mineral wool production) could increase the exergy efficiency from 3 % in the conventional Bayer Process to 9-13 % (UNEP/POPS, 2008). This technology is not included in the model because of the uncertainties associated with its applicability and dependency on local market conditions (EAA, 2014).

### **Boehmite instead of gibbsite precipitation**

At the precipitation step, alumina monohydrate (boehmite) rather than trihydrate (gibbsite) can be precipitated under atmospheric conditions, to be subsequently calcined to produce anhydrous alumina. This technique can be applied to the current Bayer process, as it only requires minor modification in the precipitation phase, all other processes remaining unaltered (Misra, 2005; Kontopoulos, 1997).

The energy savings in the calcination of boehmite are around 34.8 kg of fuel oil per tonne of alumina and 7.2 kWh of electricity per tonne of alumina (Eurothen, 2000). This corresponds to 40-50 % less fuel or electricity consumption compared with gibbsite calcination (Kontopoulos, 1997).

The technique is currently entering the demonstration phase. Therefore, commercialisation is not expected before 2025. Since the required modifications are minor, investment costs are estimated at EUR 5 /t.

## **7.3 Hall-Héroult process**

### **Wetted drained cathodes**

This option involves the development of an inert titanium diboride (TiB<sub>2</sub>) cathode (also called wettable cathode). Wettable cathodes allow the reduction of the anode — cathode distance. The potential energy savings are estimated at up to 15-20 % (JRC, 2007), or 3.05 MWh/t in combination with inert anodes. The technology is expected to become commercially available around 2020 (IEA, 2010).

Wettable cathodes are a prerequisite for inert anodes. The annual benefits of the combined installation of wettable cathodes and inert anodes are 3.05 MWh/t Al, which amounts to some EUR 152.5 /t Al (assuming an average electricity cost of EUR 50 /MWh). The total investment is around EUR 610 /t Al (Worrell, 2004). As the investment of inert anodes is around EUR 86 /t Al then the investment in wettable cathodes is about EUR 524 /t Al. There are no extra operational costs expected.

In the model, the total energy savings of wettable cathodes and inert anodes are split up according to their payback periods.

### **Inert anode (PBANOD)**

Currently, there is an ongoing research on inert anodes (Berkeley Lab, 2008), and its full commercialisation can be expected by 2030 (IEA, 2010). With inert and dimensionally stable non-carbon anodes not consumed in the electrolytic process we can expect substantial energy efficiency increases. The highest efficiencies can be achieved when the anode is combined with a stable wettable cathode. The combination of inert anodes and wetted cathodes can reduce energy requirements in the electrolysis and anode manufacturing processes by 3.05 MWh/t and CO<sub>2</sub> emissions by 1.65 t per t aluminium compared to the typical modern Hall-Héroult technology (Choate, 2003; HWWI, 2005). Fuel consumption would also be reduced as the anode baking facility is no longer required. Finally, non-carbon anodes would remove the source of carbon for PFC generation.

Inert anodes do not incur extra operational costs (Alsema, 2000). Capital costs are estimated to be around EUR 86 /t Al and include the retrofit and the new anode manufacturing equipment (SKM, 2013). However, as mentioned already, wettable cathodes are a prerequisite for the introduction of inert anodes.

It is worth mentioning the project AGRAL (EU, 2015b), co-funded by the EU under the Sustainable Industry Low carbon Scheme II (SILC II) (EC, 2015c). This project is aimed at developing the manufacturing technologies of a specific cermet (composite material composed of ceramic and metallic materials) that can be used as an inert anode in the Aluminium industry, and can decrease by 50% CO<sub>2</sub> emissions compared to currently used carbon anode

### **High temperature carbothermic reduction of alumina (Balomenos, 2009)**

Carbothermic reduction is the only non-electrochemical process that has shown potential for aluminium production. This technology has been the subject of extensive research for more than 45 years. Carbothermic technology has the potential to produce energy savings of 34 % compared to a modern Hall-Héroult carbon anode technology (Green, 2007). The different options handled have the potential to reduce capital investment by around 50 % (Sayad-Yaghoubi, 2013). Therefore, we estimate the investment costs at EUR 3000 /t Al. Once available, a carbothermic plant will be the preferred option for new plants. However, it is not expected before 2050 (IEA, 2010).

### **Lower the electrolysis temperature (PBRTE), while maintaining stable operations**

In current practice, electrolysis is performed at temperatures of 1233 K, far above the melting point of aluminium (933 K). Theoretically, a reduction of temperature to around melting point could decrease electricity use by 1-1.5 MWh/t.

The estimated savings of this practice are around 0.7 MWh/t (5 %) (JRC, 2007). The extra operational cost of decreasing the electrolyte temperature by optimisation of the electrolyte composition is about EUR 75 /t (= 5 % of the aluminium price) (Alsema, 2000).

This technique is only now becoming available on the market. To our knowledge, none of the smelters uses the lower electrolyte temperature yet. Also, the additional energy delivered to the cast house, in form of superheated metal, is typically used to remelt scrap. Thus, lowering the metal temperature might be partly offset by higher energy consumption in the cast house (EAA, 2014).

### **Application of a dynamic AC magnetic field**

To avoid short-circuiting of the cell, it is necessary to maintain a minimum distance between anode and cathode. However, the greater the electrode separation, the greater the resistance of the cell: this in turn requires more electricity to be used. Researchers at Coventry University (Carbon Trust, 2014) have found that the application of a dynamic AC magnetic field significantly suppresses ripples in the molten aluminium, enabling smaller electrode separation and therefore lower electricity use.

The energy savings achieved with this technique are between 5-20 % (Carbon Trust, 2014). The investment costs for a 250 000 t smelter are around EUR 20 million (Dijkmans, 2012), or EUR 80 /t Al.

This option is unnecessary if drained cathodes are successfully implemented (EAA, 2014).

### **Carbon capture and storage (CCS)**

Carbon capture and storage (CCS) from exhaust gases from electrolytic cells has received very little attention in the literature so far. Due to the inherent features of the effluents produced by primary aluminium smelters, current approaches for carbon capture cannot be applied in a straightforward way.

(Lassagne, 2013a; Lassagne, 2013b) present two potential solutions for the capture of direct CO<sub>2</sub> emissions from electrolytic cells. The first study verifies whether or not the traditional monoethanolamine (MEA) aqueous solvents can be economically attractive for the aluminium industry. In order to check the possibility of reducing capture costs, this study also analyses the effects of the increase of CO<sub>2</sub> concentration in the flue gas (achieved by reducing cell ventilation) and plant thermal integration. Apparently, 4 vol % CO<sub>2</sub> concentration in the flue gas is the most economically and technically sound configuration. The second study evaluates the possibility of using a new solvent that can make the capture more economically attractive. It includes a technical and economic study of capture using a blended aqueous solution of 2-amino 2-methyl 1-propanol (AMP) and piperazine (PZ). The 4 vol % CO<sub>2</sub> concentration in the flue gas is used for the study. The new solvent reduces the capital costs by 25 % and the operating costs by 29 % compared to the first solution (based on MEA).

We assume that the MEA technology would be available from 2020 and the AMP technology from 2030 onwards, since MEA is a known technique and AMP/PZ is new technology.

This option would become unnecessary if inert anodes are successfully implemented (EAA, 2014).

Table 7-2 Costs and availability of CCS techniques for a 260 000 t primary aluminium smelter (Lassagne, 2013a)

	MEA	AMP+PZ
Total Capital Cost (IPE) (EUR/t Al)	136	102
Total annual operating cost (EUR/t Al)	58	41
Available from	2020	2030

#### **7.4 On-site power production**

##### **Carbon capture and storage (CCS) applied to power plants**

Carbon Capture and Storage (CCS) can be applied to power plants. The only on-site fossil-fuel powered plants operating in the aluminium sector in the EU and Iceland today are gas-fired CHP plants. Their exhaust gases can be cleaned with CCS technology, capturing up to 90 % of the CO<sub>2</sub> emissions from the gases. A pilot project for CCS at a CHP plant was under development for several years, until it got cancelled by the Norwegian government in September 2013 (CCM, 2014).

Rubin, 2012 estimates the costs of equipping a CHP plant with CCS technology at around EUR 425 /kW of installed capacity. No additional operational costs are associated with this technique. We assume that 90 % of the CO<sub>2</sub> would be captured.

## 8 Model of the European aluminium sector

This chapter describes the model developed to analyse prospective scenarios of the industry up to 2050. The goal of the model is to illustrate the potential trend of energy consumption and GHG emissions for European aluminium. The model follows a bottom-up approach, that is, bases the prospective trend of the industry on an analysis at plant level of the cost-effectiveness of potential retrofits. Therefore, the model individually handles each alumina plant, primary smelter, on-site anode bakery, on-site power plant, on-site casting and uses some representative plants for the secondary smelters. The potential retrofits analysed are the best available technologies (BATs) and Innovative Technologies (ITs) described in chapters 6 and 7.

### 8.1 Model core structure

The starting year of the simulation is 2010 because it corresponds to the latest information available from the EEA Environmental Profile Report (EAA, 2013). The current situation of each plant (operational, mothballed, closed, planned, or under construction) is taken into account. Mothballed/closed plants are included because in some scenarios it may be possible to re-open these plants.

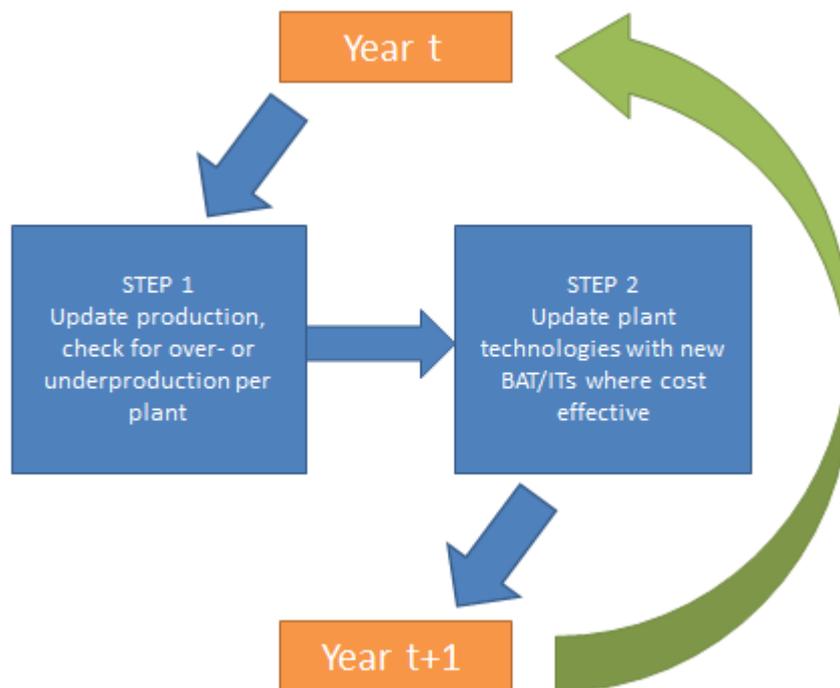
In addition to the decision-making criterion for new BATs and ITs that forms the core of the model, there is also an additional check carried out in each year simulated. Each year the existing plants have to prove to be able to deliver the total requested output (without exceeding a user-defined production maximum). Otherwise the installation of new facilities or the re-opening of mothballed or closed plants may be required. These checks form the core of the model and are further explained in the following sections, as well as all the input data needed to perform these checks.

The model works in an iterative way up to 2050, i.e. these checks are carried out year by year and the cost-effectiveness of all potential retrofits in each plant is analysed. Once the situation in each year is fully described, the year number is increased by one, and the cycle starts again.

Section 8.4 enumerates the input parameters of the model, and chapter 9 describes the exogenous values of the model. Among these exogenous variables is the electricity price, and it is noteworthy that in Europe there are large differences in the electricity prices paid by each company. These prices practically determine to a large extent which plant is profitable and which is not. Even a plant with the latest and most efficient technology can be forced to close because of higher electricity prices. A major issue for the model is that electricity prices at plant level are largely confidential, which makes it difficult to represent the actual situation correctly. The model uses a best estimate for the electricity costs by country (as explained in section 9.2).

The core model structure is illustrated in Figure 8-1.

Figure 8-1 Core structure of the aluminium-plants model



Steps 1 and 2 in this Figure will be further explained in the sections below. As for the structure of the industry in this model, the three major separate processes are:

- Alumina refineries, with bauxite as input, and alumina as output;
- Primary smelters (electrolysis plants), with alumina as input and aluminium as output, this includes on-site casting, on-site anode bakeries (for those plants which have them), and on-site power production (for the plants to which this is applicable). The on-site anode bakeries, power plants and casting facilities will be treated in the model as separate plants because they have their own BAT and IT measures. On-site means at close distance from the electrolysis plant, and under the same company umbrella. In some cases, on-site anode production produces more than is needed for their own smelting, and in this case the additional anodes are sold to other smelters;
- Secondary melters (using scrap), with scrap as input and aluminium as output.

Nearly all of the European alumina production is used in European smelters. We assume that, even if reduction of primary production is possible, the production of alumina refineries will remain constant through export of possible surpluses. Therefore, the rule for alumina production is as follows: the production is the maximum value of:

- The current (2010) production in Europe, and
- The needs of primary production in Europe

In any case, the model does not change the number of alumina refineries. Since bauxite is much more abundant in other parts of the world, it would be more profitable to build a new refinery anywhere else. Therefore, the model assumes that the total alumina production in Europe corresponds to the maximum use of the current installed capacity.

For on-site facilities such as anode bakeries, power plants and casting, it is assumed that the inputs and outputs are related to those in the primary smelter.

## **8.2 Plant performance**

One key parameter needed to assess plant performance on an annual basis is the requested production. Throughout the simulation, aluminium production equals demand. The baseline scenario assumes that the ratio between primary and secondary production remains constant. This enables us to analyse the effect of a different ratio between primary and secondary production in a specific alternative scenario.

The model bases its calculations on three inputs with regard to production/availability in the study area (EU-28 + Iceland):

- Primary aluminium production (in the form of semi-finished products, after casting into e.g. aluminium billets)
- Secondary aluminium production (also in the form of semi-finished products, after casting)

As a first step of the model, the production figures for each year are distributed over the facilities. This allocation proceeds first with the plants with the lowest production costs (the most economically advantageous). It is assumed that all the plants (except the last one with allocated production) operate at their 'practical maximum'. This practical maximum accounts for downtime due to maintenance and other disruptions, and although it is initially set to 95 % of the capacity, it is configurable in the model.

The plant with the latest allocated production serves to balance production with demand. Facilities without allocated production are mothballed. The model allows the user to configure the maximum number of years that a plant can be mothballed. Although initially this parameter is set at 5 years, it cannot exceed 9 years. Re-starting a plant that has been idle for longer is considered unrealistic. Idling a plant for 1 year only is economically uninteresting. The costs of a partial shutdown and subsequent start-up of a plant can amount up to EUR 10 million, for both shutdown and start-up (EUR 20 million total) (Dijkmans, 2014). During normal operation of the plant, the heat of the process keeps moisture outside of the factory hall, while shortly after a plant shutdown, technical degradation sets in.

In case of a need for new smelters, mothballed plants will have preference over new plants. If new plants are needed, and there are not any mothballed plants available, the new plant will be based in Iceland (cheapest electricity). We assume that those new plants will incorporate all available BATs and ITs.

### **8.3 Installation of new BATs/ITs**

As mentioned in section 8.1, the core of the model is an annual analysis at facility level of the cost-effectiveness of new Best Available Technologies (BATs) and Innovative Technologies (ITs) in the European aluminium industry, see step 2 of figure 8.1.

The implementation of the improvements respects the following conditions/constraints:

- The BAT/IT measure can only be implemented if it is a feasible measure for the plant type considered, and if it has not yet been implemented;
- The economic criterion used to decide whether any BAT/IT is cost-effective is the length of time taken to recover the cost of the investment — the payback period. In order to make an investment, its payback period has to be lower than a given number of years. The payback period is initially set to 5 years. The return on investment is produced by savings in electricity, fuel use, emissions of CO<sub>2</sub> and PFCs, and the possible reduction of other operational costs (e.g. lower labour costs).
- As long as they comply with the compatibility and payback period criterion, multiple BATs/ITs can be implemented simultaneously in the same plant. The user can specify the maximum limit to the number of BAT/IT measures allowed in each facility per year. Setting a value higher than one assumes that the high investment cost associated with multiple measures is not a problem, which may not be true in practice. In order to avoid being overly optimistic from the point of view of the investment capacity of the industry, in all simulations that follow we set this parameter to one. In any case, the simultaneous implementation of several measures saves downtime, and therefore operational costs, which is obviously more economically advantageous.

### **8.4 Input data**

This section only names inputs and outputs, while the source of the information and the values used are presented in chapter 9.

The data from the plant that the model uses as input are:

- Plant name and location
- Type of plant (alumina refinery, prebake smelter, Söderberg smelter, on-site anode producer, on-site power plant)
- Installed capacity (t/year)
- Year the plant started operation, and year of last modernisation
- Status of the plant (operational, mothballed, closed, under construction, planned)
- Capacity factor (ratio between production and total capacity)
- Fossil fuel consumption, per fuel type (per tonne of product)
- Electricity consumption (per tonne of product)
- Gross and net anode consumption (kg per tonne of product)

- Actual PFC emissions from the plant (kg per tonne of product)
- List of BAT measures already installed in this plant.

Regarding the BAT/ITs, the information included is:

- Plant type to which it can be applied
- Investment costs
- Running (O&M) costs
- Savings in terms of lower electricity consumption
- Savings in terms of lower emissions
- Other savings (e.g. more efficient working, fewer employees, etc.).

The data specific to the scenarios considered are:

- Trends in total production of cast aluminium in the study area using the primary as well as secondary production route
- Trends in the price of electricity (EUR/kWh) disaggregated by country, and for wholesale as well as industry price
- Trends in the price of fossil fuels (coal, diesel, heavy fuel oil, natural gas) (EUR/GJ)
- Trends in the price of CO<sub>2</sub> emissions (EUR/t).

Although the plant database is based on 2010, a number of changes have happened between then and the year of this report. (A few plants have been closed or mothballed). The model incorporates an update of the status of the industry up to 2014. Plants closed in 2012 are forced to do so in the model. The production scenario is adjusted to reflect the closure of these plants.

### **8.5 Limitations and possible improvements**

For plants for which there is a lack of information, the model uses averages, as explained earlier in section 3.2 and chapters 5 and 7. One notable case is the electricity price. Many plants rely on negotiated electricity prices. It is not possible to assess how those negotiated prices will evolve in the future, and even current prices are not known. For primary smelters, this is quite relevant information, since the price of electricity determines to a large extent their competitiveness. In any case, a way to counterbalance this constraint is by analysing different scenarios with alternative electricity prices.

In discussion with the sector and some other experts, some other aspects were raised. Although these other aspects can be potentially important, we only rely on qualitative

information about them, and therefore they have not been taken into account in the model. These aspects are:

- In the model, the plant size does not produce any economy of scale in the cost of new investments. That is, the cost-effectiveness analysis of new investments does not scale the investment costs based on the size of the facility.
- The amperage used in the model stays constant during the simulation, whereas in the electrolysis process it can be used to adjust the production. For instance, if in one period of the year more production is needed, the amperage at which the plant is operating can be increased. In such a way the production can be increased without additional O&M costs. In the same way, a period with lower demand can be approached.

## 9 Initial values and input scenarios

This chapter describes the scenarios developed to model the energy consumption and GHG emissions trend of the industry up to 2050. The baseline scenario of the model uses the EU Energy and GHG emissions reference scenario 2013 (EC, 2013).

In order to justify the preparation of the other scenarios, section 9.1 describes some trends that are essential for the aluminium sector. In section 9.2 we discuss the consequences of these trends for the scenarios chosen, and finally we summarise in section 9.3 the data chosen and sources for the scenarios.

### 9.1 *Qualitative description of global aluminium sector trends*

In this section we present some of the key trends for the aluminium sector in Europe, such as global consumption and production trends, environmental and sectoral policy trends, price developments, trends in EU policies and trends for the EU aluminium sector itself.

#### **Global consumption and production trends**

Primary aluminium consumption is expected to increase in global terms due to the expected growth, continued urbanisation and industrialisation of emerging economies. Aluminium consumption per capita in mature economies (such as Germany, South Korea, Japan and the United States) was relatively stable at around 20 kg in 2010, whereas in the developing economies ranged from 1 kg in India to 10 kg in China (Nappi, 2013). If emerging economies follow the same growth pattern as developed countries, primary aluminium consumption will double over the next 20 years. This doubling will require approximately 40-50 new smelters worldwide (Nappi, 2013), each with 500 000 t/y capacity. The required new capacity may be even higher as some older smelters will be decommissioned in that period (Nappi, 2013).

Since electricity is the main driver of competitiveness for aluminium smelters, new smelters will most likely be built in countries with lower power prices such as in the countries of Middle East, Russia, India, China, Malaysia and the African countries (Nappi, 2013). This will change the global production pattern for aluminium. Even though China is often foreseen as a potential major player on the global market, their global influence depends strongly on their local balance supply-demand. Meanwhile, the Middle East will probably become a leader in primary aluminium production (IAI, 2013).

#### **Environmental policies and sectoral demand trends**

The increased demand for aluminium is likely to come from the same major sectors in which it is used today, and it will be influenced by related environmental policies. Over the short-term (until 2020) a rise in demand is expected in buildings, road/transport and electrical cables (IEA, 2009). For example, aluminium is expected to be a sought-for material in the aeronautical industry, since aircraft manufacturing is on the rise (Richardson, 2014). A demand increase is also expected in automotive industry (as a lightweight material), in consumer electronics, heating, ventilation and air-conditioning applications (Harries, 2011).

Meanwhile, it is expected that carbon-related legislation will have an important influence on the aluminium industry. This effect can be two-sided: on the one hand, higher costs related

to emissions, power and raw material prices may impede supply growth, but on the other, CO<sub>2</sub> caps favour energy efficiency, green buildings and other end-use sectors that utilise aluminium-based solutions (Nappi, 2013). Therefore, stricter environmental policies are generally seen as an opportunity by producers (Harries, 2011).

### Prices

Aluminium is a US-dollar based commodity, listed on the London Metal Exchange (LME). Thus, the fluctuation of the US dollar can explain some price variations that have nothing to do with the industry fundamentals (Nappi, 2013). The general trend since the 1970s has been downwards, with an additional hit in 2009 as a consequence of the economic downturn. The aluminium price depends directly on the supply and demand of the metal. Undersupply and resulting higher prices are usually balanced within a few years. Speculation and warehousing (storing the purchased metal before delivering it to the final consumers, charging a rental fee) further affect the price — normally upwards but only in the short-term (ECORYS, 2012).

### The aluminium industry in the EU

In the EU, the aluminium supply is met by local primary production, imports and recycled aluminium by local refiners and remelters. The output of primary smelters in the EU in 2012 was 2.1 million tonnes. Meanwhile, the recycling of aluminium in the EU has been increasing steadily over the past 30 years, and in 2012 was 4.1 million tonnes. Nevertheless, as downstream activities (that transform intermediate and semi-finished aluminium products into finished manufactured products) have grown, so has the EU's import dependency. In 2012, the EU import of primary aluminium amounted to around 4.5 million tonnes (pp. 181-182 of CEPS, 2013), with Norway being the main supplier. Historically, the second biggest trading partner has been Russia, although recently Iceland replaced Russia as the second largest provider of imported metal (CEPS, 2013).

### EU policies

The aluminium industry in the EU is affected by different European Union policies and legislation, including energy, environmental and climate change, competition and trade policies. Some of the key legislative documents influencing the aluminium industry are the directives on the EU Emissions Trading System (ETS), internal energy market and renewable energy, air and water quality and waste management. General policies with an impact on the industry include the 2020 strategy, resource efficiency, low carbon and energy roadmaps. As of 2013 the ETS entered its 3rd phase and thus now covers the aluminium sector and PFCs emissions, which did not fall under its scope in the preceding phases. In terms of energy policy the largest impact on the aluminium industry comes in the form of transmission and renewable energy sources (RES) support costs, and the ETS indirect cost via electricity prices. Nevertheless, the level of these costs differs widely between Member States; in some countries the impact of these costs on the aluminium sector is negligible, while in others it is quite significant. Further costs are related to environmental legislation on pollution prevention and control (CEPS, 2013).

## 9.2 *Baseline scenario and alternative scenarios*

Based on the major trends identified for the aluminium industry, in the last chapter we analyse a total of six scenarios; a baseline scenario and five additional ones that consist of two scenarios with varying trends in CO<sub>2</sub> prices, two additional scenarios with alternative trends in the electricity prices and a last scenario in which the secondary route is the dominant one at the end of the simulation. This section describes the input data for these scenarios.

### CO<sub>2</sub> price variations

The ETS is expected to play an important role in the EU and affect the industries that fall under its scope. Therefore, the price of CO<sub>2</sub> is an important input for the model and the respective scenarios. Despite the fall of the CO<sub>2</sub> price in Europe in recent years the EC 2013 Reference Scenario foresees an increase in these prices at a level as high as EUR 100 /t CO<sub>2</sub> in 2050. Meanwhile, other sources provide more conservative projections and even a total collapse of the CO<sub>2</sub> price (IHS CERA, 2012). Therefore, with respect to the price of CO<sub>2</sub>, we analyse the following scenarios:

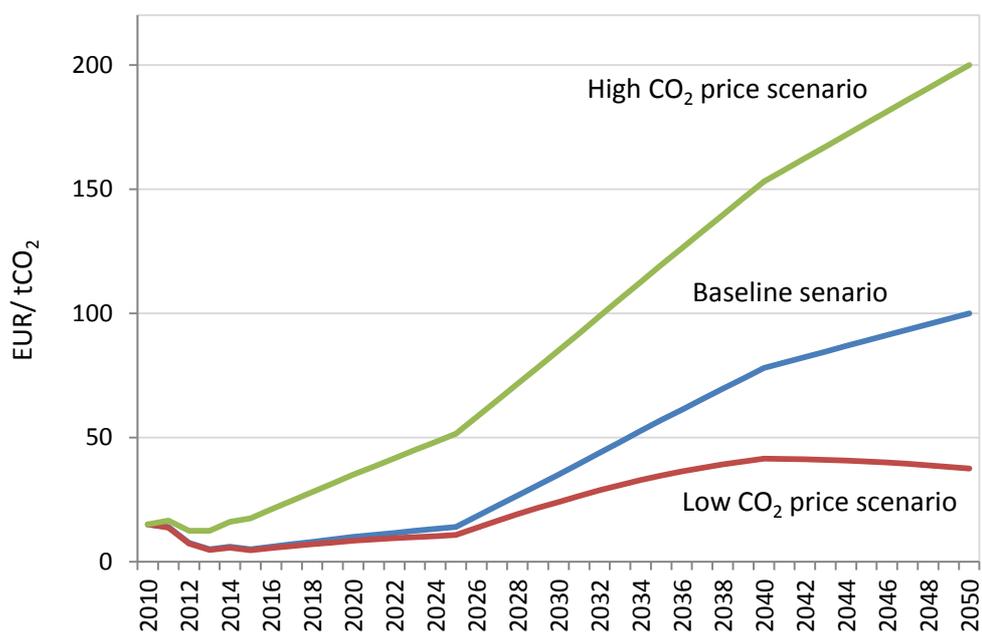
- **High CO<sub>2</sub> price**, in which in 2050 the final CO<sub>2</sub> price is **twice** the CO<sub>2</sub> price of the baseline scenario (table 9.1 gives all initial and final values in the baseline scenario and the values that differ from them in the rest of scenarios)
- **Medium CO<sub>2</sub> price**, corresponds to the CO<sub>2</sub> price of the **baseline scenario**, this trend of the CO<sub>2</sub> price is based on the (EC, 2013) reference scenario.
- **Low CO<sub>2</sub> price**, in line with the Global Redesign Planning case of (IHS CERA, 2012). This last scenario assumes that market forces and shared interests among the major powers to expand trade and investment foster robust economic growth. Moreover, disputes over the argument that greenhouse gas (GHG) policies and nuclear proliferation create tensions that lead to periodic doubts about the durability of globalisation. Such tensions and a shared interest in sustaining globalisation lead to new international institutions, as the existing ones adapt to manage a complex world

These three scenarios allow to analyse the effects of the ETS on the aluminium industry and an identification of the level of CO<sub>2</sub> prices which produce has the largest changes in energy consumption and GHG emissions of the industry.

Table 9-1 Initial and final values that define the different scenarios

Scenario	CO2 price		Wholesale Electricity price		Primary Production		Secondary Production	
	EUR /t CO2		EUR/MWh		Mt Aluminium		Mt Aluminium	
	2010	2050	2010	2050	2010	2050	2010	2050
Baseline	15	100	43	45.2	3.4	4.8	5.36	7.6
Low CO2 price		37.5						
High CO2 price		200						
High electricity price				100				
Extra high electricity price				200				
Alternative secondary						1.17		11.2

Figure 9-1 Carbon price projection (EC, 2013, IHS CERA, 2012)



## Electricity price variations

Since electricity cost represents one of the largest expenses for primary smelters, we can expect that variations in electricity price will affect these plants in an important way. Assuming that the electricity price is mostly affected by national policies and is country-specific, we use projections for the wholesale industry prices in each country for the industry (Textbox 9.1 provides an additional discussion about on-site power generation and its influence on prospective prices). The three scenarios for electricity price are based on the following electricity prices:

- **High electricity price**, the final electricity price in 2050 is **three times** the corresponding price of the baseline price, (see table 9.1)
- **Medium electricity price**, the final electricity price in 2050 is **twice** the corresponding price of the baseline price.
- **Low electricity price**, which corresponds to the trend up to 2050 of the electricity price of the baseline scenario, in line with the (EC, 2013) reference scenario.

### Textbox 9.1: What factors determine the electricity price for aluminium plants?

#### What factors determine the electricity price for aluminium plants?

(CEPS, 2013) provides a detailed analysis of the factors that determine the electricity price for primary producers of aluminium. The main factor is whether or not plants are exposed to market prices (thanks to long term contracts) or have an on-site power generation unit. In the sample used in (CEPS, 2013) (with 11 out of 16 smelters in operation in 2012), the subsample of non-exposed plants (3 plants) paid an average electricity price of EUR 24.3 /MWh, whereas the subsample of 8 exposed to the market paid on average EUR 56 /MWh. According to (CEPS, 2013) the factors that determine prices in the latter group are: national wholesale price, national policies, energy mix, grid costs, or other tariffs.

This study assumes, based on current trends and signals from the market, that new long-term contracts will not protect primary producers in the future, at least not as much as the limited number of existing long-term contracts have done so far. According to (Pawlek, 2014b) one out of the two aluminium producers with auto-production is a gas-fired CHP primarily feeding heat to the alumina refinery on the same site and exporting electricity to the national grid. The other is a hydro auto-producer with a capacity (90 MW) that is not sufficient to meet the electricity needs of the smelter. For these reasons, this study assumes that all plants in the future will be exposed to electricity market prices.

These scenarios assume that once the long-term contracts have expired, low-cost smelters will reach the power cost of the highest-cost smelters (those buying electricity in the market) (CEPS, 2013). Therefore, we assume that in the future the primary smelters will pay a power price comparable to that on the wholesale market in the respective country, whereas alumina plants and secondary aluminium producers will pay the country-specific industry price. Consequently, we use the trend in electricity prices of the baseline scenario of the EU Reference Scenario (EC, 2013), and in order to define electricity prices by country, we escalate this trend with the ratio of the wholesale electricity price and industry prices (of consumption band IE) to the respective initial (in 2010) electricity price. The initial wholesale

price and industry prices come from the Platts Pan European Power Index (PEP) (EC, 2014c) and Eurostat (Eurostat, 2014), respectively.

### **Changes in production: variations in the share of secondary production**

An increase in demand for aluminium is expected on both a global and an EU level, resulting in a rise in production. Nevertheless, building new primary smelters in the EU is considered highly improbable. Therefore, the scenarios consider that the rise in aluminium demand is met by:

- **High secondary production scenario** or (alternative secondary production scenario), from (ECORYS, 2012). We assume a secondary aluminium production of 11.2 Mt in 2050; primary production is adjusted to keep the same total aluminium production (12.4 Mt in 2050) as in the baseline scenario.
- **Low secondary production**, this secondary production scenario is shared by all scenarios (except the previous one). In this scenario the production share of the secondary route is maintained constant over all the simulations, as suggested in (CEPS, 2013).

### **9.3 Variables common to all scenarios**

This section contains an explanation of the other variables common to all scenarios, and the references used.

Since the (EC, 2013) reference scenario does not include detailed projections of fuel prices, we use the impact assessment of the policy framework for climate and energy in the period from 2020 up to 2030 (EC, 2014b) to extrapolate the price trends for coal, natural gas, heavy oil and diesel oil. The end values are comparable to the ones presented in the EU Reference Scenario 2013 (Figure 6, page 17). Again, as the (EC, 2013) reference scenario does not cover the aluminium sector, the values summarised in Table 9.2 come from several sources discussed below.

Table 9-2. Values in 2050 of the parameters common to all scenarios

Variable in 2050	Value
Alumina production	1.4 Mt <sup>(1)</sup>
Price of alumina	EUR 330 /t <sup>(1)</sup>
Price of aluminium	EUR 2 541 /t <sup>(1)</sup>
Price of coal	EUR 4.86 /GJ <sup>(2)</sup>
Price of natural gas	EUR 9.87 /GJ <sup>(2)</sup>
Price of heavy oil	EUR 10.64 /GJ <sup>(2)</sup>
Price of diesel oil	EUR 14.18 /GJ <sup>(2)</sup>

1) Own extrapolations

2) Based on (EC, 2014b)

### Alumina production (in study area only)

There are no production forecasts available. Therefore, we use an extrapolation of historical (1992-2010) production data from (BGS, 2014).

### Primary aluminium production (in study area only)

Again, we use an extrapolation of historical (1992-2010) production data from (BGS, 2014).

### Price of alumina, EUR/t

Alumina has historically been priced as a percentage of the aluminium price quoted on the London Metal Exchange (LME) (Forbes, 2014), and contract terms have fluctuated in the range of 12-14 % of the LME aluminium metal price. Therefore, the model assumes the alumina price to be equal to 13 % of the aluminium price.

### Price of aluminium (primary/secondary average, or separately if needed), EUR/t

The price forecast uses historical data, combined with price forecasts by (JRC, 2007; World Bank, 2013; ECORYS, 2012). For the long-term outlook, we take an average of the available price projections. This long-term outlook matches the trend of aluminium prices from 1960 to 2010.

### Price of coal

Current European coal import prices were taken from the Dutch statistical bureau CBS, whereas the long-term gas price forecast is taken from the impact assessment of the policy framework for climate and energy in the period from 2020 up to 2030 (EC, 2014b). The EC forecast includes projections for 2020, 2030 and 2050. The values for intermediate years are obtained by interpolation

### Price of natural gas

Current European gas prices correspond to Eurostat values, while the long-term gas price forecast is taken from the impact assessment of the policy framework for climate and energy in the period from 2020 up to 2030 (EC, 2014b). The EC forecast includes projections for 2020, 2030 and 2050. The values for intermediate years are obtained by interpolation

### Price of heavy oil and diesel

Since there are no forecasts for heavy oil or diesel available, for both fuels we derived a standard ratio between them and the price of Brent crude oil from historical data, and based our price forecast on existing (and available) Brent crude oil forecasts from (EC, 2014b; World Bank, 2010).

### Price of scrap

Aluminium scrap comes in varying sorts and qualities. There is old scrap, from waste and used products, and there is new scrap from the aluminium manufacturing process. New scrap is mainly recycled internally and therefore difficult to price. Old scrap prices depend on the scrap content and quality.

For our reference year in the model, we use an estimated average scrap price of EUR 700 /t. However, the variability of the scrap prices is similar to that of primary and secondary aluminium prices. In fact, the three prices are highly correlated (as shown by King, 2001). Therefore, the model will use as price a value directly related to the aluminium price forecast.

### Price of bauxite

Bauxite used in Europe is imported, chiefly from Guinea, Australia and Brazil. There is no world market price for bauxite. Most metallurgical-grade bauxite is purchased under long-term contracts. Contract terms are not normally made public. Bauxite prices for the EU are not available. Since both the US and the EU have to import the vast majority of their bauxite, we will assume that EU prices are similar to the US bauxite import prices (USGS, 2014).

Table 9-3 US import bauxite prices, (USGS, 2014).

Year	Price EUR/t
2010	20.4
2011	21.6
2012	21.8
2013	21.1

Although an ever-increasing demand for aluminium, combined with degrading of qualities, will tend to increase bauxite prices in the long term, price volatility of bauxite will stay low if long-term contracts persist.

## 10 Simulation Results

This section analyses the energy consumption and GHG emissions trend of the Aluminium Industry in the EU and Iceland up to 2050 under all the assumptions and scenarios previously prepared. In section 10.1 we give the **overall** energy consumption and GHG emissions in the baseline scenario for the **whole sector**. Later in the same section, we consider the results **per tonne of cast aluminium**. The first section 10.1 finalises with the analysis of these trends **per tonne of cast primary aluminium**. All values are calculated to account for the energy and GHG emissions involved in the production of the final product (cast aluminium). This means that we only include the energy consumption and GHG emissions related to alumina manufacturing required for the final product.

The results for the alternative scenarios in section 10.2 will be about cast primary aluminium production in the alternative scenarios. Since in all alternative scenarios the contribution of the secondary route is similar to the one already presented in section 10.1, the results for the secondary production route are excluded.

Before proceeding with the analysis of the results, it is useful to provide in table 10.1 the model settings common to all the scenarios. These values are configurable by the user.

Table 10-1 Model settings

Setting	Value
Payback time for BAT or IT	5 years
Capacity for a new plant (to be built in Iceland)	250 000 t
Casting efficiency (liquid aluminium consumption per tonne of cast aluminium production)	0.875 t liquid aluminium / t cast aluminium
Alumina use in electrolysis (alumina consumption per tonne of liquid aluminium production)	1.92 t alumina / t liquid aluminium
Max. number of years mothballed for primary smelter	3 years
Max. number of years mothballed for alumina refinery	3 years
Maximum number of BAT/IT measures applied in one plant in one year	1
CCS efficiency (how much CO <sub>2</sub> reduction is achieved)	90 %
Electricity emission factor	0.465 kg/kWh

### 10.1 Baseline scenario

In order to analyse the energy-saving potential by the industry in the baseline scenario, figure 10-1 shows the total energy consumed in cast aluminium production. This figure

shows the case in which, under the assumptions of the baseline scenario, the model is run without allowing any retrofits. In this case, the growing trend of energy consumption is due to the growing aluminium demand. The notches that can be observed in the increasing energy consumption trend are caused by the installation of new facilities (with state-of-the-art technologies) in the model. These new facilities are needed to meet demand. All in all, by 2050 the energy consumption is around 21 % lower than without retrofitting.

Figures 10-1, 10-2, 10-3 and 10-4 (that show the total energy consumption and GHG emissions per tonne of cast aluminium), average the performances of the two different production routes. In any case, in the baseline scenario and in all other scenarios except the last one (see table 9.1), the weight of both production routes does not change over the simulation (the primary aluminium production accounts for 38.8 % of the total production). In the last scenario, this share goes from 38.8 % in 2010 to 9.5 % in 2050.

Figure 10-1 Total energy consumption in the manufacturing of the total cast aluminium produced in the EU and Iceland, considering or not the retrofits in the model.

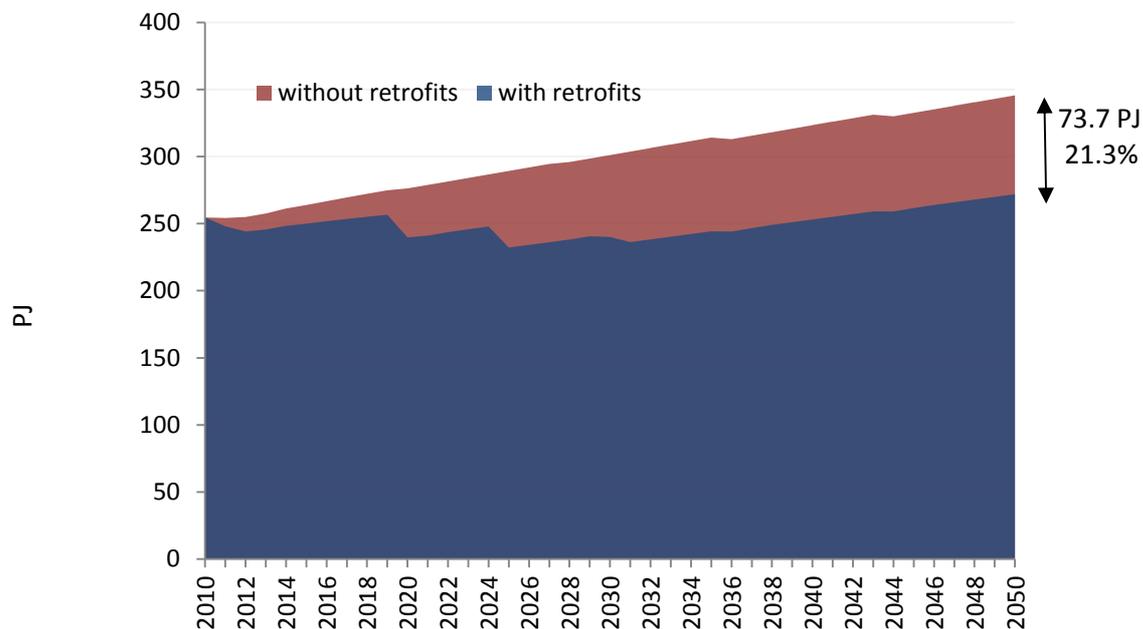


Figure 10-2 GHG emissions (both direct and indirect on the left-hand figure, and only direct on the right-hand figure) of total cast aluminium produced in the EU and Iceland, considering or not the retrofits in the model.

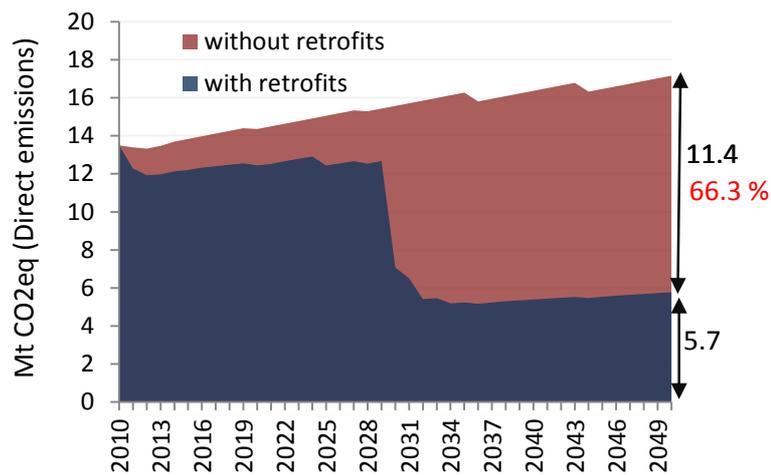
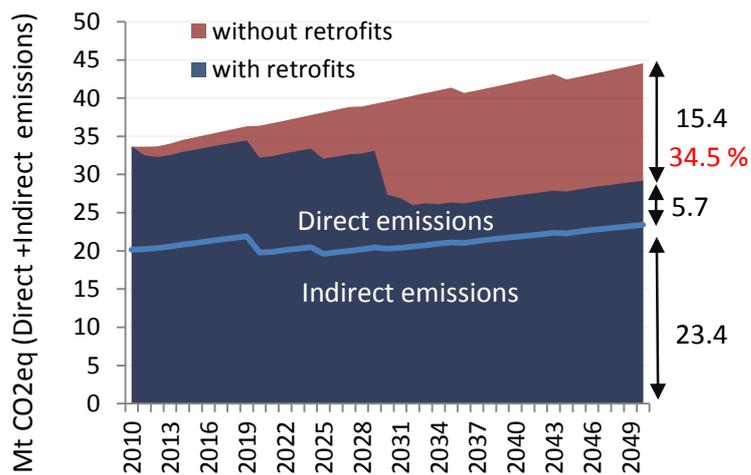


Figure 10-2 includes the total GHG emissions in the industry. The difference between the left- and right-hand figure is the inclusion or not of the indirect GHG emissions due to electricity consumption. Although indirect emissions are not produced within the aluminium sector, we include both figures to allow comparison. The absolute savings in GHG emissions are 11.4 or 15.4 Mt CO<sub>2eq</sub>, depending on whether or not we include the emissions from the power sector. Note that to estimate the GHG emissions we use the same carbon intensity factor (0.465 kCO<sub>2</sub>/kWh) throughout the simulation, without considering the expected decarbonisation of the power sector by 2050. Notice that in the right-hand figure, the direct emissions of 5.7 Mt CO<sub>2eq</sub> by 2050 are half the value of the potential savings of 11.4 Mt CO<sub>2eq</sub>; that is, the potential savings of direct emissions are two-thirds of the total direct emissions without retrofits.

Since the absolute value of the GHG emissions and energy consumption depend on the future fulfilment of the expected demand (which is an input into the model), it is useful to focus the remaining discussion on specific amounts, such as the energy and GHG emissions per tonne of product. In specific terms, at the beginning of the simulation, energy consumption is 68.1 GJ per tonne of cast primary aluminium and 4.3 GJ per tonne of secondary aluminium. At the end of the simulation, the respective values for the primary and secondary production are 52.5 GJ/t and 2.6 GJ/t. Using the production share of the primary route (38.8 %), and combining the energy consumptions from both routes, the decrease in the average energy consumption during the simulation time goes from 29.1 GJ/t to 22 J GJ/t, which means an average energy consumption decrease of 24 %.

Figure 10-3 also enables us to check that the electricity consumption in the secondary route is almost negligible compared to the corresponding value of the primary route. Switching from fuel oil to natural gas in the primary route involves the same amount of energy as the natural gas consumed in the secondary route.

As with the left-hand figure 10-2, figure 10-4 also includes the indirect GHG emissions attributable to electricity consumption. The decrease in figure 10.4 is due to the improvement in the electricity consumption of primary aluminium production. Also, the value of the carbon intensity factor could have been customised, based on the country, or by power plants associated with each facility. The specific GHG emissions of the overall aluminium production (including both routes) pass from 3.84 tCO<sub>2eq</sub>/t cast aluminium in 2010 to 2.36 tCO<sub>2eq</sub>/t cast aluminium in 2050. This is a GHG emission reduction of 38 %. However, since in most cases indirect emissions are beyond the control of the aluminium industry, we exclude them from the rest of the analysis. The direct GHG emissions per tonne of overall cast aluminium passes from 1.54 tCO<sub>2eq</sub>/t in 2010 to 0.47 tCO<sub>2eq</sub>/t in 2050, which means a reduction of almost 70 % of the initial value.

Figure 10-3 Total energy consumption per tonne cast aluminium produced in the baseline scenario (including primary and secondary Aluminium production).

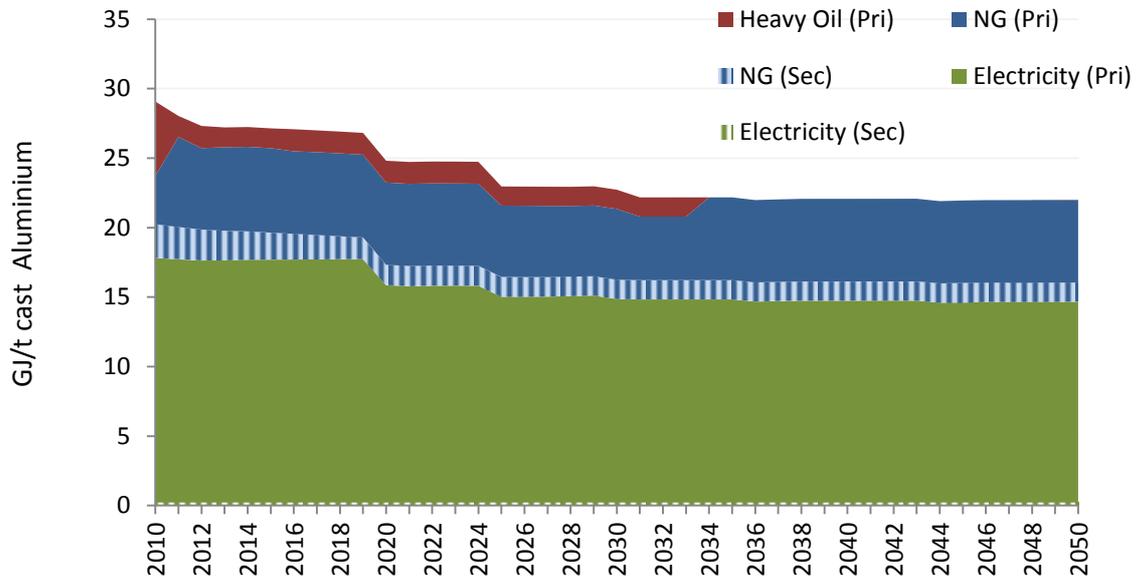
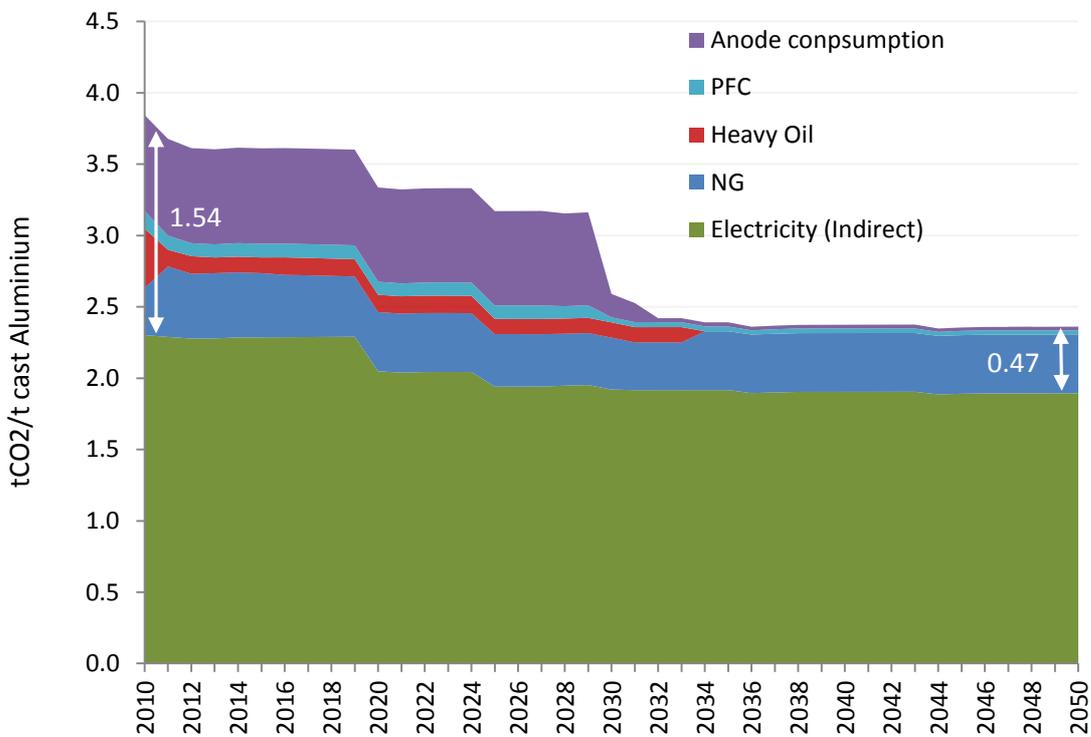


Figure 10-4 Total GHG emissions — direct and indirect (from the electricity consumed in aluminium manufacturing) emissions per tonne of cast aluminium in the baseline scenario (including primary and secondary aluminium production).



Figures 10-5 and 10-6 show the same information as figure 10-3, that is, the specific energy consumption, but now only for the primary aluminium production route. Figure 10-5 shows the energy consumption by manufacturing process, and figure 10-6 by kind of fuel consumed. Needless to say, there is no consumption of fossil fuels in the electrolysis process. Practically all the fuel oil consumption shown in figure 10.6 takes place in alumina manufacturing. This last process also uses natural gas. And natural gas is practically the only fuel used in anode manufacturing and aluminium casting.

Figures 10.7 and 10.8 show the direct GHG emissions per tonne of primary aluminium production. Again, figure 10.7 arranges the information by process, and in figure 10.8 by fuel consumed. Disregarding the indirect CO<sub>2</sub> emissions caused by electricity consumption, all the GHG emissions of electrolysis are due to the anode consumption and PFC. In these figures, the specific direct GHG emissions per tonne of primary cast aluminium pass from 3.6 tCO<sub>2eq</sub>/t in 2010 to 1.0 tCO<sub>2eq</sub>/t in 2050, which is a 72.4 % reduction of the initial value.

During the simulation there is a concentration of improvements in several stages; at the beginning of the simulation some plants still using heavy oil switch to natural gas, and there is also an incorporation of most of the pending optimisations. In 2020, wetted drained cathodes are installed in a number of primary smelters, reducing the demand for electricity. In 2025, there is the incorporation of two measures in many plants, which result in lower fuel and electricity consumption: Boehmite instead of gibbsite precipitation in alumina plants, and the application of a 'dynamic AC magnetic field' in the electrolysis. The great decrease of GHG emissions produced around 2030 is due to the introduction of the inert anode. Since the innovative 'dynamic AC magnetic field' technology is not compatible with the 'inert anode', those facilities that incorporate the 'dynamic AC magnetic field' in 2025 will later incorporate a CCS instead of the 'inert anode'. All in all, by the end of the simulation 78 % of the GHG emissions per tonne of cast primary aluminium is attributable to alumina manufacturing.

To illustrate which BATs and ITs have been installed and in which year, table 10-2 provides an overview of the BAT and IT measures implemented in the baseline scenario. Implementation in 2010 means that those BATs are currently installed in the plants. The BAT and IT measures not listed in this table are not implemented over the simulation.

Figure 10-5 Energy consumption per tonne of cast primary aluminium production in the baseline scenario (arranged by process)

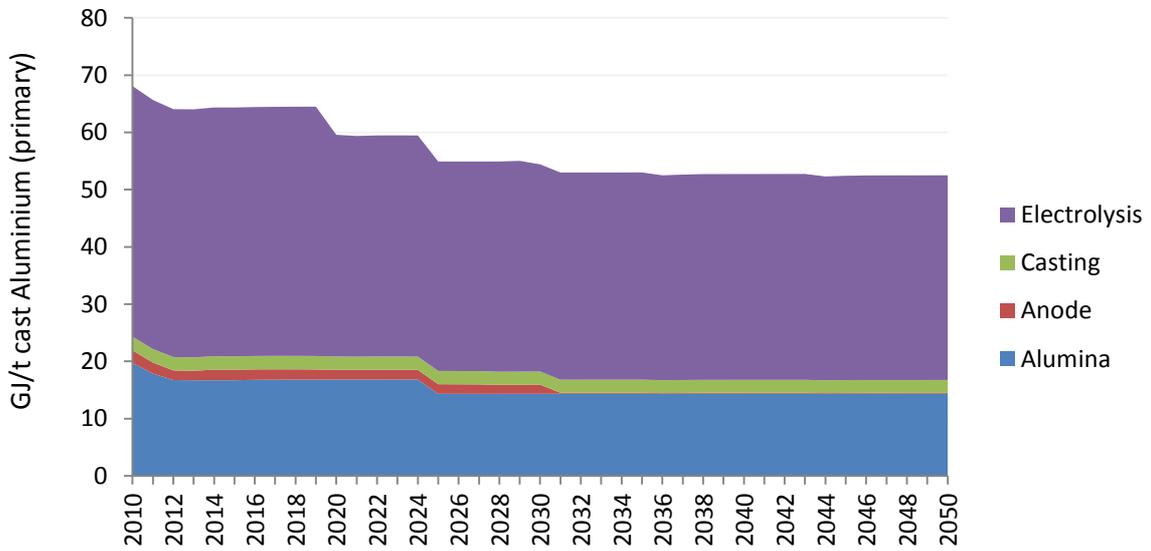


Figure 10-6 Energy consumption per tonne of cast primary aluminium production in the baseline scenario (arranged by kind of fuel)

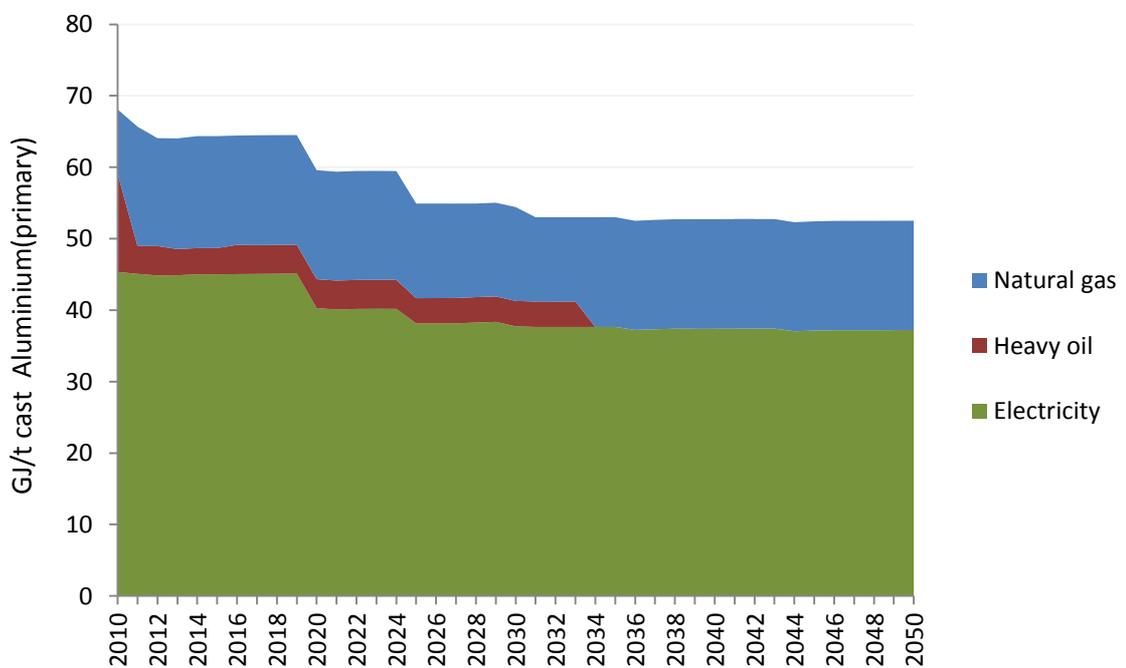


Figure 10-7 Direct GHG emissions per tonne of cast primary aluminium production in the baseline scenario (arranged by process)

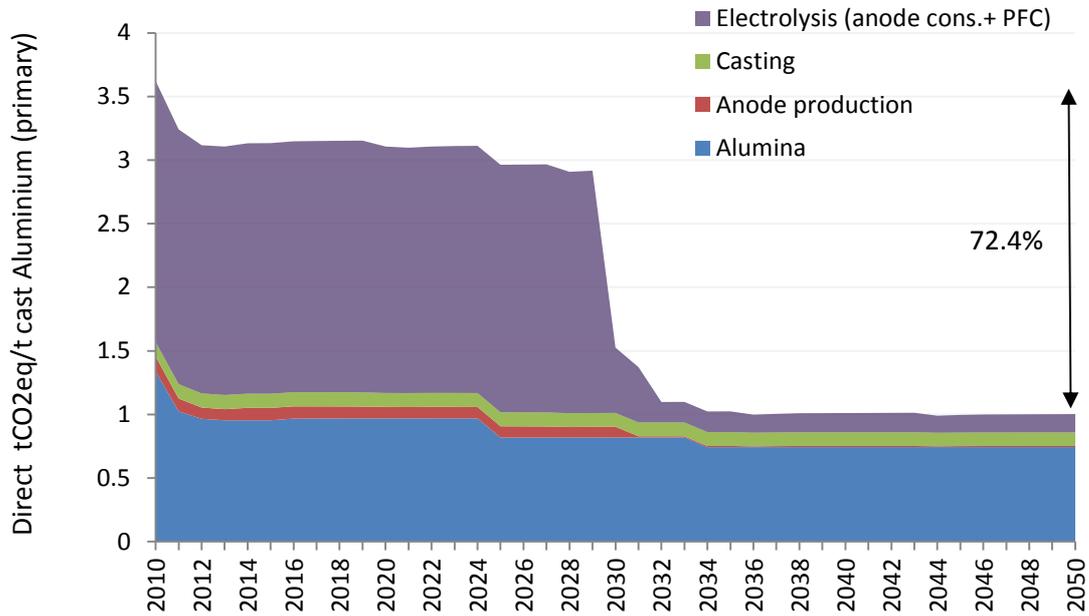


Figure 10-8. Direct GHG emissions per tonne of cast primary aluminium production in the baseline scenario (arranged by kind of fuel)

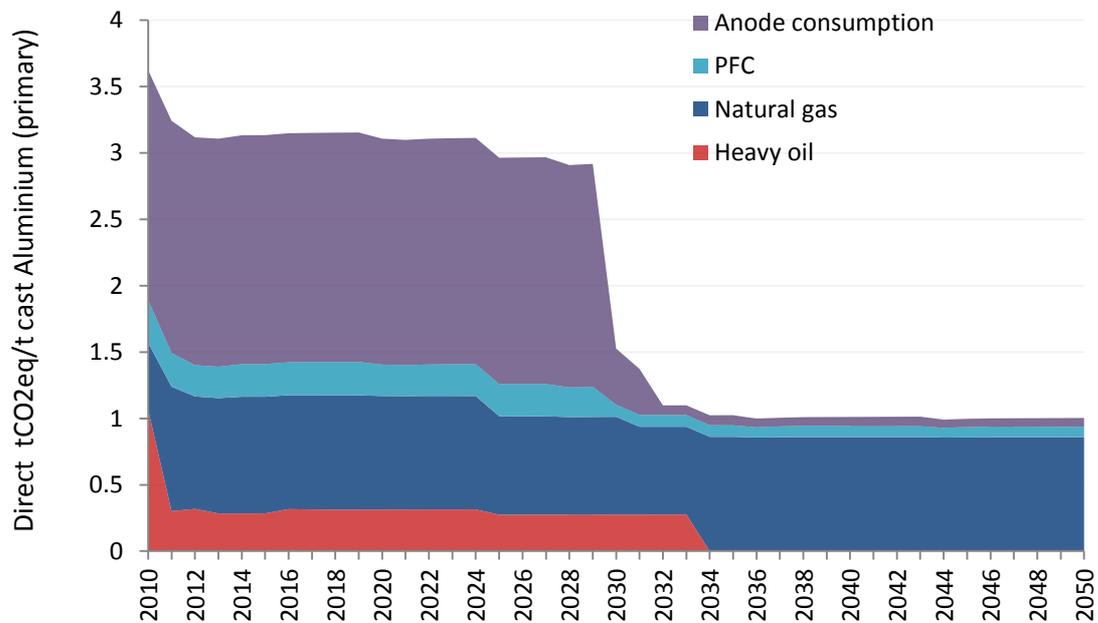


Table 10-2 Number of plants that have specific BAT and IT measures installed in the aluminium industry in Europe, per plant type for selected years (excluding secondary smelters)

Plant Type	BAT / IT name	2010	2011	2012	2015	2020	2023	2025	2030	2032	2034	2031	2040	2050	
<b>Alumina plant</b>	Boehmite instead of gibbsite precipitation	0	0	0	0	0	0	6	6	6	6	6	6	6	
	Co-generation	2	3	6	6	6	6	6	6	6	6	6	6	6	
	Fluidised bed kilns	3	6	6	6	6	6	6	6	6	6	6	6	6	
	Natural gas used as fuel	3	5	5	5	5	5	5	5	5	7	7	7	7	
	Tube digesters	1	1	1	1	1	1	1	1	1	1	1	1	1	
<b>Anode bakery — integrated</b>	Recuperative or regenerative burners	0	10	10	10	10	10	10	10	10	10	10	10	10	
<b>Pre-baked electrolysis — PFPB</b>	Application of a dynamic AC magnetic field	0	0	0	0	0	0	3	3	3	3	3	3	3	
	CCS AMP+PZ	0	0	0	0	0	0	0	0	0			3	3	
	Inert anode (PBANOD)	0	0	0	0	0	0	0	11	11	11	12	12	12	
	Optimisation of the electrolysis process PHASE 1	16	16	16	16	16	16	16	16	16	16	16	16	16	
	Optimisation of the electrolysis process PHASE 2	12	12	12	12	12	12	12	12	12	12	12	12	12	
	Optimisation of the electrolysis process PHASE 3	10	10	10	10	10	10	10	10	10	10	10	10	10	
	Optimisation of the electrolysis process PHASE 4	6	6	6	6	6	6	6	6	6	6	6	6	6	
	Wetted drained cathodes	0	0	0	0	11	12	12	12	12	12	12	12	12	
	<b>Söderberg electrolysis — PFVSS</b>	CCS AMP+PZ	0	0	0	0	0	0	0	0	3	3	3	3	3

## **10.2 Rest of scenarios**

The energy consumption per tonne of cast primary aluminium production in most of the other scenarios (figure 10.9) does not show relevant differences from the corresponding values of the baseline scenario. The only slight difference corresponds to the extra high electricity price scenario in which there is an additional 5 % decrease in the specific energy consumption (instead of reaching 52.1 GJ/t as in the other scenarios, it decreases to 48.6 GJ/t).

At the end of the simulation, the scenario with an alternative secondary production has a specific energy consumption of 53 GJ/t and 2.6 GJ/t for the primary and secondary aluminium production routes respectively. These values are quite similar to those of the baseline scenario (52.1 and 2.6 GJ/t). However, the different weight of both production routes produces an averaged energy consumption of 7.4 GJ/t cast aluminium. This value is one-third of the similar value in the other scenarios (around 23 GJ/t).

On the other hand, the trend in GHG emissions shows clear differences between the final values at the end of the simulation, and in the timing in which the decreases of GHG emissions happen. The scenarios varying the price of electricity provide all the same decreases of GHG emissions. In contrast, the scenarios with different CO<sub>2</sub> prices offer more alternatives to decrease GHG emissions and get different final values. For the low carbon price scenario, the GHG reduction achieved by 2050 is 66 % of its initial value in 2010, instead of the reduction of 72 % reached in the other scenarios. These differences are due to the timing and kind of technology related to the CCS implemented.

In the baseline scenario all facilities that in 2025 incorporate a 'dynamic AC magnetic field', in 2030 incorporate a 'CCS AMP+PZ'. The rest of the facilities that did not incorporate 'dynamic AC magnetic field' in 2025, incorporate in 2030 an 'inert anode (PBANOD)' instead of the CCS. Both the CCS and the 'inert anode' happen as soon as these innovations become available. When this happens (in 2030) the CO<sub>2</sub> price is EUR 35 /t CO<sub>2</sub>.

In the low CO<sub>2</sub> price scenario, in which the CO<sub>2</sub> evolves from EUR 15 /t CO<sub>2</sub> in 2010 to EUR 37 /t CO<sub>2</sub> in 2050, the CO<sub>2</sub> price in 2030 (EUR 24 /t CO<sub>2</sub>) makes the CCS profitable only for the two facilities with Söderberg technology.

Finally, the high CO<sub>2</sub> price scenario starts with the same price for the CO<sub>2</sub> in 2010 as the other scenarios, and ends with a final price of EUR 200 /t CO<sub>2</sub> in 2050. In this scenario in 2020, with a CO<sub>2</sub> price of EUR 35 /t CO<sub>2</sub>, the 'CCC MEA' becomes cost-effective. Again, the investment is made as soon as the IT is assumed to be available (in 2020).

Figure 10-9. Energy consumption per tonne of cast primary aluminium production in all scenarios

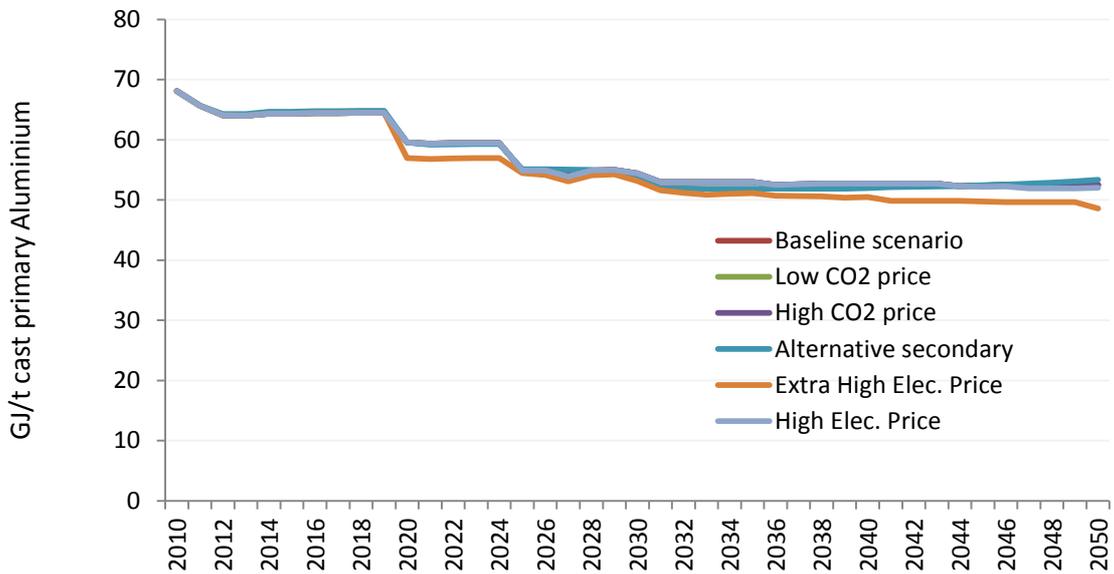
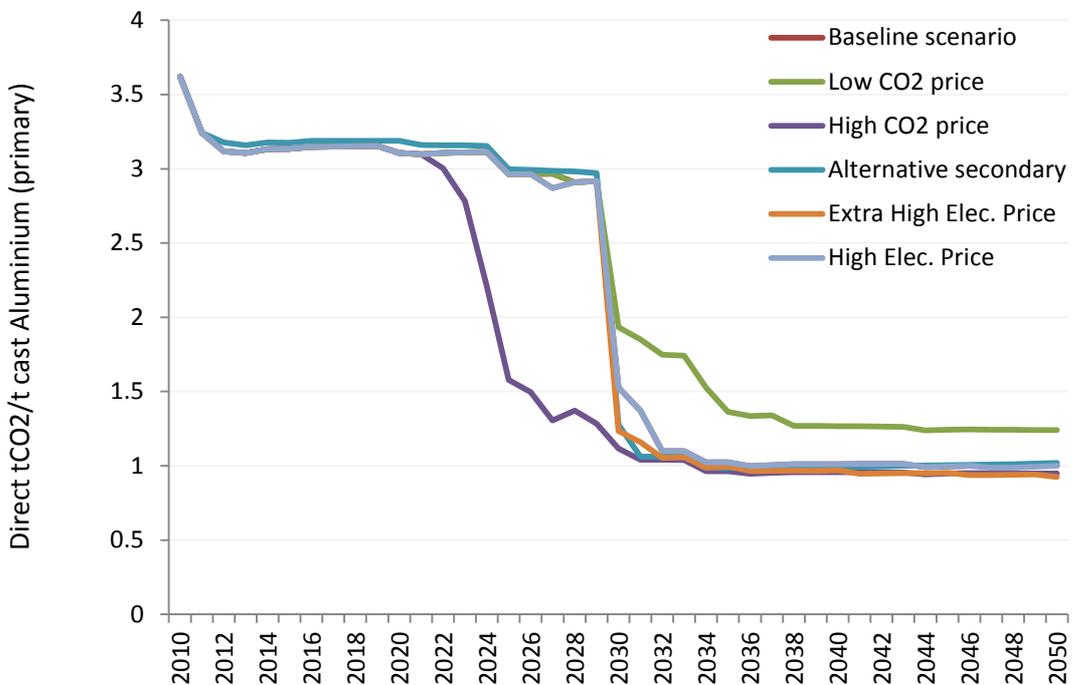


Figure 10-10. Direct GHG emissions per tonne of cast primary aluminium production in all scenarios



## 11 Conclusions

Before drawing some conclusions about the results, we need to highlight some precautions. This document reflects the potential trend in energy consumption and the GHG emissions of the industry under some assumptions. Deviation from these assumptions will make the actual trend differ from the results estimated. The first and most demanding assumption is that the European industry remains globally competitive, and therefore we assume that the European aluminium demand is met by European production in the same way as now. This can be challenging for some of the scenarios analysed if there are not similar global conditions (especially in the high electricity and allowance prices). The rationale of those scenarios is to analyse what the industry could provide in a cost-effective fashion to reduce GHG emissions and energy consumption under those circumstances. This potential is analysed without assigning more or less credibility to those scenarios. In any case, and as the communication on the Energy Union states (EC, 2015a) the policies to prevent carbon leakage should reflect the degree of efforts undertaken in other major economies. And the Commission, together with the Member States, will engage with other major economies to convince them to join Europe's ambition. This ambition is reflected in the agreement on the 2030 climate and energy framework that has defined the EU commitment for at least 40 % of domestic reduction in GHG emissions compared to 1990.

Also, although the uncertainty of some potential factors affecting the interest in adopting technological improvements have been tackled, by varying those factors in different scenarios, the values assigned to some of the detailed characteristics of the technologies is not exempt from uncertainty. Moreover, the list of technologies cannot be comprehensive, as for some of them there is no information publicly available.

Having in mind all these precautions, we also have to assert the ambition and degree of detail of this exercise, since it analyses the energy consumption and GHG emissions trend of the industry based on detailed information at facility level for all facilities involved in primary aluminium production, and in a simplified fashion, in secondary aluminium production. And as such, this model can be considered the first-of-its-kind for this industry.

The results obtained for all scenarios, except for the low carbon price scenario, agree on the final value of the specific GHG emissions of the primary production route, uncovering a potential for GHG emission reduction of 66 % for the low carbon price scenario and 72 % for the other scenarios. The decrease of GHG emissions are of the same order if we also include the secondary production route (results in an overall reduction of 69.5 %). Only when we include indirect emissions and consider both routes, the decrease of GHG emissions are reduced to 34.5 %. In absolute terms, this means in 2050 savings of 11.4 Mt CO<sub>2</sub>eq or 15.4 Mt CO<sub>2</sub>eq, depending on whether or not we consider only direct or direct and indirect GHG emissions savings, respectively.

There is also a convergence in all scenarios in the reduction of around 23.5 % of specific energy consumption in the primary production route. This value hardly changes to 24.3 % when including the secondary production route. In absolute terms, the energy savings in 2050 amounted to 73.7 PJ. The only scenario that differs from the rest is the extra-high-electricity price scenario, in which the specific energy reduction in the primary production route is 28.6 %.

In short, in absolute terms for the whole industry, energy consumption and direct GHG emissions can decrease from 2010 to 2050 by 21 % and 66 % respectively. And in almost all scenarios, for primary aluminium production there is a convergence in the reduction of specific energy consumption and direct GHG emissions of 23 % and 72 % respectively.

The model is designed to incorporate only cost-effective improvements. However, it relies on the hypothesis that some technology innovations (mainly the inert anode) will become available at some point in the future. Since these key technologies also include carbon capture and storage (CCS) or carbon capture and use (CCU), these findings confirm the critical nature of these technologies (EC, 2015a) in order to reach the 2050 climate objectives cost-effectively.

Since most of the savings uncovered in this study come from technologies that are in early stages of research, before being effectively implanted in the industry, these technologies will need a demonstration stage, and will have to go through the usual processes for diffusion of innovations. Therefore, one of the main conclusions is the clear need for a decided push and to create the right conditions to make these potential savings happen.

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